<u>Summary</u>

We thank the reviewers for taking their task seriously and providing us with detailed comments on our paper "Retrieval algorithm for rainfall mapping from microwave links in a cellular communication network". Referees #1 and #2 recommend to reject the paper, because no new results or methodology is presented. Referee #1 also advises to resubmit the paper. Moreover, they question the general applicability of the rainfall retrieval algorithm, because it has been optimized for a microwave link network in the Dutch climate. Referee #1 doubts the potential of this new measurement technique, a thought which is not shared by the other referees. Referee Heistermann and referee #4 acknowledge that our paper could be published in AMT after major revisions. All referees have concerns regarding the readability of our paper and suggest to significantly modify the code. It is recognized that the code works and it is appreciated that open source software is employed. The referees criticize the design of the code, and they provide many suggestions to improve it, e.g., remove hard-coded parameters, use functions, and program the different steps in the algorithm as modules.

It is our general feeling that we can address the concerns expressed by the referees, and refute them where appropriate, in order to improve our paper and the code, ultimately resulting in publication in AMT. The referees provide many useful suggestions, particularly related to the readability and the code.

Below we provide a response to the major concerns raised by the referees. We will address the main issues raised in the referees' summary, and also give attention to the most important specific or general comments. Note that the main review comments are repeated (regular font type), but that particularly the general and specific comments have been omitted. For these we refer to the AMTD website.

Response to referee #1
Referee #1 recommends to reject and resubmit the paper. This referee summarizes his/her findings as follows:
A method, a data set and a code (in the statistical programming language R) for the estimation of country-wide rainfall fields from commercial microwave links in the Netherlands is provided.

I don't think this paper merits publication. It is poorly written and structured, contains no new ideas, concepts or methods and is essentially reheated content from previous publications. The only new part is the R code that the authors share and the small data sample that comes with it. The code works but does nothing groundbreaking. It is highly specific to the Netherlands and contains many hard-coded empirically estimated parameters and thresholds that make it hard to transfer to other locations. I should also point out that the code does not comply with the general guidelines for programming in R and has not been tested properly. I strongly support and encourage data transmission and code sharing within the scientific community. But I seriously doubt that this contribution is going to be useful. I invite the authors to rethink their approach and resubmit a new draft that takes into account the numerous comments below. Most importantly, I think the authors should take the time to properly test their code and evaluate their methods before distributing them to the rest of the community.

R-CODE:
Here are some general suggestions that could help improve the code: (1) use shorter variable names (2) Wrap long lines (3) Use the assignment operator <- instead of = (4). Avoid hard coding, i.e., put the important input parameters in a separate config.R file, then source this file at the beginning of the main script. In this way, users can modify the variables more easily without having to modify the main code.

As stated in our paper, our intention is not to provide new analyses as such, but to provide: 1) a much more detailed description of our rainfall retrieval algorithm (not simply repeating previous papers), including an extensively tested computer code for users to adapt to their specific conditions; 2) a unique working example using real microwave link data (for the first time in the open scientific literature), which will allow users to test their own algorithms and compare the results with ours. The ultimate goal is to foster rainfall estimation using microwave links in Europe, Africa, Asia, Australia and North and South America. Moreover, a discussion is provided regarding the rainfall retrieval algorithm and its possible applications, which has not been given before in such detail. Note that AMTD produced a Similarity Report, showing that our manuscript has a Similarity Index of only 10%, mostly concerning terminology, literature references and acknowledgements. This confirms that our paper is not simply a repetition of earlier ones.

Referee #1 doubts the usefulness of rainfall estimation using microwave links in data sparse regions. However, the potential of using microwave links in these areas has been recognized by many authors to date. The interest in rainfall estimation employing microwave links in cellular communication networks is growing steadily, as can be gathered from the growing number of publications on this topic (see the extensive publication list in our paper). This interest and potential has also recently been recognized by Gosset et al. (2015), who report on a workshop held in Burkina Faso March 2015: "87 participants from 18 countries met to discuss the prospect for rainfall measurement and high-resolution mapping based on commercial micro-wave links in Africa. Experts from Europe and Israel provided training to African students, scientists and meteorologists on this innovative method.". Despite this interest, to date no computer code for data processing has been made publicly available, whereas the workshop clearly demonstrated the relevance to accelerate the uptake of this new measurement technique. This indicates the necessity of our paper.

Although rain gauges, radars and satellites have been specifically designed to measure rainfall, all of these devices face their own challenges. It is well known that radar rainfall estimates generally deteriorate for longer ranges from the radar. Satellite observations are often very indirect (e.g. estimates through cloud physical properties) or have long revisit times. Despite (new) satellite missions, microwave link data can still become important for ground-validation of or merging with satellite rainfall products. For instance, the IMERG product of the new GPM mission provides gridded rainfall products every 30 min with a spatial resolution of 0.1 degree. This is certainly a major step forward with respect to

TRMM, but one has to recognize that the rainfall retrieval algorithm heavily relies on temporal interpolation and additional data sources, since the actual satellite revisit time is typically a couple of hours. Moreover, links measure rainfall close to the ground, which is not the case for weather radar and satellites, and at spatio-temporal scales relevant for meteorology and hydrology (typically 1 s - 15 min; 0.1 - 20 km). Even if rain gauges are present, the number of links will often be an order of magnitude larger than the number of rain gauges in a region. The larger number of links in space has been demonstrated in our previous work to compensate for their lower accuracy with respect to rain gauges. Hence, rainfall information from cellular telecommunication networks is promising for hazardous weather warning, flood forecasting, food production, drought monitoring, etcetera. Finally, although it is indeed difficult to obtain transmitted and received signal level data from telecommunication companies, researchers have managed to obtain data for a limited, but expanding number of countries (Brazil, Burkina Faso, Czech Republic, Germany, France, Israel, Kenya, Switzerland, The Netherlands).

One of the referee's concerns is that we are promoting a technology that is bound to disappear. However, this is certainly not the case. Whereas The Netherlands is at the forefront internationally concerning deployment of underground fibre optical cable networks for telecommunication between base stations, the 35,000-km^2 country currently still contains between 8000 and 10000 microwave links (from cellular telecommunication companies and others). The telecommunication company we work with projects that there will still be several thousands of links in 2025. For other countries and continents the uptake of fibre optics will be significantly slower, lagging behind at least 5-20 years. Moreover, construction of fibre optical cable networks may not be feasible or economically viable in many mountainous or rural areas around the world. Therefore, we expect this type of cellular communication infrastructure to still be around for several decades worldwide. Why not attempt to use this existing infrastructure as a complementary source of rainfall information, in particular in those areas around the world with very few rain gauges, let alone weather radars?

Referee #1 also questions the general applicability of the code. Without adaptation, the developed rainfall retrieval algorithm will undoubtedly not work flawlessly for all other networks and or climates around the world. Nevertheless, many networks have similar characteristics as those in The Netherlands. A 15-min sampling strategy is common and has been used in several other networks (e.g. Messer et al, 2006; Leijnse et al., 2007a; Messer and Sendik, 2015). We advocate a pragmatic approach to first apply this algorithm to data from those networks and assess the quality of the derived rainfall maps. Sub-optimal parameter values or interpolation methods does not imply that rainfall estimates for other networks or climates would not be meaningful. As a next step the parameters of the algorithm could be adapted to local conditions, for instance based on recommendations from the International Telecommunication Union (ITU). Then it could be decided whether further modifications of the algorithm would be needed or not. For poorly gauged regions we suggest to optimize the algorithm, including interpolation methodology, employing data from a region with a similar climate and network, for which sufficient ground-truth rainfall data are available. Existing datasets from intensive measurement campaigns that have taken place all over the world (Hapex-Sahel, AMMA, etc.) could be a good starting point for this. Even if network characteristics are very different, e.g. in terms of sampling strategy, large parts of our code could still be used to develop algorithms suited for the specific needs of these networks. Although the rainfall retrieval algorithm contains several empirical parameters, the developed methods are not merely statistical in nature. Their general principles hold for other networks as well. For instance, the principle of the wet-dry classification, where data from surrounding links are used to distinguish wet and dry periods, makes use of the general fact that rainfall is correlated in space.

Although we only provide two full days of microwave link data from The Netherlands for the readers of our manuscript, our code has been tested on much larger data sets. Note that (an earlier version of) the code has been used in Overeem et al. (2011, 2013) to successfully estimate rainfall for the Netherlands. E.g., Overeem et al. (2013) apply it to a 12-day country-wide data set. Moreover, the code has also been applied to a 2.5-year data set with, on average, 2000 link paths (http://presentations.copernicus.org/EMS2015-157_presentation.pdf). The parameters concerning the wet-dry classification have been optimized using data from another period and are based on RSL data stored at 0.1 dB resolution (Overeem et. al., 2011). These values have been applied in Overeem et al. (2013) and in the current manuscript to an independent data set from another brand of links with slightly different antenna covers and a coarser 1 dB power resolution. This gives confidence in an important part of the rainfall retrieval algorithm. Moreover, we optimized the values of A_a and α using data from all summer months, all winter months and all months from a 2.5-year data set. It appears that the optimal values found for the summer months are very close to those from the 12-day calibration data set from summer, utilized here and in Overeem et al. (2013). Although the parameters based on all (winter) months are different, using the optimal values from the 12-day data set will generally only lead to a small decrease in performance (see last slide of http://presentations.copernicus.org/EMS2015-157_presentation.pdf). This confirms that even when those two parameters are based on summer rainfall, generally being more convective in nature in The Netherlands, relatively good estimates can still be obtained for winter months, which usually experience stratiform rainfall. Hence, application of the existing values of A_a and α to other rainfall types can still give reasonably good rainfall estimates. Also note that part of the algorithm has been successfully applied in all our papers dealing with rainfall estimation from microwave links, namely the relationship between path-averaged rainfall intensity and path-averaged specific attenuation. This relationship is also commonly employed in other studies.

In our paper we already discuss to some extent the sensitivity of our algorithm to the values of the parameters. For instance, Table 2 gives an overview of the parameters, their values and the factors influencing them. This can help to assess which parameters will change for other regions and networks. We will discuss this sensitivity more elaborately in a revised version of our paper.

To conclude, the feasibility of rainfall estimation for other networks and climates has been shown by many studies, albeit with slightly different rainfall retrieval algorithms.

We acknowledge that it would be preferable to develop a generally applicable code which works for different networks and climates and which would have been tested on long time series for those different conditions. Although the latter has already been performed for one 2.5-year data set from the Netherlands, as indicated above, such an endeavour worldwide is currently difficult to achieve. It would require an enormous effort and it would also require data sharing among researchers, which is still not that easy to accomplish due to confidentiality requirements by telecommunication companies, as confirmed by referee #4. Note that we are also testing the code on data from another network in The Netherlands, where TSLs (transmitted signal levels) are allowed to vary and minimum and maximum 15-min RSLs (received signal levels) and TSLs are provided. We do believe that our current algorithm, with some adaptations as suggested by the referees, is worthy of publication, because sharing code helps to come to the point where software can indeed digest data from several networks and climates. Moreover, the code is likely to be useful for many networks and may, at least, serve as a starting point for rainfall retrieval algorithms applicable to other networks. Also note that the research groups working on this topic have collectively agreed to share computer code and algorithms as much as possible. This paper can be seen as a first step, and may also enhance cooperation between research groups to jointly improve the code.

The referee also states that MWL data alone cannot be used to derive rainfall maps, referring to the interpolation methodology based on climatological variograms from rain gauge data. First of all, rainfall retrieval algorithms tested on data from a particular network and climate, are likely to work for similar networks and climates. Moreover, applying existing methodologies optimized on data from The Netherlands, does not automatically render them inappropriate for application to data from other climates. For instance, rainfall maps may still be of sufficient quality. Note that the presented link rainfall maps are, as in Overeem et al. (2013), solely based on link data, except for the parameters of the variograms, which have been computed based on rain gauge data from another period. Hence, detected spatial rainfall patterns only make use of the average ("climatological") variogram model based on 30 years of rain gauge data, but not the rain gauge data from the particular time interval for which the microwave link-based rainfall maps are derived. Thus, link and gauge-adjusted radar rainfall maps are completely independent, and correspondences are not caused by gauge-derived variograms. Also note that Rios Gaona et al. (2015) report that our interpolation methodology plays a minor, albeit non-negligible, role in the total uncertainty of link-based rainfall maps for the same 12-day data set as in Overeem et al. (2013). Hence, despite the limitations of the interpolation methodology (notably concerning its underlying assumption of isotropy, which the referee also refers to), its usefulness has been confirmed.

The referee's suggestions to improve the code (e.g., use of shorter variable names, avoiding hard coding of parameter values, collecting all parameter

settings in one part of the code) are acknowledged and can be implemented in a relatively straightforward manner.

Finally, we think that merging of rainfall data from different sources (if available) will often yield the best rainfall estimates. For instance, satellite data could be used for wet-dry classification to prevent non-zero link-based rainfall estimates during dry periods (Van het Schip et al, 2015). We believe that the main potential for rainfall estimation using microwave links is found in areas with few surface rainfall observations. Then development of a merged link-satellite rainfall product seems an interesting opportunity.

Reply to referee #2
He or she states:
I was starting to write my review when had the opportunity read that by the anonymous reviewer #1. And actually I agree almost completely with him/her. Therefore, also in my opinion the paper should be rejected, the reasons being those well detailed by reviewer #1 and also some other ones that I discuss below. The only matter of disagreement between reviewer #1 and me stands in the utility of the exploitation of the MWLs signals offered by cellular networks. If considered as opportunity sensors for the remote sensing of precipitation, in my opinion they could be very useful in 1) areas not covered by or very far from weather radars, but densely covered by cellular MWLs, as could be the case of urban conglomerations; 2) areas screened by hills or mountains and therefore not reached (or partially reached) by the antenna beam of a weather radar, as could be the case of little catchments: there, even a limited but continuous information as that provided by few MWLs could bring important integrative information for alerts, for instance. In fact, it should not be forgotten that a great advantage of cellular MWLs is the continuous signal reception and the consequent very high temporal resolution. This is certainly paid for with a degraded quality of the information due to the low quality of data, but such pieces of information would be almost for free. Certainly, telephone companies are not interested at all in any question of remote sensing (and are not stimulated by governments), but this does not concern the scientific potential of the use of MLWs signals and the related technical issues and algorithms.

Coming to the problems of the paper: its declared objective is to provide the scientific community with a detailed description of a code, that is a "slightly" adapted (adapted to what and why? This is not explained) of their own code used for another publication available on line. However, the paper is much longer than necessary, badly structured and the conclusions section - that is definitely too long and dispersive - includes critical discussions that should have been introduced before in more detail (I refer in particular to that of the non-linearity of the R-k relations). Many issues treated in the paper definitely need to be synthesized, avoiding repetitions and putting them in the framework of a more organized presentation that also requires much more work to be done, as pointed out by reviewer #1 and by my observations below. The authors should focus on a more reasoned description of the algorithm - that should be improved with a significant effort to make it independent of the local situation in the Netherlands - and leave to the references the description of the several problems that can be encountered by using this kind of opportunistic remote sensing networks. In this respect, in addition to (or even instead of) mentioning the too short and somehow

unclear 2006 paper by Messer et al. , the authors could refer to H. Messer and O. Semdyk "A New Approach to Precipitation Monitoring: A critical survey of existing technologies and challenges" IEEE Signal Processing Magazine (Volume:32 , Issue: 3) May 2015, that is much more sound from a technical point of view. Still from a reference point of view, in the introduction the authors miss to mention papers that propose a tomographic approach to the same problem:
Cuccoli, F., Facheris, L. and Gori, S.: "Radio base network and tomographic processing for real time estimation of the rainfall rate fields"; Proc. IEEE Geoscience and Remote Sensing Symposium (IGARSS), July 2009, Vol. 3, III-121 - III-124
Cuccoli F., Baldini L., Facheris L., Gori S., Gorgucci E.; "Tomography applied to radiobase network for real time estimation of the rainfall rate fields"; Atmos. Res., vol 119, 62-69, doi:10.1016/j.atmosres.2011.06.024 Cuccoli F., Facheris L., Gori S., Baldini L.: "Retrieving rainfall fields through tomographic processing applied to radio base network signals"; Proc. SPIE Remote Sensing Symposium, Prague, Sept. 2011, Vol. 8174, 81740C -1, 81740C-13.

But I would like to focus on a major point that reviewer #1 has not mentioned: the frequencies used by the NL cellular network and the value of b. The authors write "it is important that the value of the exponent b in Fig. 5 (right) is close to 1, which is the case for a range of frequencies. Here, only links with microwave frequency from 12.5-40.5 GHz are selected. The chosen frequencies can be altered in the script" (incidentally, 40 GHz falls already in the millimetre waves range, so 38.9 GHz is not a "representative microwave frequency" – see page 12). Then, in the conclusions: "the value of the exponent b is close to 1 for the frequencies employed in this study which range from 13-40 GHz. Frequencies between 37 and 40 GHz are denoted by the gray-shaded area in Fig. 5, which contains 81% of the links from the working example ...". But (page 14) they also state: "for the link frequencies used in this study (between 13 and 40 GHz) the value of the exponent b is close to 1. Because of this near-linearity of the integrand in eq. (5), the assumption on the distribution, leading to limited errors caused by using the approximation in eq. (6). This was also shown by ..." I was rather disturbed by this combination of sentences, and have three relevant comments/questions: a) going from 13 to 40 GHz (or from 12.5 to 40.5?!! Please be precise) means moving across three entire bands (the Ku, the K and the Ka band), moving from 2.3 cm down to 7.5 mm wavelength, with significant variations not only of the attenuation caused by rainfall bus also of that due to water vapour and liquid water. But above all: how many frequencies are used by the Dutch telephone companies? I am pretty sure that the authors are using data from service channels, as can be deduced from Fig. 1, but how many service channels have been activated in the NL? And why do they span such a wide frequency band? The authors do not spend a word on all this while it should be precisely clarified. Apart from that, the statement "Rainfall attenuates the electromagnetic signals transmitted from the circular antenna of one telephone tower to another" and the bubble in Fig. 1 with the notice "estimate rainfall with circular antennas" are simply ridiculous. Rainfall attenuates e.m. signals transmitted from any kind of antenna, and 'circular' antennas do not exist (choose the right one among parabolic, horn or whatever ...). b) The exponent b is far from being close to 1 at 13 GHz (also at 40 GHz, anyhow ...), and consequently the integrand in eq (5) is far from being "near-linear" as pretended in the paper! It is surprising that two of the authors put in evidence this problem in a paper of theirs that is even listed in the references (Lejinse, Uijlenhoet, Stricker: "Microwave link rainfall estimation: effects of link length and frequency, temporal sampling, power resolution, and wet antenna attenuation”, Advances in water resources 31 1881-1493, 2008) and draw opposite conclusions (section 5.1). Since we have perfect linearity in the R-k relation ONLY around 34 GHz, in the proposed approach the use of frequencies far from 34 GHz stands out as a prominent problem as it cannot provide a non-biased average value of R along the MWL. The aforementioned tomographic approach overcomes that, aiming at retrieving the specific attenuation field k(x,y) based on the average k measured along different MWL operating at the same frequency. The rainfall field can then be estimated through the k-R relation that holds at that frequency. c) In the 13-40 GHz band, not only the R-k relations change remarkably as evidenced by Fig. 5, but in general all parameters related to propagation and scattering do. For instance, a MWL operating at 21, 30 or 40 GHz is evidently much more sensitive to rainfall and humidity than one operating at 13 GHz. Therefore, all thresholds (be they empirical or not) used in the algorithm are likely to need an adjustment depending (at least!) on frequency. Not only this is not evidenced at all in the paper, but it even seems that the authors use the same thresholds at all frequencies, which would be absolutely odd and unrealistic. d) Besides and beyond the issue evidenced in point c): in the conclusions the authors “hope to promote the application of rainfall monitoring using microwave links ... around the world”, but they provide an algorithm with operative thresholds that are strictly dependent on the Dutch climatic situation, without any discussion/suggestion on how such thresholds could be adapted to different conditions. As long as such an effort is not done, one shall easily object that the Netherlands is a relatively small country, abundantly well covered by weather radars and sufficiently flat to remove any important cause of inaccuracy not only in the estimate of precipitation, but also in its classification and tracking. So what is the need there for estimating rainfall through MWLs?"

We refer to our reply to referee #1. In addition, we thank referee #2 for acknowledging the potential of microwave links for rainfall estimation, particularly in data-sparse regions, such as urban areas or small mountainous catchments (where the radar field of view is blocked). He or she recognizes the most important field of opportunity. The reason to do this kind of research for The Netherlands is to: 1) test the methodology under nearly ideal conditions and compare with existing ways to estimate spatial rainfall fields (i.e. rain gauges and/or weather radar), which provides a useful reference for countries with few surface rainfall observations; 2) develop a merged radar-link rainfall product. The potential of the latter has been shown by, e.g., Bianchi et al. (2013), Overeem et al. (2013b), and Liberman et al. (2014). Although The Netherlands has a relatively dense radar and gauge network, real-time radar rainfall images suffer from severe errors resulting in an average underestimation of 40%. The quality of an operational 3-h radar rainfall product is much better, since the bias is largely removed by applying a mean-field bias adjustment using data from 31 automatic rain gauges. However, the quality of the product still degrades with increasing range (Holleman, 2007). Hence, many more surface observations are needed to improve the quality of (near) real-time radar rainfall products. This would allow for a reliable spatial, i.e., local adjustment of radar rainfall images. This is why we are interested in merging radar and link data. The number of microwave links in The Netherlands is two orders of magnitude larger than the number of automatic rain gauges (~30). In countries with few or no rain gauges let alone weather radars, microwave links may be the only (other) source of surface rainfall information available.

We have chosen to provide an elaborate treatment of the rainfall retrieval algorithm and the corresponding code. We recognize that this reduces the readability of the paper, and we will seek to improve it using the suggestions by the referees, which we certainly appreciate. This will result in a less detailed description of the rainfall retrieval algorithm, which could be (partly) overcome by using appendices, as well as additional references to previously published papers.

With respect to the frequencies used by Dutch telephone companies (we have access to received signal level data from service channels): We indeed encountered frequencies ranging from 13 - 40 GHz. Studies show that useful rainfall estimates can be obtained for a wide range of frequencies: E.g. 7 GHz in Doumounia et al. (2014); 16-24 GHz in Rayitsfeld et al. (2012); 23, 38, and 58 GHz in Bianchi et al. (2013); 15, 18.7 and 23 GHz in Chwala et al. (2012).

The referee states that "telephone companies are not interested at all in any question of remote sensing ...". This is not always the case, as is shown by Gosset et al. (2015). Several telephone companies attended a workshop on rainfall estimation using microwave links. Moreover, they have expressed an interest in information regarding the availability of microwave links as a function of rainfall intensity.

Overeem et al. (2011) show a graph of employed frequency versus path length in The Netherlands. Shorter links are usually found in urban areas. The larger capacity needed in urban areas can be addressed by using higher frequencies. To provide a network in rural areas, longer links are needed. Rain-induced attenuation over the link path can become too large if "urban" frequencies were to be used. Hence, in rural areas links with a lower rain-induced specific attenuation (dB km^{-1}) are needed. This is accomplished by utilizing lower frequencies.

Referee #2 criticizes the use of the same thresholds at all frequencies. Table 2 lists eight parameters. In addition, the wet-dry classification uses max(Pmin) - Pmin > 2 dB (step 7, p. 8200). As referee #2 acknowledges, two parameters are assumed to be frequency-dependent (namely the coefficient and exponent of the *R*-*k* power-law). The chosen radius depends on the spatial correlation of rainfall and is, hence, not frequency dependent. Median(ΔP_L) is a specific attenuation, which will be different for other frequencies. Since frequency and link length are related, networks are designed in such a way that ΔP will be similar for different frequencies. Hence, median(ΔP) is nearly independent of frequency.

The filter to remove outliers deals with specific attenuation, i.e., it does not explicitly take into account frequency. It is also suitable for other time steps. Nevertheless, its threshold value is very high, which makes it unlikely that actual rainfall is filtered out accidentally, irrespective of the used frequency. The outliers are likely caused by malfunctioning links and not by, for instance, precipitation or wet antenna attenuation. Hence, it makes sense to apply a frequency-independent threshold value.

We used different values for A_a and α for two frequency classes in Overeem et al. (2011), but similar results were obtained for the current data set when only one single set of parameter values was used. This may be explained in part by the fact that the majority of links operates at 37-40 GHz. In case we would optimize these coefficients for different frequency classes, we find an A_a value of 1.9 dB for 13-20 and 20-30 GHz, and a value of 2.3 dB for 30-40 GHz for the 12-day calibration data set. The optimal value for α for 13-20 GHz (0.4) is around 20% larger than that for 20-30 and 30-40 GHz (0.335 and 0.32, respectively). So in general values for A_a and α are relatively close to each other for different frequency classes. Moreover, the performance of our rainfall retrieval algorithm is relatively insensitive to the exact values of A_a and α (also see our reply to referee #1).

Conclusion: Some parameters are already modelled as function of frequency, some seem not to be sensitive to frequency, some should ideally be optimized for different frequencies. We find that relatively accurate rainfall maps are obtained with the current parameter values, even though they may not always be optimal for the employed data set. This suggests that application of these values to other data sets will likely lead to reasonable results.

We use the term "circular antennas" in our paper. This is not meant as an official classification, but meant as a clarification for laymen to indicate which antennas on a telephone tower are used for rainfall estimation. This in order to distinguish from antennas with a rectangular shape, which are usually employed to communicate with cellphones. We will replace "circular antennas" with "parabolic antennas".

Whether you call an exponent of 0.8 (13 GHz) or 1.05 (40 GHz) "near-linear" is a matter of definition. In any case, these exponents are much closer to one than the ones typically used in radar reflectivity-rain rate relations. E.g. Overeem et al. (2011) assessed the influence of spatial variability on the link path for these two frequencies. They show that the under- or overestimation will generally be small. In the tropics this problem will be more pronounced because of the high spatial rainfall variability, particularly for long links operating at low frequencies (e.g. 7 GHz). Also note that Doumounia et al. (2014) obtain quite accurate rainfall estimates using a 7-GHz microwave link with a length of 29 km in Burkina Faso, having a tropical climate. Previous work has demonstrated that this error is limited for temperate climates as experienced in The Netherlands (Leijnse et al., 2008; 2010). Moreover, most links in our network have a length of at most 5 km, their average length being around 3 km.

Reply to referee Heistermann
Referee #3, Mr. Heistermann, provides the following review:

Subject and scope

In their manuscript "Retrieval algorithm for rainfall mapping from microwave links in a cellular communication network", A. Overeem and colleagues present details of a retrieval algorithm that has been originally published by Overeem et al. (2013) in

PNAS. Making the idea of rainfall retrieval operationally viable is certainly subject to intense research and the subject fits the scope of AMT well.

Innovation

The authors do not hide the fact that the actual retrieval algorithm had already benn published in a different paper. The intention of the present manuscript is rather to present details about the algorithm and, alongside, an implementation of the algorithm in the programming language R. As a result, the manuscript does not present any original research. The content would be ideally suited for a format generally known as "technical note" which is, however, not available at many journals, including AMT. So regarding the lack of other appropriate formats at AMT, I think it is justified to still submit this as a research article.

The innovation of the present submission can be seen in the attempt to provide an open source implementation of the algorithm in order to stimulate further development and applications in this field of research. Or as the authors put it, "the purpose of this paper is to provide a detailed description of a slightly modified version of the algorithm of Overeem et al. (2013)" (p. 8193, ll. 18-19), and "to promote the application of rainfall monitoring using microwave links in poorly gauged regions around the world" (p. 8211, ll. 8-10).

I certainly endorse this motivation, and I would like to thank the authors for making that effort. Let us be frank: In the scientific sector, publishing a paper is still more rewarding than publishing a software code, although publishing a software code might advance scientific progress just as much. I also think that it makes sense to accompany the publication of an open source code by a related article in a scientific journal. Admittedly, the article of Overeem et al. (2013) would have been a good opportunity to publish the code alongside. Still, I think of it as appropriate to publish a paper in AMT as both entry and reference point of an open algorithm, particularly since no other group has made their algorithms openly available, yet (at least to my knowledge).

Apart from that, I have to say that I have some major concerns about the manuscript and the code which I would like to point out in the following.

Major concerns

My main concerns are about the design of the software code, the presentation of the software code and the balance between technical details and scientific discourse in the manuscript itself. The algorithm is implemented in R which is good since R is also an open source environment. The code runs fine at least on my machine which is also good. So the authors achieved their main objective to allow the community to run the code together with the set of sample data. However, I think the presentation and the design of the code are not up to the standards of scientific software development and this will hamper making progress as a community:

1. I think it is not appropriate to publish the code as a supplement. This way, it is difficult for the authors or anyone else to improve the code and make these improvements available to the community. It is state-of-the-art (and also easy) to use

public file hosting services such as GitHub or Bitbucket which also offer version control and ample tools for collaborative development and public code review.

2. The software code is basically a collection of scripts without any modularity and a lot of stuff hard coded. Just as an example, the script "WetDryClassification LinkApproach.R" contains a lot of stuff apart from the actual wet-dry classification such as the determination of reference signal levels and corrected received powers as well as outlier filtering. It would be much more suitable to design a library (or a package) with different modules/functions, a clear application programming interface (API) and examples on how to combine the API functions in processing workflows such as the one presented in the manuscript. The code should be designed in a way that modules are reusable (so it is up to the user how to combine modules), and in a way that the various parameters of the approach are clearly assigned as function arguments (which then might have default values using the authors suggestions). This way, it is easier to add new functions e.g. for wet-dry classification or spatial interpolation which could then be combined with already existing functions. Functions should be able to exchange data in memory instead of using file I/O as a detour that compromises computational performance. Overall, I suggest redesigning the code as an R-package which would also address issues of documentation, distribution, and dependency management.

3. The readability of the manuscript suffers very much from the technical details (and also from a lack of conciseness). I think most of these details should be part of the software documentation (the API reference is an intrinsic part of an R package and can be enhanced by external sources such as web pages containing e.g. theoretical underpinning, technical guidance for system setup, and tutorials etc. – such pages can also be easily developed and hosted via e.g. GitHub).

Removing many of the technical details from the manuscript will increase readability and should make it much shorter. In particular, the authors should find a smart and elegant way to condense and reorganise chapter 3. I think of it as an opportunity to make the paper brief, crisp and informative, but still, the question remains what should actually remain in the manuscript. Surely, it is the authors to answer this, but I think such an article could really be an opportunity to familiarize non-experts (such as myself) with this methodology and at the same time provide an in-depth discussion of the limitations and challenges that should be addressed in future (community) efforts in order to make this approach more widely applicable and more compatible with other approaches (other sampling strategies, other interpolation methods, other rainfall observation methods etc.). The authors could briefly present a typical workflow just as they did, but with graphical material more to the point, showing ideal behaviour but also highlighting typical cases of failure. Finally, they should provide a more concise discussion of how the specific aspects of the implementation limit transferability (such as the data situation in the Netherlands, the daily accumulation interval, the interpolation approach etc.).

I am very much aware that all these requirements imply a lot of additional efforts. However, I am convinced that Open Source Software can only effectively and efficiently support scientific progress if the developers are willing to take the extra effort.

Overall evaluation

I think that this submission has the potential to actually add value to the original publication of Overeem et al. (2013) and to provide a valuable service to the atmospheric sciences community. In order to make this happen, though, both the manuscript and the code would require a major revision.

We thank the referee for recognizing the suitability of this paper for publication in AMT and acknowledging our intent of this paper. The remarks with respect to rewriting the paper and improving the software are constructive. The suggestion to publish the code on a website such as GitHub, which allows for further development by the community, will be implemented. Actually, this was our original intention, but we decided to first incorporate comments from the review process. Rewriting the software in a modular fashion, removing the hard-coded parts and using functions are good suggestions. This will facilitate use and advancement of the code. Note that the code has originally not been developed to become publicly available. Since the current version of the code is meant for the research community rather than for end users, one may wonder whether all suggested changes are needed. Given our experience with this code, we expect that not much is to be gained by limiting I/O. Meanwhile, the code is already used by other researchers in our group, demonstrating its current usefulness.

Referee Heistermann states that the readability of the manuscript suffers very much from the technical details. He also indicates that it is difficult to find a good balance between technical details and readability. In our opinion, Overeem et al. (2013) already give a crisp description of the algorithm (see the Appendix of that paper), which we felt was too short for people wanting to apply the code. Hence, for familiarization of non-experts, Overeem et al. (2013) is already ideally suited. The suggestion to put it into a manual on GitHub is interesting. We are also considering other possibilities, such as moving part of the text in the body of the paper to appendices.

We believe to already give a quite detailed discussion of limitations and challenges of our algorithm. Although part of the scientific discourse has already taken place in Overeem et al. (2011, 2013), we, for instance, provide a discussion of the sensitivity of the algorithm for different parameter values. Nevertheless, we will seek to structure and elaborate this discussion. We will particularly give attention to the potential of applying this rainfall retrieval algorithm to data from other networks and environments.

The referee asks: "wouldn't it make sense that the user can pass adequate exponents instead of limiting to frequencies with an exponent of approx. 1?". Actually, the file "ab_values_vertical.txt" already provides the values for coefficient *a* and exponent *b* for frequencies ranging from 1 - 100 GHz. Note that the following sentence in our paper suggests that many links are discarded: "Here, only links with microwave frequency from 12.5–40.5GHz are selected.". In reality we use almost all links in the data sets we received so far, including a 2.5-year data set, since they have a microwave frequency between 12.5–40.5GHz. As a result the value of the exponent *b* is (relatively) close to 1 for almost all links. Hence, the sentence will be modified.

We are also planning to incorporate the recommended ITU values for *a* and *b* in the code, which are available for a wide range of frequencies (International Telecommunication Union, 2005).

The referee asks for graphical material being more to the point, showing ideal behaviour but also highlighting typical cases of failure. In our opinion Figures 3, 4, and 6 already provide a systematic illustration of the algorithm. We also acknowledge that this could be expanded, for instance, by providing an example where the filter to remove outliers is applied. This would reveal the typical RSLs encountered in case of such outliers, which are likely caused by malfunctioning links. Hence, we will expand the graphical material in a revised version of our paper.

Reply to referee #4
The referee states:
SUMMARY

The manuscript describes retrieval algorithm for rainfall mapping from commercial microwave links (MWLs) of cellular communication network and provides step by step account how to apply it on MWL data: from preprocessing of a single MWL to a rainfall spatial reconstruction from multiple MWLs. The methods presented have been already published (Overeem et al., 2011, 2013), which authors acknowledged, and the manuscript thus does not reveal new scientific findings. Its main contribution to the scientific community lies in i) publishing complete computer code for preprocessing MWL data and reconstructing rainfall maps from them and ii) it provides a two days dataset of MWLs and reference weather radar.

GENERAL COMMENTS AND RECOMMENDATIONS
Although the manuscript does not present novel concepts, neither tools nor data the author's intention to provide computer codes and data to promote and enhance MWL rainfall estimation is beneficial and deserves attention. The concept of rainfall retrieval from commercial cellular MWLs has been suggested about a decade ago (Leijnse et al., 2007; Messer et al., 2006) and since then there has been a number of manuscripts published investigating different issues of this topic (many of them also in AMT). To the reviewer's knowledge this is for the first time that comprehensive MWL dataset from real cellular network is published. This is mainly because of the legal status of data which belongs to cellular operators who usually consider both MWL positions and data as confidential information and are not willing to provide it to third parties. Form this point of view the manuscript together with supplements provided address relevant scientific topic which is worth publishing within the scope of AMT and which has potential to enhance progress in MWL rainfall research and bring attention to this topic. However both manuscript and the computer scripts provided need major revisions to fulfill this mission and enable scientific community to benefit from the given dataset and methods.

The reviewer suggests restructuring this manuscript in a way to provide rather than step by step "cookbook" how to run R scripts, comprehensive statistical description of given dataset and deep discussion about limits of suggested algorithm and its transferability to different conditions. New structure should also clearly separate methods and results (which are now mixed).

The form of provided scripts enables reconstruction of results discussed in the manuscript. However all scripts are hardcoded and thus running them with different dataset or with different thresholds requires lot of script reading and coding from a potential user. The reviewer suggests recoding all the provided scripts into a library of functions with well-defined and documented input parameters and outputs. The documentation to the scripts should be provided as a separate supplement. The reviewer also suggest to provide a documentation (or appendix of the manuscript) to the dataset with description of provided data in terms of their structure and formats in form of a separate supplement. Authors should also consider providing computer scripts and documentation through some of the repositories such as GitHub which are well suited for code sharing and maintaining and include tools such as versioning, etc.

Although such changes require lot of additional work the reviewer believes that this work is worth to fulfill the author's goal, i.e. promoting of MWL rainfall monitoring."

We thank referee #4 for recognizing the potential of our manuscript for publication in AMT. Referee #4 indicates that "both manuscript and the computer scripts provided need major revisions". Hence, the review is largely in line with that of referee Heistermann. We refer to our replies to the other referees. In addition, referee #4 also provides several specific comments, which will be partly addressed below.

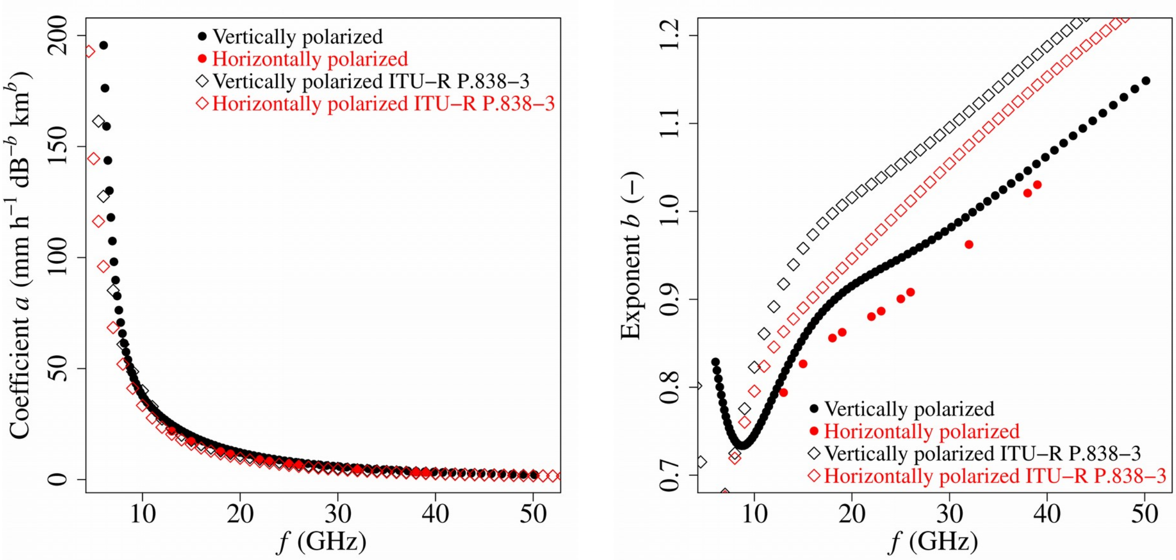
The suggestion to clearly separate methods and results, as well as discussion and conclusions, is acknowledged.

The radius of 15 km depends on the spatial correlation of rainfall. Overeem et al. (2011) explain their choice of a radius of 10 km: "Note that Berne et al. [2004] find that the range of the variogram, which describes the decorrelation distance, is larger than 15 km for a time interval of 15 min for typical intense Mediterranean rain events. In the Netherlands this range is expected to be longer, because rainfall is on average less intense and less convective compared to the Mediterranean. This justifies selecting all links for which both ends are within 10 km from either end of the already selected link in the link approach. The link approach can fail in case the surrounding links do not encounter rain but the link for which rain has to be estimated does.". This will not occur that often since the spatial extent of rainfall in short time intervals, such as 15 min, will frequently exceed 15 km. Note that the wet-dry classification uses the mutual decrease in RLSs from nearby links to assign rainy intervals. Then the majority of links should have at least a certain minimum decrease in RSL according to the thresholds median(ΔP_L) and median(ΔP). Then it could even be sufficient that the majority of links within a 15-km region experience some rainfall. To conclude, the spatial extent of areas having some rainfall will generally be larger than the spatial decorrelation distance of rainfall. "Furthermore, the average link length is 3.7 km and the links are usually not oriented parallel to each other. This increases the probability that surrounding links also encounter rain." (Overeem et al, 2011). We believe that a spatial correlation of 10 km is still rather conservative for many rainfall events in The

Netherlands. A larger value of 15 km was chosen here and in Overeem et al. (2013) to use as many links as possible, i.e., to also use links in areas with low network density.

The threshold values for the wet-dry classification have been introduced in Overeem et al. (2011). It is already stated how they were obtained: "who optimise them by visual comparison with the gauge-adjusted radar data set of path-averaged rainfall intensities employing data from 2009 (NEC links with 0.1 dB power resolution).". Moreover, the basic principle of the wet-dry classification, spatial correlation of rainfall, has been mentioned in the main text and in Table 2. One step of the algorithm can be further explained: "If max(Pmin)-Pmin > 2 dB for a given time interval that is classified as wet, the previous two time intervals and the next time interval are classified as wet for the link selected in step 1.". This can be related to the fact that previous and subsequent time intervals can be incorrectly classified as dry. One reason for this could be the fact that rainfall is sometimes very local and does not occur at surrounding links.

The telecommunication company provided no information on the polarisation for individual links, but confirmed that the default setting is vertically polarised. Horizontal polarisation was only used in case of cross-polar links. Note that the values for *a* and *b* in the *R*-*k* relationship only differ slightly between vertically and horizontally polarized signals based on drop-size distributions from The Netherlands (see figure below). The values recommended by the ITU (International Telecommunication Union, 2005), meant for computing specific attenuation for given rain rates and for worldwide application, are plotted as well. Differences up to 10% are found for the value of the exponent *b* from ITU compared to that obtained from drop-size distribution data from The Netherlands (the values for vertically polarized have been used in our paper). These ITU values will also be provided in a modified version of the code.



We believe that the extrapolation from 1 h to shorter intervals is justified. Indeed, longer time steps are more dominantly influenced by larger precipitation systems. But 1 h is still a short duration and the interpolation methodology uses seasonally varying variograms, where its parameters change as a function of day of year. So, on average, the more convective nature of rainstorms in summer and the more stratiform nature of rainfall in winter is taken into account. Note that Van de Beek et al. (2012) derived a relationship for 1-h to 24-h rainfall. Here we extrapolate this relationship to 15 min, yielding a shorter range compared to 1 h.

The referee asks to discuss the quality of maps as a function of link density. This has been investigated recently by Rios Gaona et al. (2015; Figure 6). They simulate link data from a gauge-adjusted radar data set, using the 12-day data set from Overeem et al. (2013), of which 1 day is used in our paper. They report: "From Fig. 6 it can be seen that a higher density in the link network guarantees good correlation between the estimated values of rainfall and the ground truth, and a low coefficient of variation of the residuals. From the left panel (Fig. 6a), it can be concluded that lower link densities also contribute (and in large proportion) to higher correlation coefficients. This means that without considering errors in link measurements, these latter being the largest source of uncertainty in country-wide rainfall fields, the network density and the mapping methodology considered here are, respectively, high and good enough to retrieve accurate rainfall fields at such country-wide scales (at least in the Netherlands)."

The referee asks: "How can experiment on one commercial link of given frequency, polarization, length and other specifics help to calibrate Aa and alpha of many different microwave links around the whole country?". The microwave link used in our experiment in Wageningen operates at 38 GHz and has a length of 2 km, which is a very common combination in our network. Moreover, links from the same vendor use similar antenna covers, and often similarities are found between covers from different vendors. This is important for the wet antenna attenuation. We have shown above that A_a and α seem not to depend that much on microwave frequency. Finally, along the microwave link setup we have installed a line configuration of 5 optical disdrometers, which allow us to capture in-depth information on the variability of the raindrop size distribution along link paths of lengths varying between a few hundreds of meters and two kilometers.

Depending on the quality of the satellite rainfall product, it could be used to calibrate A_a and α. Given the limitations of satellite rainfall products, we are indeed seeking more accurate (surface) rainfall data. Note that it makes sense to optimize these coefficients based on 24-h accumulations, as we did using gauge-adjusted radar data. The reason for this is to limit the influence of representativeness errors between the different rainfall sensors. It has been shown that the quality of satellite rainfall products increases for longer durations, such as the daily time scale. Calibration could also be performed on even longer time scales (months), to further limit errors in satellite rainfall products, e.g. those caused by long(er) revisit times, which would make them more suitable for calibration purposes. Naturally, it should also be investigated whether these parameters may be assumed constant over such longer time scales.

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