Review of manuscript AMT-2020-174 "Something fishy going on? Evaluating the Poisson hypothesis for rainfall estimation using intervalometers: results from an experiment in Tanzania", submitted to AMT by Didier de Villiers et al.

Remko Uijlenhoet, Wageningen, October 18th 2020

General remarks

- The authors present a new type of rainfall sensor (which they call "intervalometer") and show results from a field experiment using this instrument and a collocated disdrometer and tipping bucket rain gauge during monsoon rainfall in Tanzania with the aim to test the validity of the Poisson ("fish" in French) hypothesis, an implicit assumption in many models of the microstructure of rainfall, including those used for developing rainfall retrieval algorithms for remote sensors (notably weather radar). As such, the topic of this study seems to be well-suited for publication in AMT.
- The cornerstone of the rainfall estimation algorithms presented by the authors in Section 3 is the exponential drop size distribution (DSD) model (L.119, Eq.(1)), with a fixed intercept parameter N_0 (8000 [mm^{-1} m^{-3}]) and a slope parameter Λ depending on rain rate according to a power law ($\Lambda = 4.1\ R^{-0.21}$ [mm^{-1}]), such as proposed by Marshall and Palmer (1948) (hereafter abbreviated as MP48). This model allows conversion of raindrop arrival rates observed with intervalometers first to values of Λ (using a relationship based on the MP48 DSD model combined with a minimum detectable raindrop size $D_{\min}$ of 0.8 mm). Subsequently, these Λ-values are converted to rain rates using the MP48 $\Lambda(R)$ relation (Section 3.1). The authors admit that one source of error affecting this algorithm is "model error that arises from the assumption that the DSD is adequately described by the Marshall and Palmer (1948) exponential parameterisation rather than some other parameterisation" (L.147-148). However, they indicate that "Model error will not be accounted for as the focus of this study is to test the homogeneity assumption that underlies these models rather than compare different DSD models" (L.150-152).

  Nevertheless, I expect model error to play a significant role in the reported rainfall estimates, simply because the MP48 model is -because of its fixed intercept parameter- a very special case of the general exponential DSD model, which MP48 found to adequately describe raindrop size distributions observed in Montreal, Canada (dominated by stratiform precipitation), but which may not at all be appropriate for applications in Tanzania (with rainfall likely being of a much more convective nature – see L.329-330, where you state that "this type of rainfall pattern [sustained stratiform type rainfall] is quite atypical for the rainfall record as a whole"). Previous research has indicated that in many climatic settings the value of N_0 cannot at all be considered constant, but shows significant variability, sometimes exhibiting a clear dependence on rain rate itself, in a similar way as Λ depends on R (e.g. Uijlenhoet, 2001, Fig.3). In general, temporal (or spatial) changes in rain rate can be caused by changes in the raindrop concentration (or flux), by changes in the (mean) raindrop size, or (and this is the most common case) by simultaneous changes in the numbers and sizes of the drops. The relative contributions of each of these depend on the type of rainfall and the climatic setting (Uijlenhoet et al., 2003, Fig.1).

  The consequence of this would be a different $\Lambda(R)$ relation than the MP48 $\Lambda(R)$ relation. If this were the case for Tanzania, this could seriously affect rain rate estimates from intervalometers if not considered in a rainfall retrieval algorithm. This does not only pertain to the algorithm based on intervalometer-observations alone (as presented in Section 3.1), but also to the extended algorithm (Section 3.2) where additional disdrometer observations are introduced to correct "for biases in the measurement of rainfall rate by the intervalometer" (L.140). That is because also the proposed bias correction is based on the MP48 $\Lambda(R)$ relation. Hence, although a number of more specific remarks concerning this issue are provided below, I would appreciate a general response to this point from the side of the authors at this point.

- Section 4.2 (Figs. 7-9) represents the core scientific contribution of this manuscript, as far as I am concerned. Although the dataset being analyzed is not very extensive, these are definitely novel, interesting and relevant results. More than a quarter of the rain collected during the measurement campaign the authors organized in Tanzania was found to represent purely Poissonian rainfall according to a total of five statistical tests, a result that I did not anticipate. For the remaining rainfall patches the authors have been able to identify which of the Poisson tests were failed. The authors find that "Poisson rain is characterised by low arrival rates" (L.342 and Fig.9) and presumably by low rain rates (although that is not explicitly shown).
- Overall, I enjoyed reading this rather lengthy but well-written paper. It introduces a new rainfall sensor, the intervalometer, which is used to estimate rainfall rates from raindrop arrival rates. As indicated above and below, I have a number of questions concerning the algorithm employed to convert drop counts to rain rates. In the second half of the paper the instrument is employed to test the Poisson hypothesis in Tanzanian rainfall. I find this the most original and convincing part of the paper. The discussion (Section 5) puts several aspects of this study into the proper perspective. In summary, I recommend moderate revisions.

<u>Specific remarks</u>

- L.11-12: "estimates of total rainfall amount over the entire observational period derived from disdrometer drop counts are within 2 % of co-located tipping bucket measurements". A few lines later the authors state: "Intervalometer estimates of total rainfall when corrected for minimum drop size are within 1 % of co-located tipping bucket measurements". Is it 1% or 2%?
- L.34-43: The way in which this paragraph is phrased suggests that satellites only use radars to retrieve rainfall rates. Certainly, the most advanced meteorological satellites (TRMM in the past; the GPM core satellite at this moment; CloudSat mainly for cloud observation) carry active microwave sensors (radars), but the majority only carry passive microwave sensors (radiometers) or IR sensors. That said, for all these types of sensors, a priori knowledge of the microstructure of precipitation (e.g. DSD in rainfall) is a prerequisite for developing accurate and robust rainfall retrieval algorithms. Hence, it would be appropriate to generalize the statement concerning satellite rainfall retrievals, or limit it to (ground-based) weather radars.
- L.82-84: Although I appreciate the description of the instrument provided on the indicated github page, it is a pity that the design, operation and performance of the intervalometer and of the disdrometer developed at TU Delft have not yet been published in the peer-reviewed scientific literature, as far as I can tell.
- L.101-102, "Tipping buckets were calibrated in the field [...] at a rate slower that 20 mm.h^{-1} onto the instrument and recording the number of tips": The calibration of tipping bucket rain gauges if well-known to be intensity-dependent. Without taking this effect into account large rainfall rates (and hence rainfall accumulations) are typically underestimated (see Humphrey et al., 1997, and references therein). Could that phenomenon have played a role in this case?
- L.111, "Figure 2 presents an overview of the data available": Examination of Fig.2 suggests that during the entire measurement campaign of less than two months there were no time instants during which all instruments indicated in Fig.1 operated simultaneously. Was that indeed the case?
- L.134, "Uijlenhoet and Stricker (1999) showed that [...]". Note that in the derivation of these values it was tacitly assumed that the integration limits of the DSD were 0 and ∞, respectively. In other words, the values $\alpha = 3.25$ and $\beta = 0.762$, employed by the authors to derive their relationship between rain rate and raindrop arrival rate, are not fully consistent with the integration limits employed by the authors ($D_{\mathrm{min}} = 0.8$ mm and $D_{\mathrm{max}} = \infty$). Among others, the rainfall rate depends on these integration limits in much the same way as the raindrop arrival rate (Eq.(6), L.133). This will undoubtedly affect subsequent analyses presented by the authors.
- L.138-139, "The rainfall rate (*R*) can be estimated by re-arranging the Marshall and Palmer (1948) Λ−R relation": Apart from the issue with the integration limits (see previous remark) one could question the applicability of the Marshall-Palmer DSD parameterization (derived from DSD

measurements under mostly stratiform conditions in Montreal, Canada) to raindrop arrival rate measurements from Tanzania, for rainstorms with a presumably much more convective nature (as exemplified by Fig.8).

- L.148-149, "Many alternative models for the DSD have been proposed and tested in the literature of which the most widely used are the exponential [...]": However, the Marshall-Palmer parameterization is a particular form of the general exponential DSD model. Therefore, the exponential model cannot really be termed an "alternative model" compared to the Marshall-Palmer parameterization.
- L.155-156, "the probability distribution of the drop diameters arriving at a surface per unit time [...] is a gamma distribution": Note that this statement is not true in general, but only if the DSD (in a volume) is of the exponential form ánd if the $v(D)$-relation is a power law. If the DSD (in a volume) is of the gamma form (and the $v(D)$-relation is a power law), then de pdf of the drop diameters at a surface will still be a gamma distribution, but with different parameters than Eq.(7).
- L.162, Eq.(9): This is an unnecessarily complicated form of the expression for the expected raindrop diameter at the surface. By definition, the expected value of D is the first order moment of Eq.(7), i.e. the integral (between $D_{\min}$ and ∞) of D times the pdf. Direct calculation of this integral leads to: $\mu_D = \Gamma(2+\beta,\Lambda D_{\min}) / \Gamma(1+\beta,\Lambda D_{\min}) \Lambda^{-1}$, which reduces to $(1+\beta) / \Lambda$ if $D_{\min} = 0$. As an added value, using this expression will also simplify Eqs.(11), (12), (13) and (16) significantly.
- L.164: You probably add the subscript "exp" to μ_D, D_A and Λ to contrast them with their observed ("obs") values a few sentences later (L.166-167). However, this may lead to confusion for the reader because "exp" could be interpreted as meaning both "exponential" and "expected". Therefore, please add a short statement explaining why you introduce this notation here and what the intended meaning of the subscript "exp" is.
- L.192-194: To compensate for "a small time delay between the first sensing of a raindrop with the intervalometer and the first tip registered by a tipping bucket [...] rainfall data is aggregated over an entire day". Indeed, for a steady rain rate of 1 mm/h a tipping bucket rain gauge with a resolution of 0.2 mm tips on average 5 times per hour (i.e. once every 12 min). At 12 mm/h this is once per min. So the mentioned "small time delay" can indeed be of the order of a minute or more. However, why immediately aggregate to an entire day rather than to, say, one hour? That would definitely add relevant hydrological information for potential end users.
- Figs.4 and 5, Table 1: You mainly evaluate the performance of the intervalometer as compared to the tipping bucket rain gauge in terms of rainfall accumulations over several rainfall events. However, although getting the rainfall volumes right is important, for many applications being able to capture the intra-event the dynamics is also of relevance. I wonder what scatterplots at, say, the hourly (or even shorter) time scale would look like and what the corresponding correlation coefficients would be. They could also be important performance indicators of the new intervalometer.
- Fig.5: It seems to me that it is important to stress that the corrected rain rate estimates in the left-hand panels (for the Pole Pole site) correspond to the *calibration* dataset, whereas the corrected rain rate estimates in the right-hand panels (for the MIL1 site) represent the independent *validation* dataset, even if covering only a few events.
- Fig.5: At what time scale is the correction carried out, at the event scale, the daily scale, or for the entire campaign as a whole? I could not grasp this clearly from the text, but perhaps I overlooked something.
- Fig.6, caption: Are these indeed "Estimated mean drop sizes" or would the term "effective mean drop sizes" be better? After all, they correspond to the *effective* mean drop sizes that bring the intervalometer-derived rain rates in accordance with those from the tipping bucket rain gauge, if I have understood correctly.
- Fig.6: At least as informative from the perspective of rain rate estimation are the *volume-weighted mean diameter* and the *median-volume diameter* (see Uijlenhoet and Stricker, 1999, Table 4). They are more indicative (than the mean diameter shown in Fig.6) of the *effective* drop size contributing most to the rain rate. An advantage with respect to the mean diameter (i.e. the

expected value corresponding to the DSD itself) is that these characteristic diameters are less sensitive to the small droplet end of the size spectrum, hence much less prone to the issue of instrumental truncation at some lower diameter limit (D_{min}).

- L.312-313, "Overall, only 28.3 % of all patches can reasonably be assumed to be Poisson distributed": I would not call this "only 28.3 %". Apparently, more than a quarter of the rainfall during the experiment "are patches of stationary rainfall that exhibit no correlation between drop counts within a 95 % confidence interval, match a Poisson distribution very well and have a mean dispersion of approximately 1" (L.313-314). If you would have asked me in advance, I would not have guessed that such a significant fraction of all rain collected during your campaign would pass *all* of the tests you outlined in Section 3.4.
- L.341, "random sampling effects": For purely Poissonian rainfall closed-form expressions for the strength of such sampling fluctuations can be derived (e.g. Uijlenhoet et al., 2006). There is no need to incorporate this reference in your manuscript. It is just provided for your information.
- Fig.9: These are interesting results. I wonder what these plots would have looked like if you would have used rain rate [mm/h] on the x-axis rather than the raindrop arrival rate. Regarding the bottom panel, it seems it would be good to refer back to Fig.6 somewhere in the last paragraph of Section 4.2 (L.357-366), because both are plots of mean raindrop diameter versus drop arrival rate.
- L.402-403: The authors conclude that "Marshall and Palmer's (1948) parameterisation of the DSD is a good approximation of the observed DSD over the period of the experiment". However, they have not explicitly tested this conclusion using the available disdrometer observations. Therefore, it seems that the evidence for this conclusion could have been stronger than it currently is (based only on the "derivation of reasonably accurate rainfall measurements", L.401-402).

<u>Editorial remarks</u>

- L.24: Insert comma before "but progress ...".
- L.25: The reference "(TAH, 2017)" is not listed in the reference list.
- L.28, 33, 34, 62, 63, etc.: Insert hyphen between "ground" and "based".
- L.41: Replace closing quotation mark before "truthing" with opening quotation mark.
- L.53: Replace semicolon by colon.
- L.54: Replace closing quotation mark before "streakiness" with opening quotation mark.
- L.56: Replace "like" by "e.g." and put it after the opening parenthesis of the citation.
- L.57: Insert hyphen between "scale" and "dependent".
- L.58: Remove comma after "Others".
- L.64: Insert hyphen between "two" and "month".
- L.64: Insert "The" before "Marshall and Palmer".
- L.69: Insert comma before "respectively".
- L.74: Remove comma before "in the US".
- L.85, 86: "at e.g." --> "in e.g." (2x); to put parentheses only around publication years, use \citet instead of \citep for references in LaTeX.
- L.88: Insert "typically" before "0.2 mm".
- L.120: This should not be listed as a separate equation (Eq.(2)), but rather as line in the main body of the text.
- L.130: Correct "0.5 mm ≥ D ≤ 5.0 mm" to "0.5 mm ≤ D ≤ 5.0 mm".
- L.130: Correct "The mean rainfall arrival rate" to "The mean raindrop arrival rate".
- L.131: Add "mm" after "0.8".
- L.134-135: Insert hyphen between "self" and "consistency".
- L.146: Insert comma after "sensor".
- L.149: Insert comma after "literature".
- L.154: "constrain" --> "constraint".
- L.157: Replace the full stop at the end of the sentence with a colon.

- L.159: This should not be listed as a separate equation (Eq.(8)), but rather as a specification of the constraints on the parameters of Eq.(7).
- L.166: Insert comma before "these can be". For clarity, the mathematical notation "$f(\rho_{A,obs})$" may even be omitted completely, because it is already described in words ("Now, if the observed mean drop sizes [...] are some function of [...]").
- L.170: Replace closing quotation mark before "corrected" with opening quotation mark.
- L.171: Replace the full stop at the end of the sentence with a colon.
- L.172-175, Eqs.(11-13): Here, the exponent -1/0.21 is employed, whereas on L.139 the exponent -4.762 is used. Please use the same notation.
- L.179: Insert space after "e.g.".
- L.181, 191: Replace closing quotation mark before "corrected" with opening quotation mark.
- L.186: Replace the full stop at the end of the sentence with a colon.
- L.190, "Expected mean drop size": Either use "expected" or "mean".
- L.198: Replace the reference to Uijlenhoet and Stricker (1999) by a reference to Uijlenhoet et al. (1999).
- L.205: "(eg. (Feller, 2010))" --> "(e.g. Feller, 2010)".
- L.205: Replace the full stop at the end of the sentence with a colon.
- L.207: "Where" --> "where".
- L.212: Replace the full stop at the end of the sentence with a colon.
- L.217: "homogeneous" --> "homogeneity".
- L.225: Insert "interarrival" before "time".
- L.238: Insert a comma before "whereas".
- L.239-240: Put parentheses only around publication years, i.e. use \citet instead of \citep for references in LaTeX.
- L.249: L.198: Replace the reference to Uijlenhoet and Stricker (1999) by a reference to Uijlenhoet et al. (1999).
- L.272: "Rates" --> "rates".
- L.274, caption Fig.4: Replace closing quotation mark before "online" with opening quotation mark (similar for "Exp" and "Corr").
- Caption Fig.3: "an example" --> "a sample".
- Fig.9: Y-axis labels of top and middle panels should also read "Mean Drop Diameter [mm]", because they represent mean diameters for each 10 s drop count.
- L.377: "over estimated" --> "overestimated".
- L.378: Insert comma before "which".
- L.378: "over-estimated" --> "overestimated".
- L.393: Insert comma before "which".
- L.395: Insert hyphen between "disdrometer" and "observed".
- L.426: "aim" --> "aims".
- L.443: Insert comma before "which".
- L.447: Insert comma before "such".
- L.448: Insert comma after "However".
- L.452: Insert comma before "making".
- L.460, "E.g.", "Or whether": This should be one sentence, replacing the full stop after "rainfall conditions" with a comma.
- L.462: "ground based" --> "ground-based".
- L.463: Insert comma before "respectively".
- L.471: Insert comma before "thus".
- L.478: Insert comma after "(1998)".
- L.482: Replace full stop at end of sentence with colon.
- L.492: Insert comma after "patches".
- L.509: "ground based" --> "ground-based".
- L.512: "wide scale" --> "wide-scale".
- L.528: In the reference list, the titles of books should be written with all nouns capitalized; the titles of papers only with the first word of the title capitalized (except for proper nouns).

- L.529-532: The first three references in the reference list have no author and do not appear in alphabetical order. Please correct.
- L.558-560: The correct journal name, issue number, page numbers and doi for this reference are: *Hydrol. Earth Syst. Sci.*, **23**, 4737–4761, doi:10.5194/hess-23-4737-2019.
- L.610: Write "Poisson" with a capital "P".

References (if not yet listed in the manuscript)

- Humphrey, M.D., J.D. Istok, J.Y. Lee, J.A. Hevesi, and A.L. Flint, 1997: A new method for automated dynamic calibration of tipping-bucket rain gauges. *J. Atmos. Oceanic Technol.*, **14**, 1513–1519, doi:10.1175/1520-0426(1997)014<1513:ANMFAD>2.0.CO;2.
- Uijlenhoet, R., 2001: Raindrop size distributions and radar reflectivity–rain rate relationships for radar hydrology. *Hydrol. Earth Syst. Sci.*, **5**, 615–627, doi:10.5194/hess-5-615-2001.
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- Uijlenhoet, R., J.A. Smith and M. Steiner, 2003: The microphysical structure of extreme precipitation as inferred from ground-based raindrop spectra. *J. Atmos. Sci.*, **60**, 1220–1238, doi:10.1175/1520-0469(2003)60<1220:TMSOEP>2.0.CO;2.