Response to reviewers for manuscript amt-2020-415: **Ångström exponent errors prevent accurate visibility measurement**

We thank the editorial team and the reviewers for your valuable inputs in enhancing the quality of our manuscript and appreciate the opportunity provided to revise it for publication in *Atmospheric Measurement Techniques*. We are happy to submit our point-by-point responses to the reviewers' comments and suggestions. The reviewers' comments/suggestions are in black. Our responses are in red. All the suggested changes have been incorporated in the manuscript and are outlined here.

General Comments:

The paper presents theoretical background of visibility measurements and points out systematic errors in essentially all visibility measurements. The theoretical background of the errors is pointed out on lines 34 – 64 of the discussion paper. The explanation is convincing, I really learned new things in reading it. It is obvious that there are systematic errors in visibility measurements worldwide. The topic is definitely important, not only to the scientific community but also to a wider audience: visibility measurements for instance at airports, harbours and at sea are relevant to practically everybody.

The paper is important and basically well written and I can recommend publishing it in AMT. However, before that I wish you would do some modifications.

General response: We thank the reviewer for the valuable review and encouraging comments.

1. Comment: First, I can see in your Fig. 2 that there were bimodal size distributions in your simulations already but you did not really pay any attention to it. Bimodality of size distributions have a strong effect on the Ångström exponent, see, e.g.,

Schuster, G. L., Dubovik, O., and Holben, B. N.: Angstrom Exponent and Bimodal Aerosol Size Distributions, J. Geophys. Res., 111, D07207, https://doi.org/10.1029/2005JD006328, 2006.

There are a lot of references in that paper and there are a lot of refs to it that discuss this matter. Among other things it shows that the Ångström exponent often varies with wavelength. And with the ratio of coarse and fine particles. How do these affect your results?

1. Response 1: Thank you for this valuable comment. We have added the reference and explanation. In this study, Eq. (6) specifies the determining variables of the Ångström exponent (q), which includes size distribution. The following sentence in Lines 159–161 to "In addition to the measurement wavelength, q is determined by the physical and chemical parameters of aerosol particles in Eq. (6), i.e., the refractive index and probability distribution function for the diameter of the aerosol particles, as discussed by other researchers (Schuster et al., 2006)."

Figure 2a shows the probability distribution function of aerosol particles used by the four groups in the simulation calibration, and Fig. 2b presents four different values of q. In this study, the design of the simulation calibration reflects the influence of size distribution on q, where the differences in size distributions of aerosol particles between groups caused the differences in the values of q given by the four groups. The aim of the simulation calibration is to reveal that it is impossible not only to obtain reliable Ångström exponents but also to determine the visibility error caused by erroneous values of q using current visibility measurement methods. We did not change Fig. 2 in order not to distract the focus of this study. As for the changes in q caused by the size distribution and the refractive index of aerosol particles, Fig. 3a shows the possible range of q in 10 typical regions for reference.

The volume ratio of coarse and fine particles is one of the parameters that describes the size distribution of aerosol particles. It seems a bit difficult to discuss this problem using the ratio of coarse and fine particles. Additional calculations are provided below for reference. Figure 1 shows that wavelength and refractive index have a complex effect on the extinction of aerosol particles, and therefore, the calculated values of q vary over a wide range. It is clear from Fig. 1 that the extinction coefficient of fine particles is more sensitive to size distribution and refractive index than that of coarse particles. Considering the contributions of coarse and fine particles in the atmosphere to the extinction coefficient, we consider that fine particles might determine the value of q rather than the ratio of coarse and fine particles in ambient atmosphere. Of course, further work needs to be done to support such a claim.

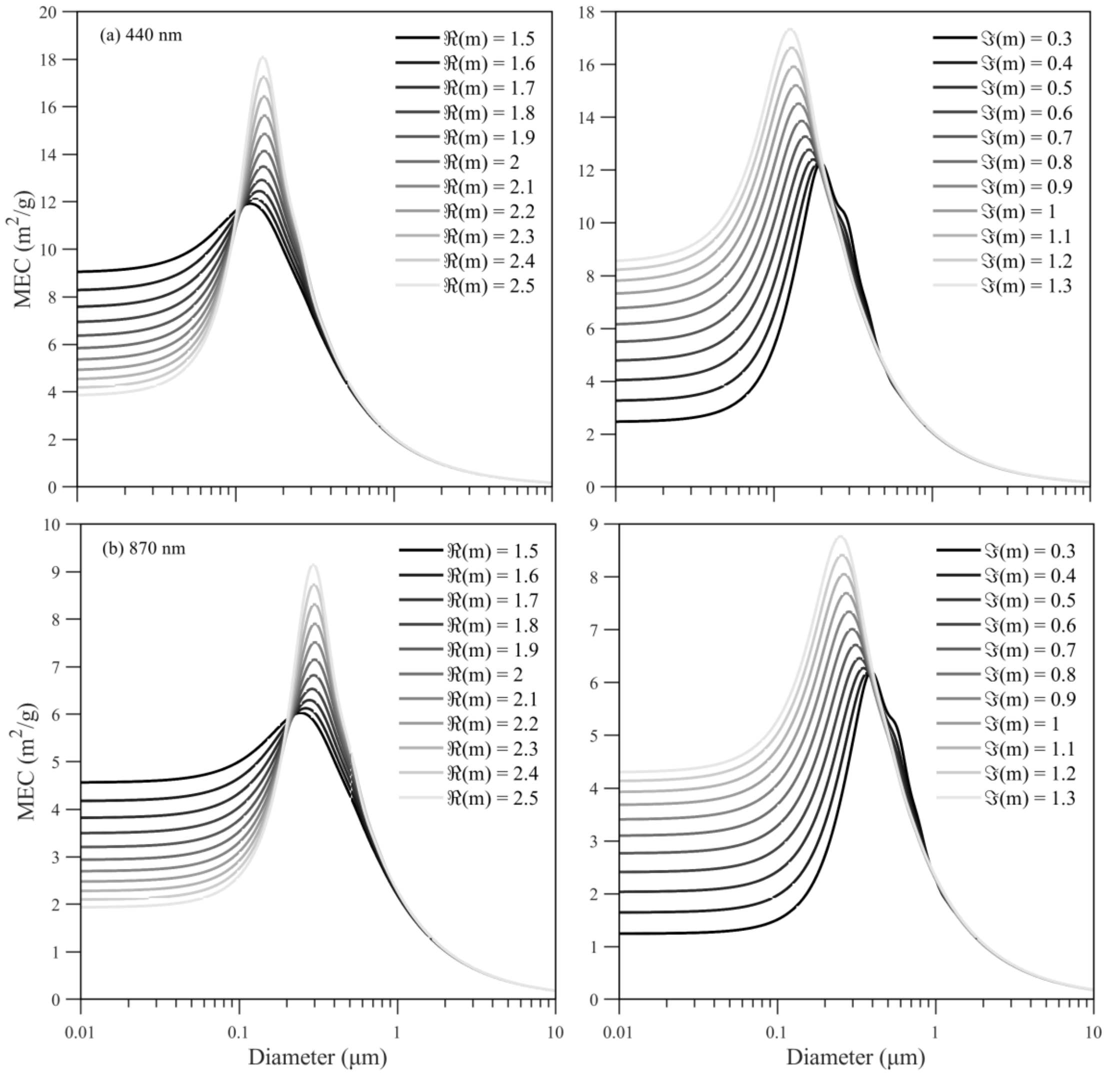

Figure 1: Relationship between the mass extinction coefficient (MEC) and the diameter of aerosol particles with different indices at a wavelength of (a) 440 nm and (b) 870 nm. The left panel shows the influence of the real part of the complex refractive index on MEC with the fixed imaginary part at 0.79. The right panel shows the influence of the imaginary part of the complex refractive index on MEC with the fixed real part at 1.95.

2. Comment 2: L40 “Obviously, WMO believes ...”. WMO is not a person, it cannot believe anything. Rewrite.

2. Response 2: We have revised the sentence in lines 37–39, which now reads " WMO claims that "visibility and MOR should be equal" if the influence of the contrast threshold can be excluded, which implies that the choice of measurement wavelength of the light source will not affect the measurement of visibility."

3. Comment 3: L42 "Ångström indicated the spectral dependence of visibility as early as 1929 (Ångström, 1929) …".

I was wondering, whether Ångström really wrote about visibility and acquired a copy of the original paper. I was right. There is not even the word "visibility" in the whole paper. There is the wavelength dependency of absorption and transmittance and the derivation of the exponent that was later called the Ångström exponent. So, transmittance depends on the Ångström exponent and visibility depends on transmittance according to your Eq. (1). Your Eq. (2) follows from these but it is not given by Ångström (1929)

3. Response 3: Thank you for pointing out this lapse. The sentence has been modified as follows: "However, Ångström indicated the spectral dependence of the extinction coefficient as early as 1929 (Ångström, 1929). Combining the inverse relationship between visibility and extinction coefficient (Eq. (1)), we obtain:"

4. Comment 4: L59 "…opinion of the WMO …". again, WMO is not a person, it does not have opinions. Rewrite.

4. Response 4: We thank the reviewer for this useful comment. We agree that we should have phrased these points differently and not focus on WMO, but rather on specific conclusions presented in the reports by WMO. Similar to our response to Reviewer 1, in lines 55–73, we have rewritten as follows: "The Guide to Instruments and Methods of Observation (WMO, 2018) cites the intercomparison of visibility measurements (Middleton, 1952; WMO, 1990), where the difference in MOR and visibility by day is attributed to the difference in the contrast threshold. The conclusion reached in this guide states that "Visibility and MOR should be equal if the observer's contrast threshold is 0.05 (using the criterion of recognition) and the extinction coefficient is the same in the vicinity of the instrument, and between the observer and the objects." This conclusion implies that there is no need to consider a deviation from the true values of visibility measured at a wavelength of λ_0 ($V_{\lambda 0}^{T}$) when converting the visibility measured at λ_1 ($V_{\lambda 1}$) to λ_0 ($V_{\lambda 0}$) using Eq. (3), i.e., the errors in the values of q are negligible. Therefore, visibility meters with different measurement wavelengths can obtain consistent visibility measurements and the following statements are true: (1) the measurement wavelength of visibility meters can be arbitrarily selected because the visibility measured at any wavelength can be mutually converted; (2) the reference visibility can be artificially defined, such as the MOR, because the reliability of visibility data will not be reduced by converting the visibility measured at various wavelengths into the reference wavelength; and (3) multiple visibility benchmarks such as MOR and meteorological visibility by day can be used simultaneously, in the same way that units such as grams and kilogrammes can be completely substituted to measure mass.

In fact, existing methods of visibility measurement using visibility meters with different wavelengths currently in use are formulated under the premise that the WMO's recommended approach is adequate. For example, the light source of Biral RWS-30 is at 850 nm (Biral, 2018), that of Optec LPV-3 is at 550 nm (Optec, 2011), and Vaisala LT31 uses a white light source (Vaisala, 2018). However, this guide does not explain why the MOR is consistent with human observations of visibility when the contrast threshold is the same. In other words, no theoretical basis is provided to prove that reliable values of q can be obtained in the visibility measurement."

5. Comment 5: The Eq. (7) is strange, I have never seen it in this form. First, what do you mean with "water particles"? Does it mean humid particles or pure water droplets? Further, GF is generally defined as the ratio of humid and dry particle diameters. So, how was Eq. (7) derived? If it was used like it is written now, then you should correct it and repeat your simulations with a corrected one.

5. Response 5: Thank you for pointing out this error. We agree that the words "water particles" were inappropriate. We have now changed them to "pure water". We have added a definition of hygroscopic growth factor and the modified sentence now reads as follows (Lines 102–105): "As for hygroscopic particles on which water vapour condenses, the refractive index of mixed particles can be calculated using the weighted average of the volume ratio of each composition, and the diameter of mixed particles can be calculated using the hygroscopic growth factor (GF), which is defined as the ratio of humidified particle diameter to the diameter at dry conditions (Jacobson, 2001; Chen et al., 2012; Zhang et al., 2017)."

There was a missing superscript in Eq. (7), and we have now corrected the typographic error. Fortunately, the correct equation was used in the calculation. The correct form of Eq. (7) is $m = \frac{m_A + m_W (GF^3 - 1)}{GF^3}$, and the equation is derived in the following manner:

$$m = \frac{m_A V_A + m_W V_W}{V_A + V_W}$$

$$= \frac{m_A \cdot \pi/6 \cdot D_A^3 + m_W \cdot \pi/6 \cdot [(D_A \cdot GF)^3 - D_A{}^3]}{\pi/6 \cdot (D_A \cdot GF)^3}$$

$$= \frac{m_A + m_W (GF^3 - 1)}{GF^3}$$

References

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WMO: The First WMO Intercomparison of Visibility Measurements: Final Report (D.J. Griggs, D. W. Jones, M. Ouldridge and W.R. Sparks) (WMO/TD-No. 401), World Meteorological Organization, Geneva, Switzerland, 1990.