Reverberation chamber enhanced backscattering

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Reverberation Chamber Enhanced Backscattering: High-Frequency Effects

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Abstract—The need for accurate efficiency measurements at high frequencies of large form-factor devices is ever increasing. In this work, the potential of performing antenna efficiency measurements in an electrically extremely large (up to 250λ) reverberation chamber is investigated and compared to its use at lower frequencies. It is found that there are large deviations in the enhanced backscattering constant at high frequencies. Closer investigation, by introducing a position-dependent enhanced backscattering constant calculation, shows that the deviation mostly occurs at the horn antenna directed at the stirrer. This could be aggravated by the use of a moving wall type of stirrer. The work concludes by demonstrating the potential impact of these deviations on the antenna efficiency. The deviations clearly show the need for more research into these effects.

I. INTRODUCTION

In the face of 5G's desired flexibility [1]–[3] the need automated measurement systems and techniques increases. In addition, wireless capability is added to more and more devices, such as trash compactors [4]. In the future, no doubt large devices will also include the use of high frequencies. This increases the need for fast and accurate methods for antenna efficiency measurements, including those for large-form-factor devices. The efficiency is a critical parameter for, in particular, mass-production and compact antennas, but traditional radiation efficiency measurements are challenging and time-consuming. The radiation efficiency η_{rad} is one of two antenna efficiency definitions: it is the ratio of the total radiated power to the accepted power, as opposed to the total efficiency η_{tot} , which is the ratio of the total radiated power to the available power. Several methods to measure antenna efficiency have been traditionally applied [5]–[11], but they all require a reference antenna (or two identical antennas), or are frequency-dependent in their setup such as the Wheeler-cap method [5].

Recently, three reverberation chamber (RC) methods to measure antenna efficiency that avoid these problems were proposed [12]. They do not require any reference antennas, accurate alignment, polarization, specific antenna holders or highly-directive antennas. Instead they rely on knowledge of the RC (the chamber time constant τ_{RC} [12]–[15]) that is used to calculate the efficiency of one, two or three antennas. The one- and two-antenna methods apply assumptions on the enhanced backscattering constant e_b [12], [16], while the three-antenna method does not. Accurate results were shown in the 1 to 6 GHz band for all three methods [12]. Considering

Fig. 1. The setup in the RC with the hinged moving wall stirrer (top right) in its frontmost position. As indicated, the left antenna is in position I, while the right antenna is in position II.

Fig. 2. Photographs of Horn A (a), Horn B (b) and Horn C (c), including their SMA adaptors.

the trend of harvesting all possible frequency bands, it is key to push this approach to a wider frequency range and verify it for more chamber types, such as chambers with a moving wall [17] or VIRCs [18]. In addition, measuring large-form-factor devices at high frequencies dictates the use of an electrically extremely large reverberation chamber. While, in principle, the method should remain valid for this frequency range and has been demonstrated at millimeter-wave frequencies [19], some results indicate that this is not necessarily the case in all situations - especially when the RC becomes electrically extremely large [20], [21].

In this paper, a $4.05 \times 5.7 \times 3.15 \text{ m}^3$ RC with moving wall is characterized from 750 MHz up to 18 GHz and used for efficiency measurements of antennas using the methods proposed in [12]. The average dimension of this room corresponds to approximately 250λ at 18 GHz. In particular, the enhanced backscattering constant over frequency and its impact on the three methods is studied. To this end, an

expression is introduced to derive the backscattering constant at an individual antenna position and orientation.

In Section II the setup is described, which is followed by some of the basic properties of the configuration, the chamber's time constant τ_{RC} and Rician K-factor K , where the former is needed to calculate efficiency and the latter serves to determine if the room is well stirred. The enhanced backscattering constant e_b , a critical parameter in the two-antenna method and ideally equal to 2, is then studied and discussed in detail. Next to the conventional approach, a position/orientation dependent variation is introduced to study local effects in the room. Next, the impact of these result on efficiency measurements is shown in Section III. This will give a clear view on what the impact of a deviating e_b on an efficiency measurement can be. Finally the work is concluded in Section IV.

II. CHAMBER CONFIGURATION AND PROPERTIES

The reverberation chamber used in this work performs mode stirring by a moving/folding irregularly-shaped wall, as shown in Fig. 1. The measurements are performed in tuning mode, i.e. the stirrer is moved and a pause is build in to allow all surfaces to stop vibrating before starting a new sweep on the VNA. $N = 100$ mode-stirring samples are taken this way, in addition to the use of 100 MHz frequency stirring. All measurements are performed in antenna pairs, and the positions and orientations of the antennas are kept as constant as possible when switching antennas. In Fig. 1 the left antenna is in position I, while the right antenna is in position II. Three dual-ridged horn antennas (DRHAs) are used for the experiments: a Com-power AH-118 (referred to as horn A), an EMCO 3115 (referred to as horn B) and a Schwarzbeck BBHA-9120-D (referred to as horn C). Combinations between these horns are referred to as configuration A-C, B-A and B-C for horn A with C, B with A and B with C, respectively. These abbreviations are also used in subscripts to indicate to which configuration a parameter belongs. The three antennas, shown in Fig. 2, are chosen since they cover similar frequency ranges. Their similarity will also result in comparable behavior in terms of their radiation patterns and polarization. Nonetheless they are clearly different, resulting in different input reflection coefficients and efficiencies. All measurements are performed in the maximum range allowed by the antennas, 0.75-18 GHz, with a 100 kHz sample spacing.

The efficiency measurement methods introduced in [12] are all based on a comparison of the quality factor of the chamber including antennas and the quality factor of the empty chamber. The latter is estimated by the slope of the (exponential) decay in the power-delay profile (PDP), captured in the chamber's time constant τ_{RC} [12]–[15]. Ideally, τ_{RC} is independent of the antenna type that is used, and is a function of frequency as the losses in the chamber are frequency-dependent. The time constant is shown in Fig. 3, where it can be seen that the three antenna combinations deviate very little from one another. Furthermore, the time constant varies much less for frequencies above approximately 8 GHz than it does

Fig. 3. Time constants for the three antenna combinations. The three configurations deviate very little from one another. The small glitches observable at 9, 12 and 15 GHz occur at the frequencies where a switch between calibration sets has to be made.

Fig. 4. Rician K-factor obtained from the three sets of two-antenna measurements. The K-factor decreases (i.e. gets better) for increasing frequency.

for frequencies below that - it starts to level off, corresponding to a nearly linear increase in the room's quality factor. This means that there are no significant leaks developing at the higher frequency end, which would result in losses and a decreasing τ_{RC} . The time constant gives no reason to doubt the chamber's performance at the high-frequency end when compared to lower frequencies.

To verify that there is no strong direct coupling between the antenna pairs, the Rician K-factor (the ratio of unstirred energy to stirred energy) is determined. The K-factor can be estimated from S-parameters using [22]:

$$K \approx \frac{|\langle S_{21} \rangle|^2}{\langle |S_{21} - \langle S_{21} \rangle|^2 \rangle}. \quad (1)$$

In Figure 4 the Rician K-factor obtained for the three measurement sets is shown. It can be seen that the K-factor decreases for increasing frequency, ranging from below -35 dB at 1 GHz

Fig. 5. The enhanced backscattering constant is seen to deviate significantly from its ideal value of $e_b = 2$, even when it is assumed to be uniform throughout the reverberation chamber. When it is calculated for the individual positions/orientations it can be seen that it tends to be lower than 2 for position I, while it is larger than 2 for position II. Position II corresponds to the antenna directed at the moving wall.

to below -45 dB at 18 GHz. This is a low K-factor [19], [23], indicating that the unstirred contribution to the average fields is small for the antennas, antenna placements and room that are used. This can be attributed to the use of highly directional antennas, oriented away from one another. The K-factor gets better for increasing frequency (likely due to increasing gain of the antennas), again giving no indication that something might be problematic for antenna efficiency measurements at the higher frequency end.

The quantity e_b , an enhanced backscatter constant [12], [16], [24], [25], is used and assumed constant within the working volume in the calculations for the efficiency in the 2-antenna method [12], while in the one-antenna method the assumption is made that $e_b = 2$. This will be further explained in Section III. It has also been used for chamber characterization [20], [25]. Since the assumptions on e_b are the main differences between the different efficiency measurement methods, it is useful to verify for each particular chamber and frequency range how well these assumptions hold.

The frequency-dependent (but spatially uniform) value of e_b used in the two-antenna method can be calculated for measurement A-C by [12]:

$$e_{b,AC} = \frac{\sqrt{\langle |S_{11,A-C,s}|^2 \rangle \langle |S_{22,A-C,s}|^2 \rangle}}{\langle |S_{21,A-C,s}|^2 \rangle}, \quad (2)$$

with similar expressions for each of the other antenna combinations. $\langle \cdot \rangle$ is used to indicate averaging over paddle positions and a 100 MHz bandwidth of frequency stirring, and the subscript s denotes the stirred components of the S-parameters (i.e. the S-parameters with their mean subtracted). Since only information from a single antenna pair is used for this e_b , only one e_b can be obtained for each measurement, leading to the implicit assumption that e_b can be frequency-dependent but has to be spatially uniform. These e_b 's obtained from the

measurements are shown in Fig. 5 as indicated by 'Uniform'. In this figure it can be observed that the e_b 's obtained from the different sets of antennas and measurements match fairly well, having a mutual difference below 7.5% up to about 9 GHz (approximately 130λ room size) and below 15% over the entire band. Up to approximately 6 GHz (approximately 90λ room size) the measurements deviate less than 15% from the ideal value of 2, and keep below 20% deviation up to 9 GHz. Above 9 GHz some differences and, in general, more variation and deviations up to 40% from the ideal value can be observed. This implies that the chamber performs less ideal for higher frequencies in the context of antenna efficiency measurements [20], [25]. In addition, as will be shown in Section III, the one-antenna method (which assumes $e_b = 2$) becomes less suitable for increasing frequencies here, as any deviation in e_b from its ideal value will directly impact the efficiency that is obtained. Note that the similarity in e_b between the different measurements does not imply that it is constant within the working volume since the antenna positions and orientations were not changed.

By combining the results of the three measurement sets and taking into account the position and orientation of the antennas in each of the measurement sets, e_b can be calculated directly for each position. This is referred to as 'position-dependent' e_b . Solving the equations for the three-antenna method in a different manner, in position/orientation I the position-dependent e_b using the antenna combination A-C as a base can be calculated:

$$e_{b,AC,I} = \frac{\langle |S_{11,A-C,s}|^2 \rangle \langle |S_{21,B-C,s}|^2 \rangle}{\langle |S_{21,A-C,s}|^2 \rangle \langle |S_{21,B-A,s}|^2 \rangle}, \quad (3)$$

with similar expressions for the other position and antenna combinations. Note that this assumes that the antennas used are sufficiently similar in terms of their radiation pattern and polarization. If they are not, this will be seen as a difference between the three e_b 's for that position. However, these calculations do compensate for the contributions of each of the antennas' total efficiency (and thereby also their input match).

The results for the position-dependent e_b are compared to the conventional e_b in Fig. 5. While there are some mutual deviations again (possibly due to a small misplacement, orientation or antenna behavior), especially visible in position II, these keep below 10% up to 17.5 GHz and 25% over the entire band for positions I and II, respectively. On the other hand, the deviation from the Uniform e_b is up to 33% for position I, and up to 55% for position II in the bands above 6 GHz (approximately 90λ room size). For some frequencies, the ratio of the e_b 's in positions I and II can be as large as 2.3. As will be shown in Section III, when this occurs it will have a significant impact on the efficiencies obtained with the two-antenna method.

An increase in e_b has been shown previously for a high-gain horn directed at a paddle [20], around 3.75 in a chamber used around 45 GHz and dimensions of approximately 100λ . A similar effect is observed here, with the antenna pointed at the

TABLE I
MANUFACTURER SPECIFIED ANTENNA GAINS

Frequency [GHz]	Horn A Gain [dBi]	Horn B Gain [dBi]	Horn C Gain [dBi]
2	6.1	8.4	10.4
4	12.3	9.1	12.6
6	12.8	10.6	13.0
8	11.5	10.5	11.3
10	12.2	11.3	12.1
12	14.0	12.0	13.2
14	10.8	11.5	11.7
16	15.8	16.3	17.2
18	12.8	7.2	8.9

moving wall experiencing a higher e_b than the other antenna, peaking around 4 and staying mostly above 3. The average dimension of the room in this work (4.3 m) corresponds to approximately 60λ at 4 GHz, where the deviations seem to start, and close to 90λ at 6 GHz, where the deviations become very clear. They remain very clear over the entire band upwards of 6 GHz, right up to the maximum frequency used of 18 GHz (approximately 250λ). The effect becomes more pronounced in the conventional ('assuming uniform') e_b as well.

In order to provide insight into the effect of antenna gains, the manufacturer specified antenna gains are given in Table I. Given the more pronounced effect on the backscattering constant for the antenna aimed at the stirrer, it seems likely that antenna gain will have some influence on the observed backscattering constant. However, there does not appear to be a direct relationship between the effect and antenna gain: the gains of all three horn antennas peak at 16 GHz, with a significantly higher gain than at other frequencies, while the observed deviations in the backscattering constant are most pronounced between 12 GHz and 14 GHz.

High backscattering constants were also observed in another chamber at frequencies around 250λ [21]. The root cause of this effect remains unclear, but it appears that the stirrer and its coupling with the antenna have an impact on it. One could interpret the backscattering constant as the ratio of the number of unique paths in S_{11} to the number of unique paths in S_{21} [24], with the ideal being 2. From this point of view, the results presented in this section may be interpreted as the presence of more unique paths for position II than for position I. It seems quite possible that the use of a large wall instead of a more conventional rotating paddle aggravates this effect by providing an entirely changing surface to one of the antennas, in particular when combined with high-gain antennas pointed at it. Note that the latter is usually done in order to achieve a low K-factor. As demonstrated in the next Section, these deviations pose a problem for the one- and two-antenna efficiency measurement techniques when they occur.

Fig. 6. Resulting radiation efficiencies for Horn A. The one- and two-antenna method results for antenna combination B-A are clearly unphysical for the higher frequencies, while the two-antenna method for combination A-C also deviates significantly from the three-antenna method.

III. IMPACT ON ANTENNA EFFICIENCIES

In this section the antenna radiation efficiencies obtained from the one-, two- and three-antenna methods are compared, focusing on the impact of the earlier observed behavior in e_b . Total efficiencies are omitted for brevity - the radiation efficiencies pose more stringent requirements on the setup, since they include compensation for the antenna input mismatch. As the antenna positions/orientations are the same and the radiation patterns of the antennas are similar, it is assumed that the change in e_b does not impact the three-antenna method, which is used as the reference value for this comparison. The reader is referred to [12] for a detailed description of the calculations and procedures. The key difference between the three methods is in the assumptions that need to be made on the enhanced backscatter constant e_b :

- One-antenna method: $e_b = 2$;
- Two-antenna method: e_b is uniform;
- Three-antenna method: no assumption on e_b .

The radiation efficiencies are given in Fig. 6 (Horn A), Fig. 7 (Horn B) and Fig. 8 (Horn C). For Horn A the radiation efficiencies computed using the one- or two-antenna method deviate less than 15% from the three-antenna method up to 6 GHz (90λ), but can increase up to 35% for the one-antenna method (set B-A between 12 and 14 GHz). This is the range where the position-dependent e_b obtained in Section II deviates most, and this effect results in an over-estimated efficiency (unphysical, above 100%) for the one- and two-antenna methods when the antenna is in position II. The deviation of the two-antenna method remains below 17.5% over the entire band. For Horn B the deviations of the two-antenna method are larger than that of the one-antenna method: below 6 GHz (90λ) the one-antenna method deviates less than 5%, while the two-antenna method deviates up to 10%. Over the entire band the one-antenna method deviates 7% at most, while the two-antenna method shows deviations

Fig. 7. Resulting radiation efficiencies of Horn B. Especially the two-antenna method results deviate from the three-antenna method.

Fig. 8. Resulting radiation efficiencies of Horn C. All results except for the three-antenna method are unphysical for the higher frequencies.

up to almost 17%. This can be explained by the measured e_b 's in Fig. 5: since Horn B was always in position II, the e_b obtained in the two-antenna method is over-estimated, while the ideal value of 2 would have been more accurate. The radiation efficiency of Horn B using the three-antenna method is close to the 91% obtained for a similar antenna in [12]. For Horn C the deviation of the one-antenna method remains below 19% up to 6 GHz (90λ), while the two-antenna method remains below 11%. Over the entire range the deviation of the one-antenna method peaks at 36%, while the deviation of the two-antenna method peaks at 19%. Again, this happens in the range between 12 to 14 GHz, where large deviations were observed in the position-dependent e_b . Since Horn C is always in position II, all one- and two-antenna methods over-estimate the efficiency for Horn C, resulting in unphysical estimates greater than 100%. While not explicitly shown, the total efficiency results are very similar in fashion, since they are only scaled with the antennas' reflection coefficients.

IV. CONCLUSION

In this work, the behavior of the enhanced backscatter constant in an electrically very large (up to 250λ) was investigated. Despite good results in the antennas' S-parameters, the chamber time-constant and Rician K-factor, it was found that the enhanced backscattering constant deviates significantly from its ideal value for high frequencies, starting around 60λ room size. By introducing a position-dependent calculation for the enhanced backscattering constant, it was shown that the deviation mostly originates from the antenna directed at the moving-wall stirrer. Finally, the potential impact of the deviations in the backscattering constant on the efficiency were shown, illustrating that the effect is problematic for the one- and two-antenna methods if it occurs. These interesting results show the need for more research to find the underlying cause of the effect.

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