Degradation of Dynamic Range for Shielding Effectiveness Measurements Due to Long-Term Use of a Dual Vibrating Intrinsic Reverberation Chamber

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***Abstract*—This article presents the degradation effects of long-term use of a dual vibrating intrinsic reverberation chamber (dual VIRC) for shielding effectiveness (SE) measurements. At the beginning with a new fresh dual VIRC setup it is possible to achieve a very high dynamic range (DR) but the DR degrades due to long-term use of the dual VIRC. The effect of 10 years use of the dual VIRC on the DR is shown as function of usage time. Also, the effect on the DR of a new dual VIRC with better conductive cloth has been presented.**

***Index Terms*—Degradation, dual vibrating intrinsic reverberation chamber (VIRC), dynamic range, long-term use, shielding effectiveness measurements.**

I. Introduction

THE technique for measuring SE with a dual vibrating intrinsic reverberation chamber (VIRC) has been used now at Thales Nederland for 10 years since 2012. This SE measurement technique is familiar with the well-known procedure for measuring SE in a nested configuration that is described in the IEEE Standard 299.1 [1]. The SE has been determined by this procedure for a very limited number of polarizations and angles of incidence. In most applications the electronic modules will be exposed to electromagnetic (EM) fields with various polarizations and angles of incidence. In IEC 61000-4-21 [2] a procedure for measuring SE of materials is described using reverberation chambers. This nested reverberation technique represents the EM-environment better than conventional SE measurements.

A new technique to measure the SE of complex samples is described in [3]. This technique makes use of two identical VIRCs. Just like with nested reverberation chambers the device under test (DUT) will be exposed to EM-fields with all possible polarizations and angles of incidence. As with the nested reverberation method there are several different approaches to determine the SE of a sample using the dual VIRC method. These different approaches have been extensively researched in [4], [5], and [6].

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The maximum SE that can be measured depends on the DR of the dual VIRC at that moment. Due to the use of the dual VIRC the cloth material starts aging. The movement of the dual VIRC causes at a certain moment cracks in the cloth material due to wear. These cracks cause leakage between the transmitting and the receiving part of the dual VIRC. Due to this leakage the DR of the dual VIRC degrades.

The question is: What is the influence of long term use of the dual VIRC setup on the SE measurement result? The answer could be found in the DR results as function of usage time. The degradation of the DR as function of usage time due to long-term use of the dual VIRC will be shown in this article. First, the results for the old version (2012) of the dual VIRC are depicted. Then the results for the new version (2020) of the dual VIRC will be shown. Also a comparison between the old and new version of the dual VIRC will be made.

This article is organised as follows. Section II provides a brief description of the dual VIRC setup, while Section III shows how to determine the SE. Section IV explains the DR and Section V goes about the aging of the dual VIRC. Section VI provides an overview of the DR results for the old dual VIRC setup with Kassel cloth (2012) and Section VII does the same for the new dual VIRC setup with Nora Dell cloth (2020). Finally, Section VIII gives the conclusion.

II. Dual VIRC Setup

The used methods and techniques for SE measurements are mentioned in the IEEE Standard 299.1 [1] and IEC 61000-4-21 [2]. Since 2012 SE measurements have been carried out at Thales Nederland with the dual VIRC. Measuring SE using a dual VIRC is described in [3] and [7]. Fig. 1 shows the schematic setup for SE measurements using a dual VIRC.

A transmitting antenna is placed in the TX-VIRC and a receiving antenna is placed in the RX-VIRC to measure the power that is coupled into the RX-VIRC. The generator and analyzer are controlled by a PC.

Measurements were carried out in a frequency range of 200 MHz to 18 GHz. From 200 MHz to 1 GHz two discone antennas were used [8]. The discone antennas have been designed for 300 MHz to 2 GHz, so measurements below 300 MHz show a great variability. Also field uniformity in the VIRC below 300 MHz is limited because of the size of the VIRC. The SE was calculated for every frequency using the recorded maximum values. It is

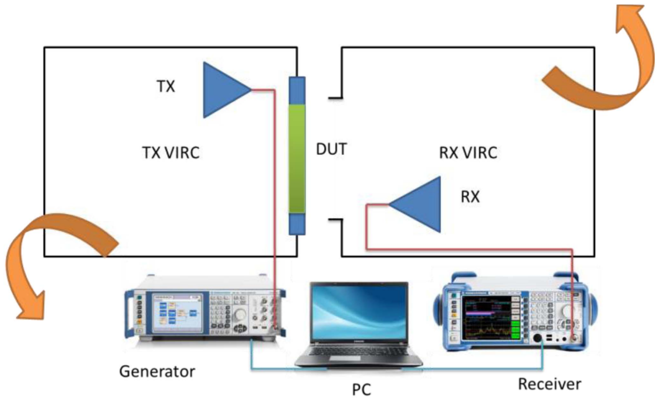


Fig. 1 Schematic setup for SE measurements using a dual VIRC.

Fig. 2 Dual VIRC setup from 2012 with Kassel cloth.

also possible to calculate the SE based on the recorded average values. The advantage of using the maximum values (max-hold) is that a higher dynamic range can be obtained, compared to using the average values [3]. The disadvantage is a higher variability.

One upper corner of each VIRC is moved by means of a dc motor. At each frequency the measurement is carried out during 2 s. In this time the motor makes about 2 revolutions. In both frequency ranges 200 MHz–1 GHz and 1–18 GHz 100 frequencies are measured. Therefore during the measurement of a sample the dual VIRC is moving for $2 \times 100 \times 2$ s = 400 s. For the measurement without the sample another 400 s is needed.

Fig. 2 shows the dual VIRC setup from 2012 which has been built up with Kassel cloth from Shieldex ([9]). Kassel is a nylon cloth with a silver + copper plating. The Kassel cloth has an electrical surface resistance of less than 0.03 Ω/□.

The new (fresh) dual VIRC setup from 2020 which has been built up with Nora Dell cloth from Shieldex is shown in Fig. 3. Nora Dell is a nylon cloth with a silver + copper + nickel plating. The Nora Dell cloth has an electrical surface resistance of less than 0.009 Ω/□ which is lower than for the Kassel cloth. Therefore, a better shielding of the Nora Dell cloth and also a better DR of the dual VIRC setup was expected. In Table I, the specifications of the Shieldex cloths Kassel RS and Nora Dell are given.

The frequency range 200 MHz–18 GHz is covered with two different antennas. Fig. 4 shows the discone (upper) and the horn antenna (lower) that are used inside the VIRC. The

Fig. 3 Dual VIRC setup from 2020 with Nora Dell cloth.

TABLE I
SPECIFICATIONS OF KASSEL AND NORA DELL CLOTH

Shieldex	**Kassel RS**	**Nora Dell**
Metal Plated	Silver + Copper	Silver + Copper + Nickel
Electrical Surface Resistivity	< 0.03 Ω/□	< 0.009 Ω/□
Total Weight	85 g/m^2	100 g/m^2
Total Thickness	0.11 mm	0.125 mm

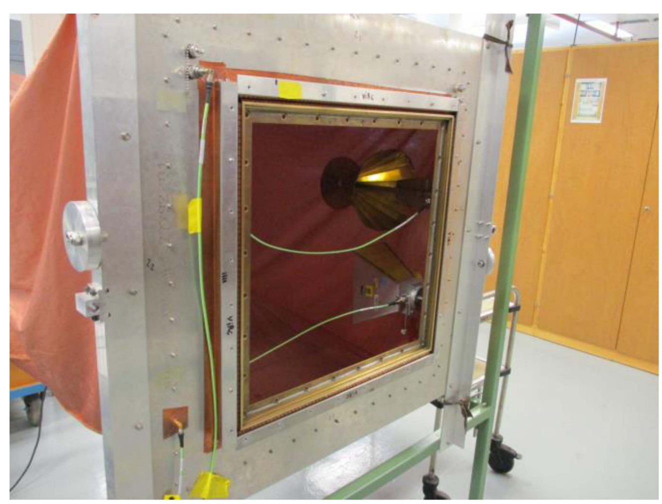


Fig. 4 Discone and horn antenna inside a VIRC, including open brass frame.

discone antenna covers the 200 MHz–1 GHz frequency range and the horn antenna covers the 1–18 GHz frequency range. More information about wideband antennas for reverberation chambers is given in [8]. In Fig. 4 also the open brass frame is shown which can be used to mount the material under test or DUT in the dual VIRC setup.

III. Determining the Shielding Effectiveness

SE is used as a parameter to quantify how well a barrier shields EM-fields. The SE is typically defined as the ratio of the transferred power (P_t) through the DUT to the incident power (P_i), i.e.,

$$\mathrm{SE} = 10 \log \left(\frac{P_i}{P_t} \right) \tag{1}$$

The definition of SE leads to several and different measurement models which is shown in literature. During the years several different approaches have been used to calculate the SE.

In [3] four different approaches (SE_1 to SE_4) have been discussed with emphasis on the use of (nested) reverberation chambers [4], [5], [6]. It should be noted that the procedure to determine the SE in IEC 61000-4-21 [2] is the same for the nested reverberation and the dual VIRC setup.

Because of the ease of use, at Thales Nederland is chosen for the use of SE_2 [3]

$$\mathrm{SE}_2 = 10 \log \left(\frac{P_{rx,ns}}{P_{rx,s}} \right). \tag{2}$$

SE_2 is the ratio of the measured power in the *RX* VIRC with sample, $P_{rx,s}$, and without the sample, $P_{rx,ns}$ [4]. The advantage of using SE_2 is that no switching between antennas (in different VIRCs) is needed and that only two antennas are needed instead of three for each frequency band. This minimizes the handling during the measurement and also the amount of equipment that is needed. The accuracy of the SE results using SE_2 satisfies the needs of Thales Nederland.

IV. Dynamic Range

In case of SE measurements the DR is the maximum SE that can be measured with that measurement setup. For the dual VIRC this means that the DR is the difference between the SE measurement result (received power) of a maximum open situation (open brass frame of Fig. 4) and the SE measurement result (received power) of a maximum closed situation (closed welded brass frame of Fig. 5). The DR can be determined by using (2): $\mathrm{DR} = \mathrm{SE}_2$ with $P_{rx,ns}$ is measured received power at maximum open situation and $P_{rx,s}$ is measured received power at maximum closed situation.

At lower frequencies there will be aperture size effects which will influence the SE measurement results. This is due to the larger wavelengths with respect to the aperture size. In the maximum open situation, the measured power $P_{rx,ns}$ will be determined by the wavelength in relation to the maximum open dimension of the open brass frame. In the maximum closed situation, the measured power $P_{rx,s}$ will be determined by the wavelength in relation to a leaky path somewhere in the dual VIRC setup, which probably will be a crack in the cloth material or a bad connection between brass frame and dual VIRC, but very likely not the welded closed brass frame itself. Assuming that the dimension of the maximum open frame is much larger than the dimension of a leaky path in the maximum closed situation, this means that the influence of the larger wavelength (at lower frequencies) in relation to the aperture size is larger for $P_{rx,ns}$ than for $P_{rx,s}$. This is because $P_{rx,s}$ is probably already limited by the noise level of the receiver at these lower frequencies and the dual VIRC setup. This means that for lower frequencies $P_{rx,ns}$ will decrease more than $P_{rx,s}$ which results in a lower DR.

Fig. 5 Closed welded brass frame for dual VIRC setup.

The connection between the *TX* VIRC and the *RX* VIRC is carried out by means of a knife and groove connection which also is used in doors of cages of Faraday. The knife is formed by the aperture-edge of the *RX* VIRC. The groove is formed by the edge of the brass interface frame with double finger stocks, see Fig. 5. Between the brass (open/closed) frame and the *TX* VIRC a serrated gasket is used to ensure good conductive contact between the frame and the *TX* VIRC. The frame is pushed to the *TX* VIRC by means of 4 metal strips (see Fig. 4). Every time when a new SE measurement session with the dual VIRC is started, all conductive parts of the brass interface frame and edge are cleaned, especially the knife. This ensures an optimal and reproducible conductive connection between the *RX* VIRC and the *TX* VIRC and therefore also a reproducible DR.

Every time before a new SE test session was started, the DR has been measured to check if the setup is working properly and to know what the actual achievable maximum SE level is. By doing this a lot of DR data has been gathered during the long term use of the dual VIRC.

V. Aging of the Dual VIRC

Due to the use of the dual VIRC the cloth material starts aging. The rotating movement of the upper corner of the VIRC causes wrinkles in the cloth material around the moving corner, as shown in Fig. 6. Because the "sharp" wrinkles in the cloth material often occur at the same spot, the copper cladding on top of the cloth starts wearing at these "sharp" wrinkles.

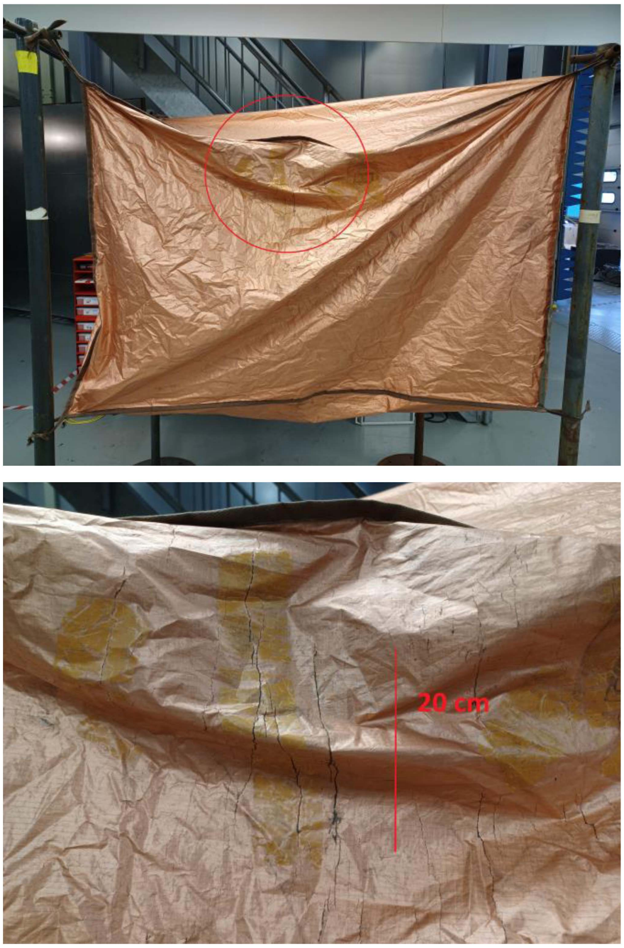
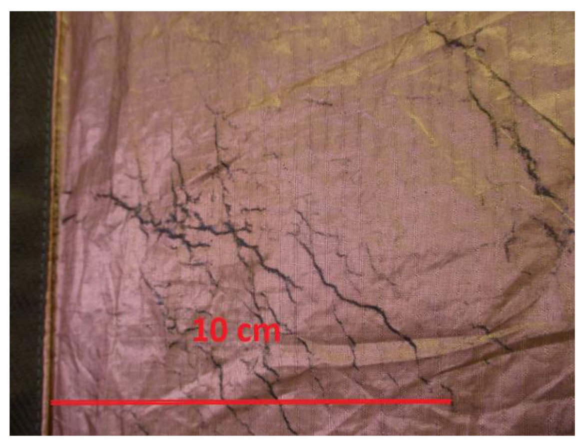
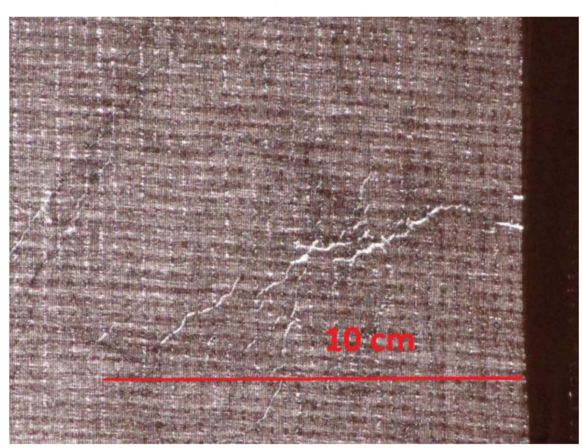


Fig. 6 Wrinkles and cracks in Kassel cloth due to wear (1) (picture from outside VIRC).

Fig. 7 Cracks in Kassel cloth due to wear (1) (picture from inside VIRC).



(a)



(b)

Fig. 8 Cracks in Kassel cloth due to wear (2) (picture from (a) outside and (b) inside (with backlight at the outside) VIRC).

The movement of the dual VIRC causes at a certain moment cracks at the wrinkles in the cloth material because the copper is worn away at that spot, see Fig. 6 (outside VIRC) and Fig. 7 (inside VIRC). Fig. 8 shows another spot on the VIRC with cracks (as example).

In Figs. 7 and 8, the cracks are shown from the inside of the VIRC looking to a backlight at the outside of the VIRC. Because light (which is also EM energy) can be seen in a line, this means that also RF energy can pass through that line if the wavelength fits to the dimension of the line (crack). The lengths of the different cracks in Fig. 7 measure up to 20 cm but also small cracks can be seen like 1 cm or even smaller. Based on about 0.5 λ crack-length this means that frequencies above 750 MHz ($\lambda = 40$ cm) up to 15 GHz ($\lambda = 2$ cm) could pass through the cracks with the right polarization. Due to the multiple reflections inside the VIRC all kinds of polarizations exist inside the VIRC. Also, many smaller cracks are visible in Figs. 7 and 8 which means that also for higher frequencies the leakage of all these small cracks together can be of influence. So, if there is a leakage somewhere in the VIRC, the reverberated EM energy will find it and go through it. These cracks will cause

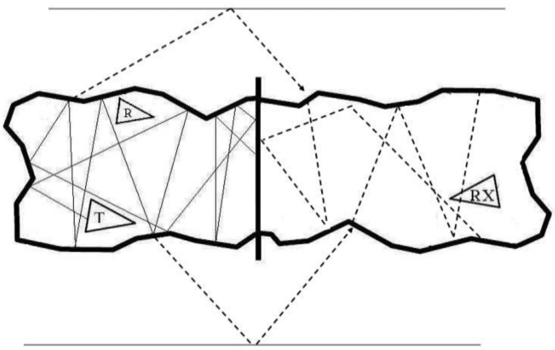


Fig. 9 Outside reflections limiting the DR of the dual VIRC.

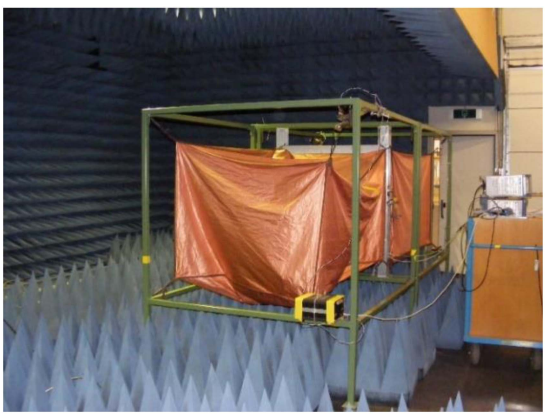


Fig. 10 Dual VIRC in semianechoic environment.

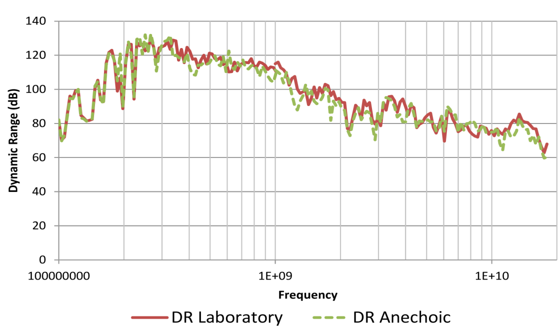


Fig. 11 DR of the dual VIRC setup, measured in the laboratory and semi anechoic chamber [3].

RF leakage between the transmitting and the receiving part of the dual VIRC.

EM energy can leak from the *TX* VIRC via the environment of the dual VIRC (e.g., floor or ceiling) to the *RX* VIRC, see Fig. 9. In 2012 (beginning of use of the dual VIRC) a test has been done at Thales Nederland where the DR has been measured in the laboratory environment and in a semi anechoic environment with the same dual VIRC setup (without any change in the dual VIRC setup), see Fig. 10. The DR results [3] of this test have been shown in Fig. 11. At that time the dual VIRC was pretty new so there was almost no wear of the cloth visible yet. From Fig. 11 can be seen that there is almost no difference between the DR results measured in both environments. That means that the

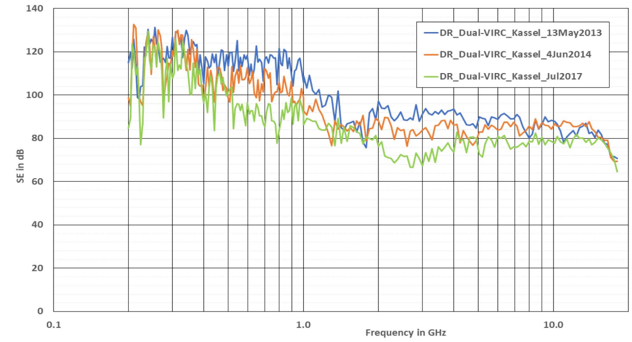


Fig. 12 DR Dual-VIRC Kassel 2012–2017.

coupling between *TX* VIRC and *RX* VIRC via the environment of the dual VIRC was negligible at that time (2012).

Every time before a new SE test session was started, the DR has been measured. In this way, a lot of DR data has been gathered during the long-term use of the dual VIRC. By doing this it became clear that the DR of the dual VIRC was decreasing as function of usage time during the lifetime of the dual VIRC.

On average the dual VIRC at Thales Nederland has been used every year for about 10 days, which means about 80 h per year. The dual VIRC setup with Kassel cloth (see Fig. 2) was used from 2012 until 2020. It is estimated that this dual VIRC setup has been used for about 500 h. In 2020, the Kassel cloth has been replaced by Nora Dell cloth (see Fig. 3). This new dual VIRC is still in use now and has been used for about 120 h until beginning 2022.

An investigation has been started to get a better understanding of the decreasing of the DR of the dual VIRC as function of use. Because a lot of DR data is available over the lifetime of the dual VIRC, this data has been analysed. The results of this analysis are shown in the following chapters. In chapters VI and VII, the DR results will be shown and compared for different moments in the lifetime of the dual VIRC setup with Kassel cloth and Nora Dell cloth, respectively.

VI. DR Results Dual VIRC Setup With Kassel Cloth

In 2012, Thales Nederland started doing SE measurements with the dual VIRC which was built up with Kassel cloth, see Section II. The DR results are shown in Fig. 12 for the period 2012–2017.

It can be seen that during the second year from 2013 (blue line) to 2014 (red line) the DR degraded by about 10 dB for the frequency range 500 MHz to 5 GHz. During this timeframe the dual VIRC has been used for about 150 h. Unfortunately there is no DR data available for the period 2015–2016 because in this timeframe the dual VIRC has not been used. Another 10 dB degradation in the frequency range 500 MHz to 15 GHz for DR can be seen from 2014 (red line) to 2017 (green line). Also, in this timeframe, the dual VIRC was used for about 150 h. So during the first 4–5 years (about 300 h) use of the dual VIRC the DR degraded with about 10-20 dB in the frequency range 500 MHz to 15 GHz.

The DR results with Kassel cloth for the period 2017–2020 (about 200 hours use of dual VIRC) are shown in Fig. 13. The

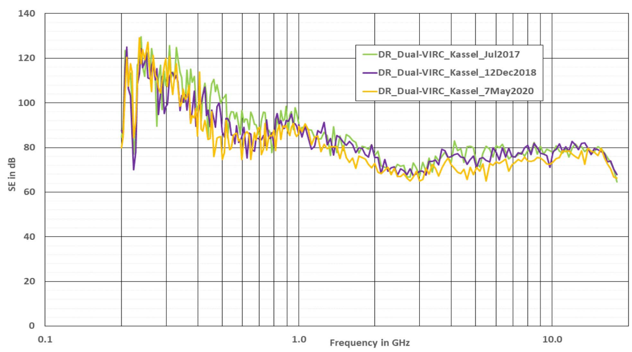


Fig. 13 DR Dual-VIRC Kassel 2017–2020.

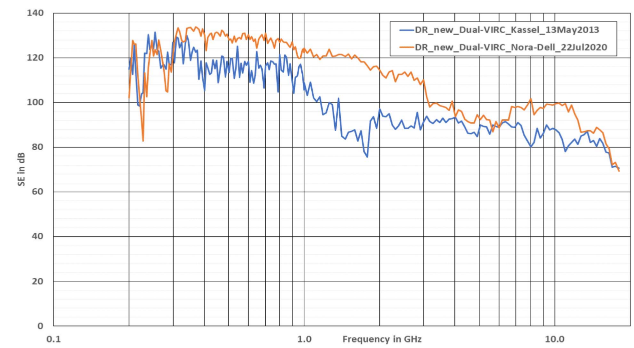


Fig. 14 DR of fresh Dual-VIRC with Kassel (2013) and Nora Dell (2020).

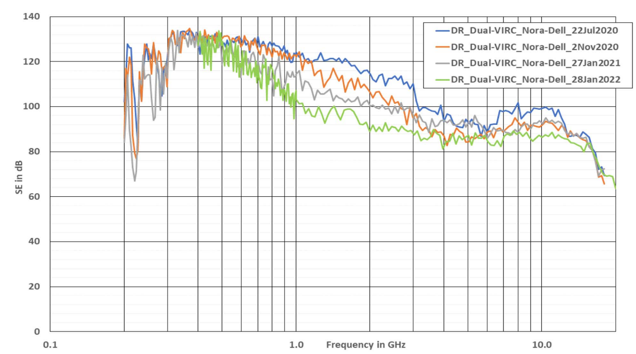


Fig. 15 DR dual-VIRC Nora Dell 2020–2022.

green line for the result of July 2017 in Figs. 12 and 13 are the same. From Fig. 13 can be seen that the DR degrades about 5–10 dB in the frequency range 400 MHz to 10 GHz from 2017 to 2020 (about 200 h use).

It can be concluded that the DR is degrading more in the first few years (2012–2017, 300 h use) of use than in the second part of usage time (2017–2020, 200 h use) of the dual VIRC. This can be explained by the fact that at some positions on the VIRC at a certain moment (after about 300 h use) the copper at the spot of the crack is worn away completely. At that moment these cracks do not change much anymore and therefore the leakage also does not change much on those spots. The frequency range of 400 MHz to 10 GHz fits well with the lengths of the cracks (1–20 cm = > 750 MHz–15 GHz) as shown in Section V. In the second part of the lifetime on other spots new small cracks occur but not as big as in the first part. These small cracks ($<$ 5 cm) result in decrease of the DR at frequencies above 3 GHz.

A longer usage time of the dual VIRC causes more wear. The more wear, the more leakage occurs. Due to this increasing leakage also the influence of the environment of the dual VIRC gets more important. It is recommended to repeat the test with the dual VIRC in an anechoic room with a more leaky (aged) dual VIRC setup, to see what is the influence, compared to Fig. 11.

VII. DR Results Dual VIRC Setup With Nora Dell Cloth

In July 2020, the Kassel cloth of the dual VIRC has been replaced by Nora Dell cloth, see Section II. Fig. 14 shows a comparison between the DR of the new fresh dual VIRC with Kassel cloth (blue line 2013) and the DR of the new fresh dual VIRC with Nora Dell cloth (red line 2020).

It can be concluded that the initial (fresh) DR of the Nora Dell dual VIRC is 10–20 dB higher than the Kassel dual VIRC for the frequency range 400 MHz to 12 GHz. This is due to the lower electrical surface resistance of the Nora Dell cloth with respect to the Kassel cloth (0.009 Ω/□ versus 0.03 Ω/□, respectively). The lower electrical surface resistance of the Nora Dell cloth results in a higher SE of the dual VIRC walls and therefore also in a higher DR.

The large improvement of the DR after the mounting of the Nora Dell cloth shows (see Fig. 14) that this must be due to the changing of the cloth because the remaining setup (mounting and connecting structure) of the dual VIRC did not change.

The DR results with Nora Dell cloth for the period 2020–2022 are shown in Fig. 15. From this figure can be seen that the DR degrades about 10–20 dB in the frequency range 500 MHz to 12 GHz in the timeframe 2020 to 2022 (blue line to green line). It is remarkable that during the first half year (blue line to grey line) the DR degrades with about 10–20 dB in the frequency range 700 MHz to 3 GHz. It has to be mentioned that the dual VIRC has been used intensively (about 80 hours) during December 2020 and January 2021. This resulted in a sharp degradation of the DR of the new setup. The wear is not yet visible as cracks in the Nora Dell cloth, but due to the intensive use invisible (5–15 cm) cracks will already occur due to sharp wrinkles, see Section V. One year later (January 2022) the DR has been degraded by another 10 dB in the frequency range 500 MHz to 15 GHz. After the first 80–100 h use also the wear of Nora Dell will be more and more present with more and longer cracks. The cracks are still not visible yet, but if there is a leakage path, the dual VIRC will find it. Even small invisible cracks result in a lower DR at these relative high DR values (100–120 dB) at high frequencies (1–12 GHz).

The DR result of June 2014 (red line) from Fig. 12 (Kassel cloth) is compared to the DR result of January 2022 (grey line) from Fig. 15 (Nora Dell cloth). In both cases the dual VIRCs had been used for about 2 years. These results are shown together in Fig. 16. It can be concluded that after two years use (about 150 h) the remaining (absolute) DR of the Nora Dell dual VIRC is a little bit higher (5–10 dB) than the Kassel dual-VIRC in the same usage time frame, especially for the frequency range 1–3 GHz.

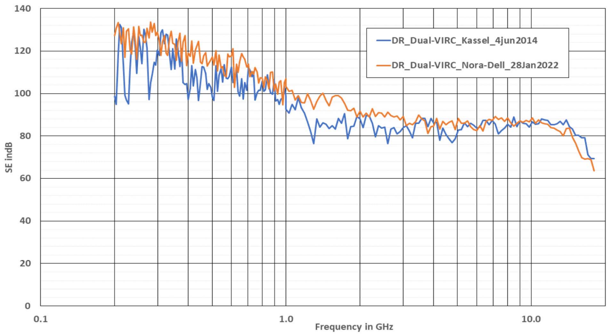


Fig. 16 DR of dual-VIRC with Kassel (2014) and Nora Dell (2022) after about 150 h usage time.

This is due to the cracks that are at most visible in the Kassel cloth and which measure about 5–15 cm and are matching with frequencies 1–3 GHz. The better performance of the Nora Dell cloth can be explained by the fact that the metal layer of Nora Dell, which has a better electrical surface resistivity than Kassel, is thicker (0.125 mm) and contains more metal (100 g/m^2 total weight) than Kassel (0.11 mm thick and 85 g/m^2 total weight). Due to this extra metal the effect of wear of Nora Dell could be lower than for Kassel. This results in a lower leakage and thus a higher DR.

By comparing the DR results of Figs. 12 and 15 it can be concluded that the degree of degradation of the DR as function of usage time is in the same order of magnitude for Kassel and Nora Dell cloth. According to Fig. 16 the absolute DR of Nora Dell cloth as function of the same usage time is 5–10 dB higher than for Kassel cloth.

VIII. Conclusion

Due to the movement of the dual VIRC wear occurs. This wear results in cracks in the cloth of the dual VIRC walls and causes RF leakage. If there is a leakage somewhere in the dual VIRC setup, it will be found due to the reverberation effect. Due to this leakage the DR of the dual VIRC will degrade as function of usage time of the dual VIRC. The degradation of the DR depends on the amount and lengths of the cracks. The frequency behavior of the degradation is depending on the lengths of the cracks. The amount of cracks and the degree of wear determine the decrease of the DR.

It can be concluded that the DR is degrading much more in the first few years (300 h) of use than in the second part (200 h) of usage time of the dual VIRC. This is due to the degree of wear of the cloth material. The initial DR of the dual VIRC with Nora Dell cloth is 10–20 dB higher than the dual VIRC with Kassel cloth for the frequency range 400 MHz to 12 GHz. This is due to the lower electrical surface resistivity of the Nora Dell cloth. After 1.5 to 2 years use (about 150 h) the remaining DR of the dual VIRC with Nora Dell cloth is a bit (5–10 dB) higher than the dual-VIRC with Kassel cloth in the same usage time frame. This could be due to the extra metal that is used in the Nora Dell cloth in comparison with the Kassel cloth. The degree of degradation of the DR as function of usage time has the same order of magnitude for Kassel and Nora Dell cloth. The absolute DR of Nora Dell cloth as function of the same usage time is 5–10 dB higher than for Kassel cloth.

It is recommended to move the dual VIRC in a "smooth" way with less stress on the VIRC wall cloth material to avoid sharp wrinkles in the cloth material. These wrinkles can cause (heavy) wear which results in leakage of the VIRC walls and therefore in degrading of the DR of the dual VIRC setup.

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