II. DESIGN OF THE WATER-BASED BLACKBODY CALIBRATION TARGET

The design of the water-based blackbody calibration target is based on the requirements for accurate radiometric measurements. The target should exhibit a microwave emissivity close to unity as well as a homogeneous and well known temperature distribution to provide a distinct brightness temperature reference [8], [9]. In addition, a very low coherent backscattering $S_{11}$ is required to avoid standing waves and the resulting baseline ripples in spectroscopic observations [7], [10], [11].

Commonly used microwave absorbing materials include low density foams and different plastics impregnated with carbon black or some other weakly conducting filling materials [12], [13]. However, these absorber materials are not well suited to be applied as calibration targets because their very low thermal conductivity can lead to significant temperature gradients. Therefore, most state-of-the-art calibration targets make use of a thin absorber layer based on iron loaded epoxy resins, which is coated onto a metal structure to ensure a homogeneous temperature distribution [1], [4], [6], [14]. On the one hand this coating needs to be sufficiently thick to absorb the entire radiation, but on the other hand it should be thin enough to be well coupled to the metal backing and keep the temperature gradients in the material small. But even with this design it is not trivial to ensure low thermal gradients in the absorber coatings, especially if brightness temperatures shall be obtained, which deviate from the thermal environment [2], [6], [9], [14]. In addition, temperature fluctuations in the thermal environment like a diurnal temperature variation or the influence of an air-conditioning system in the laboratory lead to an inhomogeneous temperature distribution, which cannot be measured by using only few temperature sensors attached to the metal backing.

Typical target designs are quasi-periodic geometries consisting of absorbing pyramids [1], [2], [15]. This target geometry is often applied in radiometers for space missions due to its compact size. In this design, metal kernels are introduced into the pyramids to reduce the thermal gradients at the tips, often with the drawback of an increasing reflectivity [1]. Nevertheless, this target design can exhibit significant temperature gradients along the pyramids and the difference between the brightness temperature as it is measured with a radiometer and the temperature of the metal structure can exceed 100 mK [2], [9]. Alternative geometries with improved electromagnetic and thermal properties are wedge-shaped [16] and conical [3], [4], [6] cavity absorbers, but these designs have the disadvantage of being more space consuming due to a larger depth. Although the temperature gradients are reduced with this design, the absorber coating cannot be fully insulated from the non-isothermal environment. Consequently, one main challenge in the design process of a blackbody...
target is to find the best tradeoff between the conflicting electromagnetic and thermal performance.

In [17], an aqueous blackbody calibration source has been proposed using water as the absorption medium to circumvent the conflict between the electromagnetic performance and the temperature distribution. Compared to commonly used microwave absorbers water has the advantage of a high electromagnetic absorptivity and, at the same time, an extremely high temperature uniformity when it is circulated. In addition, the temperature is well controllable with a thermal control system which makes the calibration target robust to the temperature fluctuations in its environment. In comparison to the target design in [17], which acts like an optical trap with four water reflections, we use a conical target geometry to increase the number of specular reflections at the water surface and reduce the reflectivity of water-based targets. A low loss plastic shell with an exponential profile is used to define the water–air interface [18]. The advanced cone profile is needed to compensate the comparatively high refractive index of water and to obtain a high emissivity. Initial measurement results of the coherent backscattering $S_{11}$ presented in [18] show the very good electromagnetic properties of this concept. In this paper, we focus on the validation of the outstanding thermal properties of the proposed concept by radiometric measurements. For this purpose we have designed and manufactured a temperature controllable target by using a commercial stereolithography three-dimensional (3-D) printer. Numerical investigations and the experimental characterization demonstrate the advantages compared to traditional calibration target designs. The water-based calibration target exhibits a reflectivity of conventional epoxy-based calibration targets, but without suffering from large temperature gradients. This makes it an excellent alternative to be applied as a precise reference source in laboratories and for the accurate calibration of ground-based microwave instruments.

This paper is structured as follows. Section II describes the target design with numerical calculations and the manufacturing of the water-based conical calibration target. The results of the experimental characterization are presented in Section III including active measurements of the coherent backscattering $S_{11}$ and radiometric measurements at 110 GHz. A conclusion is given in Section IV together with a discussion of the main results and an outlook on future work.

II. TARGET DESIGN AND MANUFACTURING

A commonly applied blackbody target geometry with a low reflectivity are conical cavity absorbers [3], [4], [6]. This target design exhibits a relatively low reflectivity due to the multiple specular reflections of an incoming electromagnetic wave at the absorber material and the consecutive penetration of the radiation into the material. We have transferred this concept to design and manufacture a temperature controllable conical blackbody calibration target using water as absorption medium.

A. Water-Based Calibration Target Design

Fig. 1 illustrates the fundamental concept of the considered blackbody calibration target geometry. It comprises a conical shell made of low loss polymethyl methacrylate (PMMA), which is immersed into water to define the water–air interface. In order to compensate the comparatively high refractive index of water and obtain a high emissivity of the target, we use an exponential cone profile following [19]. This design has been demonstrated to exhibit a lower reflectivity compared to a linear profile while keeping the target length constant [19], [20]. The shape of the curved cone profile is described through

$$r(z) = r_a \cdot \frac{\exp \left( \frac{z}{r_0} \right) - 1}{\exp \left( \frac{l}{r_0} \right) - 1}$$

with the length of the cone $l$, the aperture radius $r_a$, and the cone curvature $x_0$. The length of the target was limited to $l = 121.1$ mm by the build volume of our 3-D printer. We have chosen an aperture radius of $r_a = 38.8$ mm to be compliant with the beam dimensions of the measurement setup used in this paper. The conical PMMA shell has a thickness of 2.0 mm and we have selected a curvature parameter of the exponential profile of $x_0 = 0.65$.

B. Numerical Investigation

We have carried out numerical studies with the considered calibration target design using the body of revolution method of moments (BoR-MoM) [21] implemented in GRASP [22]. The conical PMMA shell with a thickness of 2.0 mm has been implemented in the numerical model as a dielectric material with $\epsilon_r = 2.585$ and $\tan \delta_r = 0.0008$ from [23]. A constant permittivity of pure water of $\epsilon_r = 7.289$ and $\tan \delta_r = 1.6035$ has been assumed to simplify the numerical calculation. This value is extracted from the model presented in [24] at a temperature of 20 °C and 110 GHz. As the attenuation coefficient in pure water exceeds 7.93 mm$^{-1}$ above 100 GHz most of the radiation is absorbed directly behind the PMMA shell. Therefore, we approximated the water as a 4.0 mm thick dielectric shell to decrease the computational effort. The simulations have been excited with an ideal Gaussian beam with a beam waist of $\omega_0 = 10.0$ mm located in the aperture of the cone and aligned with the cone axis. The beam approximates the field distribution of the test setup used for the active measurements of the coherent backscattering $S_{11}$. Both, the total reflectivity, which is a measure for the emissivity, and the coherent backscattering $S_{11}$, which leads to baseline ripples in the spectra, have been calculated with the full wave method between 100 and 150 GHz. As a comparison a fast ray tracing
method as described in [19] has been used to calculate the total reflectivity between 50 and 200 GHz.

Fig. 2 shows the simulated total reflectivity and the coherent backscattering $S_{11}$ of the considered target design. The total reflectivity is below $-30.2$ dB and the coherent backscattering $S_{11}$ is less than $-38.2$ dB in the considered spectrum. The total reflectivity of the full wave calculation is in good agreement to the values obtained with the fast ray-tracing method. The total reflectivity and the coherent backscattering $S_{11}$ decrease at higher frequencies, because the divergence of the Gaussian beam is reduced with increasing frequencies. This results in a better performance of the blackbody with an exponential profile as shown in [19]. The pronounced variations with frequency are a result of the 2.0 mm thick PMMA and could be reduced in future models with a thinner shell.

The dielectric properties of pure water significantly depend on the temperature. Therefore, we have investigated the impact of this temperature dependence on the reflectivity of the target using the ray-tracing method. Fig. 3(a) illustrates the real part of the permittivity and the loss tangent of pure water at various temperatures between 50 and 400 GHz, which are extracted from the model presented in [24]. The refractive index of pure water increases with temperature and the strongest dependence is observed at lower frequencies. The electromagnetic absorption in pure water increases with increasing temperature, too. Fig. 3(b) shows the resulting total reflectivity of the water-based target at various water temperatures considering a frequency dependent permittivity. The highest reflectivity is observed at a temperature of 60 °C and the electromagnetic performance improves with a decreasing temperature. Again a decreasing reflectivity with increasing frequencies is observed.

### C. Target Manufacturing

Fig. 4 shows a CAD model and the picture of the operational water-based target. It consists of two conical parts, which have been manufactured by using the commercial stereolithography 3-D printer Form1+ from Formlabs [25]. Both elements were printed layer by layer through selectively UV-curing of a colorless proprietary PMMA resin from the same company. The minimal feature size achievable with this 3-D printer is specified to be 300 μm and the layer thickness was set to 100 μm. The finished parts were rinsed with isopropyl alcohol in order to remove the residual resin. The inner shell with an exponential shape was manually polished with a fine abrasive paper to remove the surface defects from support pillars that are printed together with the model to ensure stable manufacturing conditions. However, some of the surface defects located in the tip
of the cone could not be mechanically accessed and were left unpolished. These defects could potentially degrade the electromagnetic performance of the target. An external shell, which is a cone with a linear profile, makes the target more compact and defines a clear interstice around the inner dielectric shell. The two cones are flanged together at the quadratic base around the aperture with a sealing O-ring and four mechanical clamps. The outer cone has a water inlet at the base as well as an outlet at the tip. In addition, it features spiral guiding structures at the inside to ensure a homogeneous water flow.

We have integrated three platinum resistance thermometers (PRT) at different locations at the outer part of the target to measure the water temperature. For this target prototype we have considered two kind of PRT with different geometries and integration procedures. Two screwable PRT are located a quarter revolution behind the water inlet and next to the water outlet. These temperature sensors are not fully immersed into the water and therefore only usable at room temperature. At other temperatures the influence of the environment increases. A cylindrical ceramic PRT is integrated directly at the water inlet. In the following investigations, we have only considered this PRT, because it is the only one which is totally immersed into the water. A 4-wire read-out is used to obtain most accurate temperature read-outs. We have calibrated all PRT used in this paper in the temperature oven against two standard platinum resistance thermometers (SPRT) 5615 from FLUKE between 10 and 60 °C using the actual read-out electronics to reduce the uncertainty of the measured temperatures. The parameters of the Callendar–Van Dusen equation of each PRT have been determined based on the measurements at seven temperatures between 10 and 60 °C to have a relation between the measured resistance and the actual temperatures that are measured with the two SPRT. The expanded standard uncertainty of the SPRT calibration at the water triple point reported by the calibration laboratory, with a coverage factor of \( k = 2 \), is 10 mK [26]. We have considered the standard uncertainty of 5 mK for the SPRT calibration in the entire temperature range of interest, because the deviation to the uncertainties calculated according to the ITS-90 propagation of error curves is negligible. On the basis of the measurements with the two SPRT and experience, we have estimated additional errors in the PRT calibration, such as temperature inhomogeneities, read-out errors, and self-heating effects, to be no more than 10 mK. This gives an upper bound for the combined uncertainty due to the two parts of 11.2 mK.

The target is mounted into a plastic box and surrounded by styrofoam beads acting as a temperature insulation. This insulation is needed to minimize the temperature gradients inside the cone. The in- and outlet are connected to a closed cycle thermal control system and the target is filled with deionized water, which contains an unknown fraction of antifreeze fluid. This antifreeze fluid is assumed to have only a small influence on the electromagnetic properties. As a verification of this first assumption, we have measured the surface reflectivity of the used mixture and pure water at 110 GHz and at normal beam incidence which are −9.35 and −9.51 dB, respectively, and hence identical within the measurement accuracy.

III. EXPERIMENTAL CHARACTERIZATION

This section presents the results of the experimental characterization with active measurements of the coherent backscattering \( S_{11} \) between 105 and 145 GHz and radiometric measurements at 110 GHz. The brightness temperatures are compared to the read-out temperatures of the PRT. In addition, we have measured the baseline ripples in the calibrated spectra caused by the water-based target.

A. Coherent Backscattering \( S_{11} \) Measurements

We have measured the coherent backscattering \( S_{11} \) between 105 and 145 GHz at temperatures of 10, 35, and 60 °C using a sensitive sliding load measurement method. Fig. 5 shows the schematic diagram and a picture of the measurement setup. A corrugated feedhorn and an elliptical mirror generate a vertically polarized electromagnetic beam. The beam is then transmitted through a horizontal wire grid and a wire grid at 45°. These wire grids act as polarizing beam splitters and half of the power is transmitted toward the target, whereas the other half of the power is guided into a termination load. The termination load is a conical absorber with a reflectivity below −70 dB. The reflected signal travels back to the horizontal wire grid, where again half of the radiation is reflected and then guided toward the detector antenna. A vector network analyzer is used to measure the amplitude and the phase of the reflected signal. The water-based target is mounted on a translation stage. Its axial movement leads to a phase change of the reflected signal, whereas the phase of other signals from the setup remain unchanged. The coherent backscattering \( S_{11} \) is determined by fitting the radius and the offset of the resulting circles in the complex measurement plane. A more detailed description of the method can be found in [20].

![Fig. 5. Sliding load test setup with water-based target on a translation stage.](Image)
Fig. 6 shows the measured coherent backscattering $S_{11}$ of the water-based target and a commercially available TK-Ram pyramid absorber from Thomas Keating Ltd. for a comparison [13]. The coherent backscattering $S_{11}$ of the target is measured to be less than $-55.8$ dB in the considered spectrum which is significantly below the values of the TK-Ram. In contrast to the simulations from Section II-B no difference between the results at different temperatures is observed. However, most of the measurements are dominated from the noise level of the measurement setup and the results only give a value for the upper bound of the coherent backscattering $S_{11}$. One potential reason for the disagreement between the simulations and the measurements below 115 GHz and above 130 GHz could be a permittivity of the printed PMMA, which is different to the value assumed in the numerical model.

B. Brightness Temperature Measurements

We have investigated the effective brightness temperature of the water-based target with a radiometer at 110 GHz. The radiometer was equipped with a low noise amplifier, a single sideband filter and a Schottky diode mixer. The intermediate frequency (IF) was analyzed by using a real time fast Fourier transform spectrometer AC240 from Acqiris with 1 GHz bandwidth.

1) Measurement Setup: Fig. 7 shows the schematic diagram and a picture of the measurement setup. The receiver optics includes a corrugated feedhorn and an elliptical mirror. The Gaussian beam has a radius of about 18 mm at the aperture of the target. For the calibration a microwave absorbing foam fully immersed in liquid nitrogen (LN2) is used as the cold reference. An incidence angle of the beam at the cold load of 3° to the LN2 surface was set to reduce the effect of standing waves between the cold load and the receiver. A temperature insulated epoxy-based pyramid target [1] at room temperature serves as the hot reference. The radiometer periodically looks at the cold and the hot reference targets, and the water-based target for 2 s by using a flat flip mirror.

2) Cold Load Emissivity Correction: An effective cold load temperature is considered in the following calibration, which differs from the boiling point of LN2 at the pressure of 950 hPa in Bern of $T_{LN2} = 76.8$ K [27]. Reflected signals at the LN2 surface originating from the surrounding, which is at ambient temperature, result in a higher brightness temperature. A cold reference temperature of $T_C = 78.4$ K has been calculated by

$$T_C = (1 - R_{LN2}) \cdot T_{LN2} + R_{LN2} \cdot T_H$$

(2)

with the reflectivity of the cold load of $R_{LN2} = -20.8$ dB and with the temperature of the surrounding of $T_H = 298$ K. The reflectivity of the LN2 target was determined using the Fresnel equations with a refractive index of the LN2 of 1.2 [23] and assuming that the reflected signal is close to normal incidence in a first approximation. This correction is mostly needed at target temperatures, which deviate from the temperature of the ambient temperature target. A calibration of the measurements without this correction would lead to systematic differences in the brightness temperatures of up to 300 mK at 60°C.

We have carried out measurements to verify the calculation of the corrected cold reference temperature. Fig. 8 illustrates the schematic diagram of the test setup. A second cold load with a microwave absorbing foam fully immersed in LN2 is
placed at the location of the water-based calibration source in the radiometer setup described previously. A plain aluminum plate is installed with an inclination angle of 30° to the LN2 surface. In contrast to the standard cold load located below the flip mirror allowing only one reflection at the LN2 surface, two specular reflections are reached with the second cold reference target. Consequently, the emissivity of the target is increased from 99.17% to 99.99%. Therefore, it can be assumed that the reflected signals from the surrounding area only have a minor influence on the brightness temperature, which is then equal to the boiling point of LN2. An effective brightness temperature of the standard cold load of $T_C = 78.2 \, K$ is measured, when using the second LN2 load as the cold reference. This is almost the value calculated with the Fresnel-equation-based approach and therefore verifying the assumptions made here.

3) Experimental Results: We have measured the effective brightness temperature $T_B$ of the water-based calibration target at various temperatures between 10 and 60 °C. In the following data evaluation, the mean value of all spectrometer channels is considered. A standard hot and cold calibration procedure has been applied using the corrected cold reference temperature of the LN2 target of $T_C = 78.2 \, K$. The reference temperature of the hot load is the mean value of two PRT measurements at the metal backing. The effect of the non-unity emissivity of the water-based target is negligible, because a low reflectivity of the water-based target of less than $-40 \, dB$ is simulated at 110 GHz. The continuously circulating water has been heated up to the maximum temperature of 60 °C in steps of 10 °C every 60 min and then cooled down to room temperature with the closed-cycle thermal control system. Fig. 9 illustrates the effective brightness temperatures and the PRT read-out temperatures, as well as the associated temperature differences. The differences are smoothed by using a moving average of ten consecutive data points. The mean difference of the entire time series is below 16 mK. Significant differences between the temperatures are only observed during the fast changes of the temperature as it is the case at the temperature steps. These transients are caused through a short time lag between the two measurements, which result in a negative systematic difference at increasing temperatures and a positive systematic difference at decreasing temperatures. In the time periods with a stable water temperature, the visual inspection yields no evidence of a significant trend. Hence, we have conducted a more detailed investigation of the time periods in which the temperature of the target has been stabilized.

Fig. 10 shows time periods of 45 min at each temperature step in which the temperature of the water has reached the set value of the thermal control system. The fast temperature variations with the peak to peak value of approximately 0.5 K and a period of about 35 s, which are clearly observable in the PRT read-out temperatures, are caused by the temperature stabilization of the closed-cycle thermal control system. In the used thermal control system, the heating element is switched ON periodically to counteract the cooling system which runs continuously. Nevertheless, the averaged differences between the PRT read-out temperatures and the brightness temperatures within each of the time periods are between $-40$ and $+36 \, mK$. A conservative estimation of the expanded uncertainty, using a coverage factor of $k = 2$, is given for each time period, which has been calculated by means of a Monte Carlo analysis. In this analysis, we have assumed normal probability distributions of the temperature measurements of each PRT with the combined standard uncertainty of 11.2 mK as estimated in Section II-C and the cold reference temperature...
difference from a negative mean difference of averaged values and the resulting standard deviation of measurement errors, because of the extremely large number of reference temperature. The calculation does not include random temperature and the PRT read-out temperatures on the final re-temperature, the effect of the uncertainties of the hot reference brightness temperatures are all very close to the hot reference temperature. The estimated standard uncertainty is then determined from the calculation of the mean differences for every sample.

Carlo estimation involves the sampling from these distributions and the calculation of the mean differences for every sample. The estimated standard uncertainty is then determined from the standard deviation of the calculated values. Since the measured brightness temperatures are all very close to the hot reference temperature, the effect of the uncertainties of the hot reference temperature and the PRT read-out temperatures on the final result is higher in comparison to the uncertainty of the cold reference temperature. The calculation does not include random measurement errors, because of the extremely large number of averaged values and the resulting standard deviation of the mean of about 1 mK. A potential trend of the determined mean difference from a negative mean difference of −40 mK at 10 °C to a positive mean difference of +36 mK at 60 °C indicates the possibility that the effective cold load reference temperature is slightly higher in comparison to the value considered in the brightness temperature calculation. Within the boundaries, the resulting deviations are small in comparison to the alternative target designs [9], especially at target temperatures which are different from the temperature of the environment.

C. Investigation of Baseline Ripples

We have used the radiometric test setup to study the baseline ripples in the spectra which are caused through the water-based target. Therefore, we have applied a procedure in which the difference of two calibrated spectra, one measured with the shift of a quarter wavelength, is calculated to make sure that only the standing waves between the target and the receiver are determined. The movement of the target using a translation stage results in a shift of the standing wave of 180°, whereas the other signals remain unchanged and are then canceled out with a subtraction of both spectra. Fig. 11 shows the resulting baseline ripple measured with the water-based target at room temperature operation and with a TK-Ram absorber [13] for comparison. The amplitude observed with the water-based target is almost a factor of four smaller in comparison to the TK-Ram absorber. This is less than it is expected from the previous measurements of the coherent backscattering \( S_{11} \). A potential reason for this discrepancy in the two measurements are slightly different beams in the two measurements setups. However, the result again demonstrates the comparatively low reflectivity of the proposed target design. Nevertheless, these measurements of the baseline ripples only give a relative impression of the reflectivity compared to the TK-Ram absorber and the amplitudes might be different with other receivers, because the standing waves also depend on the input matching of the receiver [10].

IV. CONCLUSION AND DISCUSSION

The water-based conical blackbody calibration target presented in this paper simultaneously provides a very low reflectivity and excellent thermal properties. It consists of a conical low loss plastic shell with exponential profile, which has been manufactured with a stereolithography 3-D printer to define the water–air interface. Numerical calculations and active measurements of the coherent backscattering \( S_{11} \) demonstrate that the proposed concept exhibits a comparatively low reflectivity. The measured coherent backscattering of below −55.8 dB is a large improvement compared to the aqueous blackbody described in [17], even if the selected dimensions of the target are not the optimum regarding the reflectivity due to the limitations of our 3-D printer. This issue can be improved as demonstrated with the initial investigations in [18]. Radiometric measurements at 110 GHz indicate differences between the brightness temperatures and the read-out temperatures of the PRT, mounted into the water-based target, of less then 40 mK for varying water temperatures between 10 and 60 °C. The baseline ripples in the measured spectra caused by the water-based target are small compared to traditional target designs. Combining outstanding electromagnetic and thermal properties at the same time makes the proposed water-based target design an excellent alternative to be used as a precise reference source in laboratories and the accurate calibration of ground-based microwave instruments.

The deviation between the PRT read-out temperature and the measured brightness temperature of conventional epoxy-based target geometries is mainly caused by the non-unity emissivity and an inhomogeneous temperature distribution in the coating due to the low thermal conductivity of the commonly applied materials. These differences are significantly reduced with the water-based calibration target and the temperatures measured with the PRT and the measured brightness temperatures agree very well. This leaves the absolute PRT calibration as the most significant source of uncertainty of the current target prototype. Depending on the calibration target specification, temperature sensors with a more accurate absolute temperature calibration could be implemented in future models of the target to reduce the uncertainty on the measured temperatures. In addition, the number of used temperature sensors could be easily increased based on the experience we have made regarding the choice of the best suited PRT geometry and their integration.

The application of alternative liquids with a low reflective index, such as dispersion with alcohols, are an idea to further reduce the reflectivity and potentially increase the temperature range of water-based calibration targets. Since a sharp cone tip, as well as a smooth and well-defined surface are of particular importance to obtain a very low reflectivity, we will focus on
improving the manufacturing accuracy of the plastic shell. In addition, a thinner plastic shell would reduce the pronounced variations of the reflectivity with frequency. In this context, we will evaluate alternative manufacturing methods such as plastic thermoforming.

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