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Enabling autonomous driving

Autonomous vehicles see the world through sensors. The entire concept rests on their reliability. But the ability of a radar sensor to deliver the required performance greatly depends on its installation situation. A new tester provides the necessary insight.

Advanced driver assistant systems that assist the driver and increase road safety are readily available in entry-level vehicles and commonplace in the automotive world. Fully autonomous vehicles (including test vehicles) regularly make the headlines, especially when an incident occurs. These complex systems still have far to go before they are ready for series production, but it is certain that they will become reality in the near future.

Reliable sensors are essential for autonomous driving

Sensors that detect nearby objects are key components for autonomous vehicles. These include cameras and lidar sensors, but especially radar sensors. Millions of automotive radars are produced every year. They are standard equipment in high-end vehicles. Today, automotive radar sensors are mainly used to increase driving comfort and prevent accidents. Most radar sensors that enable adaptive cruise control operate in the 76 GHz to 77 GHz frequency range (1 GHz bandwidth) to sense other vehicles and objects far ahead. Advanced functions, especially those that sense nearby objects – such as lane change assistance and blind spot detection – require larger bandwidths to achieve the necessary high range resolution. This is available in the 77 GHz to 81 GHz frequency range. Additionally, the extended automotive frequency band up to 81 GHz helps mitigate radio interference.

For reasons having more to do with appearance than functionality, automotive radars are covered by a radar dome (radome) constructed from a material transparent to RF signals. The emblem on the grille is often used for this purpose, but plastic bumpers are also good hiding places for radars. In the past, emblems mainly promoted the brand and had no other significant role. However, their use as radomes now makes them more like RF components. If that is not taken into account in their design, it can have a very adverse impact on the detection performance and accuracy of the radars behind the emblems.

In particular, the three-dimensional shape of brand emblems with locally varying material thickness can cause RF performance problems for operation in the millimeterwave band. Bumpers are typically coated with metallic paint, which attenuates high frequencies. To ensure radar reliability, it is therefore essential to validate the material properties of radomes and examine their influence on radar signals. Uncertainties and risks in automotive sensors are unacceptable for autonomous driving because any errors originating here cannot be adequately corrected by postprocessing. Consequently, vehicle manufacturers and their suppliers need new measurement capabilities to be able to evaluate the radar conformity of radomes.

Radomes can significantly degrade radar performance

Automotive radar sensors mainly use frequency-modulated CW (FMCW) signals. Due to the propagation delay and the Doppler frequency shift, the sensors can measure and resolve the range and radial velocity of multiple targets. Depending on the antenna array properties, it is also possible to measure and resolve the azimuth and even the elevation angle. After detection and tracking, the sensor electronics processes the signal to generate a target list that contains the measured positions and velocities of the objects and also type information (pedestrian, car, etc.). This list is sent to the vehicle's electronic control unit where it is used to make realtime decisions for vehicle maneuvers. The accuracy and reliability of this data is extremely important for the safety of the vehicle and its passengers.

The accuracy of a radar depends on many factors, such as hardware components, software processing and the radar echo itself. The parameters of signal echoes with a low signal-to-noise ratio (SNR) cannot be measured as accurately as those with a high SNR. In addition, effects such as multipath propagation and distortion due to radomes greatly impact measurement accuracy. Inaccuracies in the azimuth measurement cause the target to appear misplaced from its actual position. This is illustrated in Fig. 1. An angular measurement error of only 1° at the radar sensor would cause a target that is 100 m away to appear to be laterally displaced by 1.75 m. This displacement could cause the target to be interpreted as being in a different lane. To ensure reliable operation, the angular measurement error at such distances must be significantly less than 1°.

Problems of a standard automotive radar

Fig. 2 shows the effect of azimuth displacement based on measurements on real automotive components. A commercial off-the-shelf automotive radar was presented with a static target at a distance of 12.4 m and an angle of 11.5°. The chart shows how different radomes influence the radar cross section and angle of incidence.

The values shown in blue (without a radome) are provided for comparison. As can be seen, there is no effect on the estimated angle of incidence when a suitable radome (red) is used. However, the radar cross section is reduced by the two-way attenuation (in this case about 2 dB). If an unsuitable radome is used (orange), the average radar cross section drops by about 4 dB relative to the comparison measurement, which can prevent detection of weakly reflecting targets. The effect of the unsuitable radome on detecting the angle of

Incorrectly detected location due to azimuth measurement error

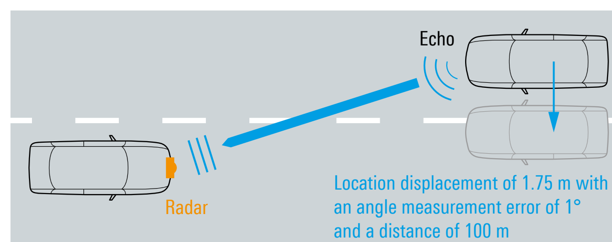


Fig. 1: Location of targets is incorrectly detected due to azimuth measurement errors. The autonomous vehicle controller could respond with a fatal maneuver.

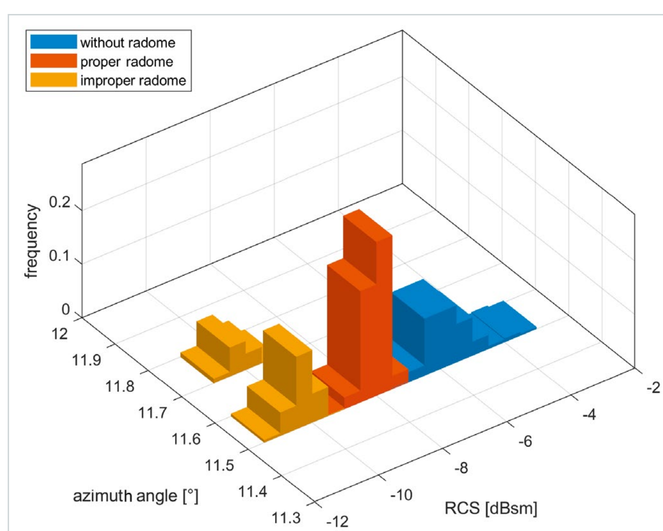


Fig. 2: Influence of different radomes on radar cross section (RCS) and angle of incidence. Unsuitable radomes can cause angle errors.

incidence is also visible. It is no longer seen at a constant 11.5°, but instead as alternating between 11.5° and 11.7°, so the signal processing electronics do not obtain an unambiguous value. With this radome, automotive radars cannot meet the target accuracy of 0.1°.

Radar calibration alone is not enough

A modern radar sensor with an antenna array in the receiver frontend determines the azimuth (and sometimes also the elevation angle) by measuring the phase and amplitude ratios obtained from beamforming with a phased array antenna. For optimal azimuth accuracy, each radar sensor must be individually calibrated. The following procedure is typical for radar calibration. First the sensor is mounted on a turntable in an anechoic chamber. A corner reflector in far field at a known distance is often used as the reference target. The radar pattern is then measured and stored in the sensor memory. This information is used later by the detection algorithm. Correction is calculated during signal processing and takes place during operation.

The vehicle manufacturer integrates the calibrated radar sensors in the vehicle, often behind an emblem or the bumper. The RF transmission loss of the radome material attenuates the signal twice because the signal must pass through the material on the way to the target and on the way back. This reduces the radar's detection range, as can be seen from the following analysis.

According to the laws of signal propagation, the power of the transmitted signal is inversely proportional to the square of the range r, which means it is reduced by the factor $1/r^4$ over the round trip. For a 77 GHz radar with 3 W output power, 25 dBi antenna gain, a target with a 10 m^2 radar cross section and a signal detection threshold of –90 dBm, the maximum range of this configuration would be 109.4 m using this equation. If the two-way attenuation of the radome is 3 dB, the maximum range of the same radar is reduced by 16 % to just 92.1 m.

But material attenuation is not the only factor that impairs radar performance. The reflectivity and uniformity of the radome material are also important. Reflections, for example from metallic particles in the paint, and RF mismatch of the base material produce interference signals within the radome, i.e. close to the sensor. These interference signals are received and downconverted in the receiver chain, reducing the radar's detection sensitivity. Many vehicle manufacturers try to mitigate this effect by tilting the radome so the emitted radar signal is reflected elsewhere and not directly back into the receiver frontend. This solution is naturally subject to design constraints, and it does not eliminate the parasitic reflections that cause loss of RF energy.

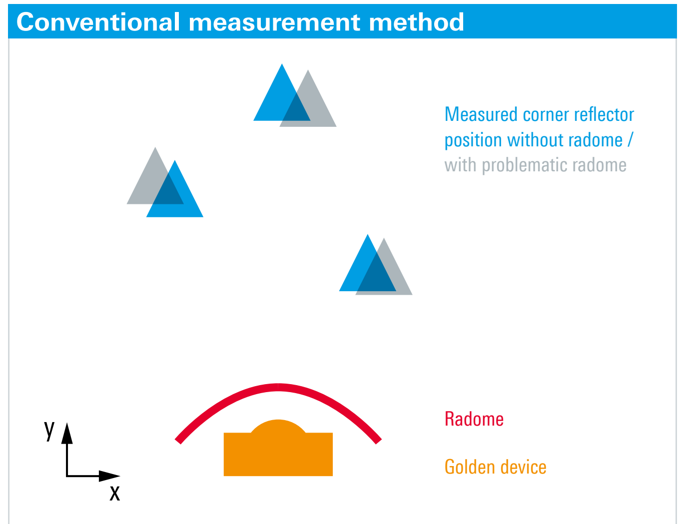


Fig. 3: Typical test setup with a golden device.

Another problem is that material inhomogeneities such as inclusions and density variations disturb the outgoing and incoming wavefront. It is distorted, leading to less accurate angle measurements. Radar sensor calibration cannot compensate for this effect because the calibrated radar may be mounted behind radomes from different manufacturers.

Conventional radome testing

Radome manufacturers typically use a reference radar (golden device) to test their products. For this test, corner reflectors are mounted in front of the radar at predefined distances and azimuth angles (Fig. 3). Differential measurements are conducted with and without the radome and then compared. The radome passes the test when the distances and azimuth angles determined by the radar and the echo signal levels are within specified limits. However, this method only checks specific azimuth angles, making it easy to miss problem areas in the radome.

Another measurement method works in a similar manner but needs only one reflector. In this method, the radar sensor and radome are mounted on a turntable and the measurement is repeated at different angles. The actual angle, which can be read from the turntable (ground truth), and the angle measured by the radar are compared. This method is as accurate as the positioning accuracy of the turntable. However, this test takes a very long time and is therefore not feasible for production line tests.

Conclusive tests at the push of a button with the R&S®QAR radome tester

The R&S®QAR quality automotive radome tester (Fig. 4) overcomes the limitations of traditional methods. Instead of a golden device with a tiny antenna array, it uses a large panel with several hundreds of transmit and receive antennas operating in the extended automotive radar frequency range from 75 GHz to 82 GHz. It "sees" what an automotive radar would see if it also had hundreds of antennas. But thanks to the large aperture, it measures range, azimuth and elevation with a much higher resolution (in the millimeter range). This high resolution allows the measurement results (i.e. reflectivity) to be visualized as an X-ray image, enabling immediate quality assessment even by persons with limited test and measurement experience. Unlike measurements with real radars, time-consuming measurement sequences are not necessary to determine the radome properties – the R&S®QAR obtains results in a one-shot process, similar to taking a picture with a camera.

The radome under test is placed in a specified area in front of the panel. Two measurements are possible – one to determine the reflectivity of the DUT, the other to determine its transmissivity.

First, a reflectivity measurement is made to determine how much energy is reflected by the radome material. This is the energy that does not pass through the radome. It degrades the performance or even, as described above, impairs correct operation. Certain areas can have higher reflectivity for various reasons, e.g. material defects, air inclusions, unwanted interactions between different material layers, or an excessive amount of certain material components. The measurement method delivers spatially resolved measurement results by coherently linking all reflected signals according to magnitude and phase. The visualization of the results allows intuitive and quantitative assessment of the DUT's reflective behavior.

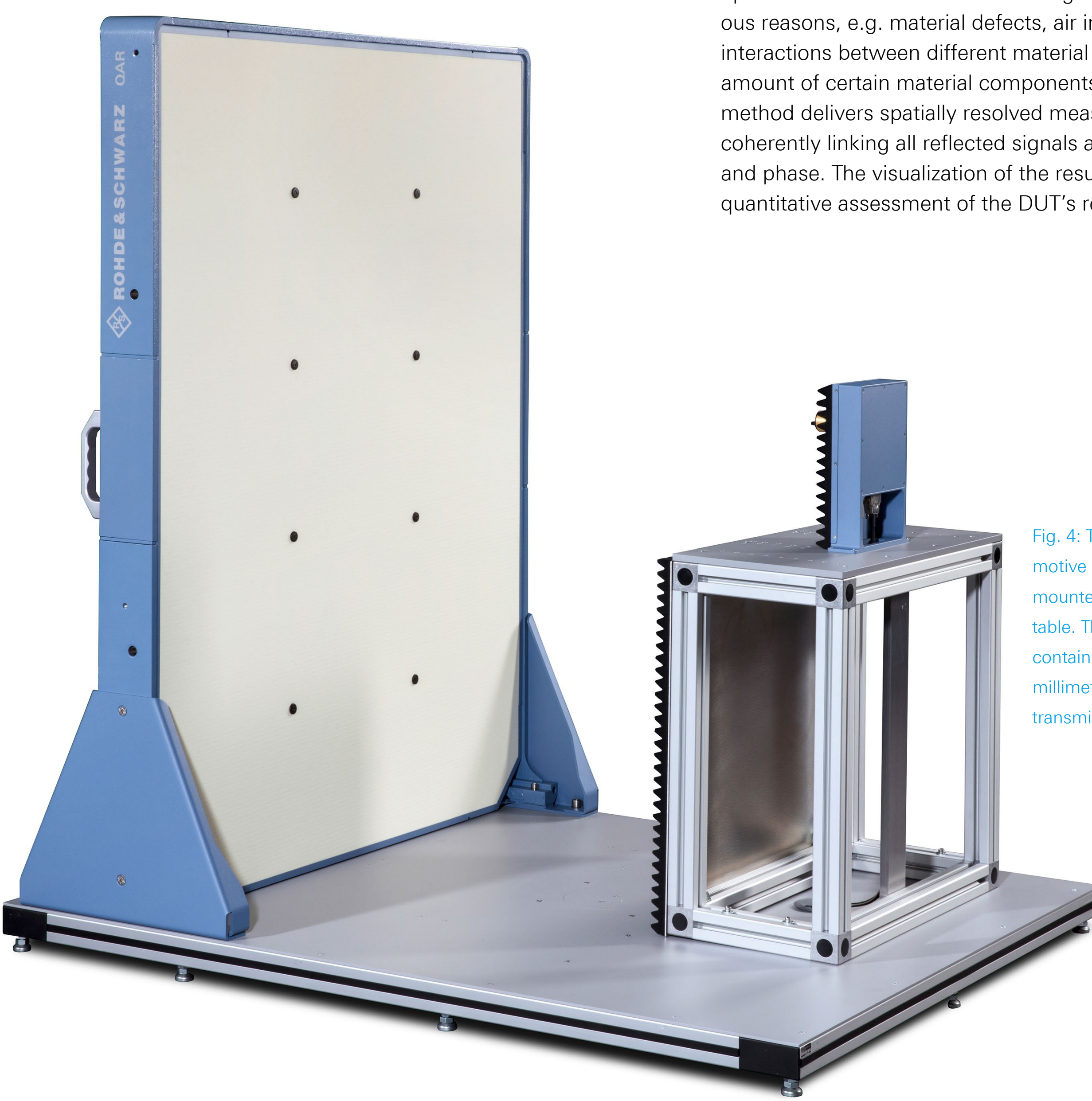


Fig. 4: The R&S®QAR quality automotive radome tester. The DUT is mounted at the front edge of the table. The blue unit on the table contains the optionally available millimeterwave transmitter for transmission measurements.

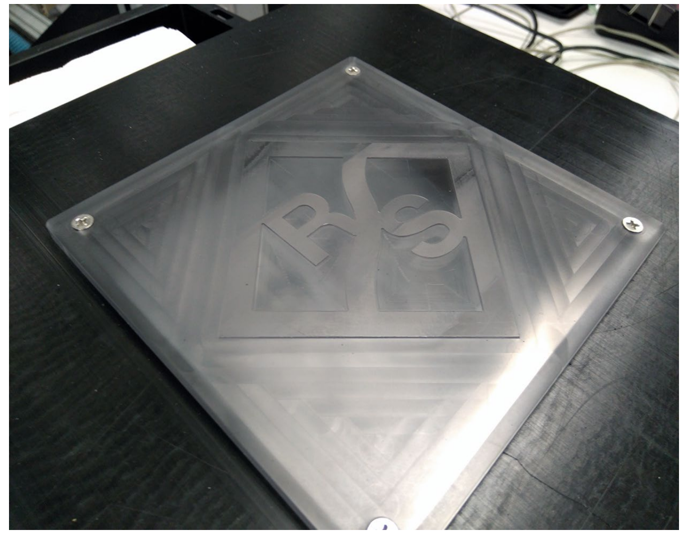


Fig. 5: Demo radome with the Rohde & Schwarz logo protruding only 0.5 mm above the surface of the radome body. Even this small increase in thickness leads to a mismatch at 77 GHz (Fig. 6).

For demonstration purposes, a demo radome was produced that contains the Rohde & Schwarz logo milled with different thickness (Fig. 5).

The high-resolution radar image in Fig. 6 shows what a radar sensor covered by this radome would see. The brightness levels represent the reflectivity. The brighter an area, the more it reflects the radar signal. Metal objects show up as white (the screws in the four corners). The clearly visible contours of the logo indicate localized high reflectivity and a very non-uniform overall image. The greater thickness of 0.5 mm in the logo area would be enough to considerably degrade radar performance on the road.

In this example, the middle of the radome where the sensor is usually mounted has an average reflectivity of –11.0 dB with a standard deviation of –18.2 dB. In many use scenarios, this is too high to ensure reliable radar operation. In practice, the expected reflectivity depends on the sensitivity of the radar unit and the maximum detection range to be covered.

Next, the frequency matching and attenuation of the radome material are measured. A transmitter unit located behind the DUT (Fig. 4) sweeps over a selected frequency span. This allows precise assessment of the radome's transmission frequency response. The frequency response delivers detailed information about the RF matching of the DUT at the exact

Fig. 6: High-resolution millimeterwave image of reflectivity (left) and one-way attenuation (right). The blue outline in the logo indicates the radiation cross section of the test transmitter or radar. This area is used in the assessment.

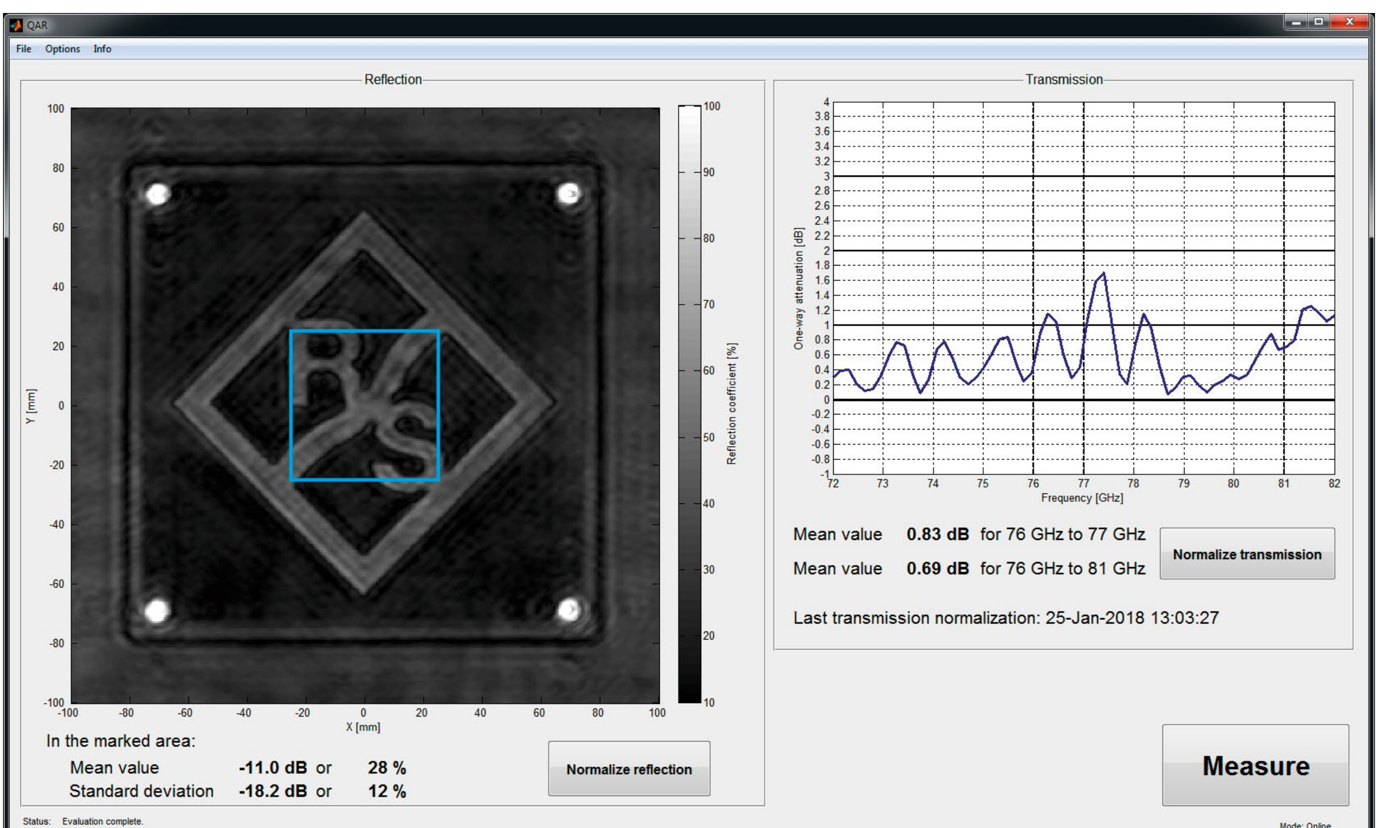
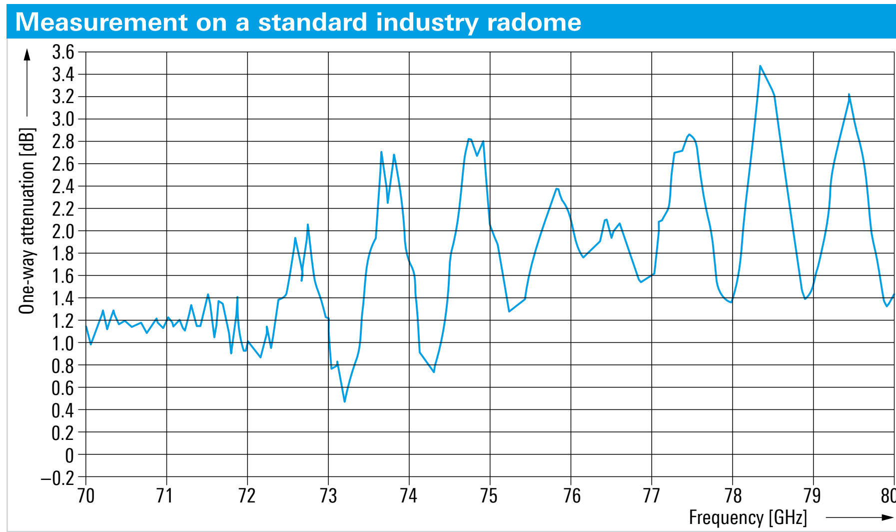


Fig. 7: Transmission measurement on a commercial multilayer radome with a complex 3D design.



frequency band intended for radar operation. This information is independent of the actual signal waveform used by the radar unit and is therefore valid for all types of radars that can be installed behind the radome.

The graph on the right in Fig. 6 shows this measurement for the demo radome. Due to the high waviness between 76 GHz and 79 GHz, this radome would not be suitable for radars in that frequency band.

A transmission measurement on a real 3D radome from the automotive industry yielded the similarly jagged curve in Fig. 7. This radome would have various performance issues:

- The frequency matching is unfavorably located at around 71 GHz instead of 76 GHz. This is often caused by increased thickness of some radome layers.
- The erratic attenuation variations in the 79 GHz band indicate a significant increase in the standing wave ratio. This indicates reflections at the radome boundaries and strong interference effects.
- The overall one-way attenuation is relatively high, which would result in a noticeable reduction in the detection range.

Summary

Autonomous driving requires radars that reliably, e.g. without errors, detect objects in the surrounding area. Whether this is possible depends not only on the quality of the radar, but also on its installation situation. Radars are often installed behind brand emblems or bumpers. These vehicle body parts (radomes) can degrade the signals to the point that objects are not detected or are detected in the wrong places. Today, such parts not only serve their original purpose but also need to have defined RF properties. Accurate and practical measurement methods are needed to verify these properties. The R&S®QAR tester provides a much faster and better method of assessing the quality of automotive radomes than using golden devices. The R&S®QAR measures the RF transmissivity of the DUT, which reveals the basic suitability of a radome design, and also the reflectivity, which is visualized as a type of X-ray image to allow even nonexperts to make a reliable pass/fail assessment, especially in end-of-line tests.

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