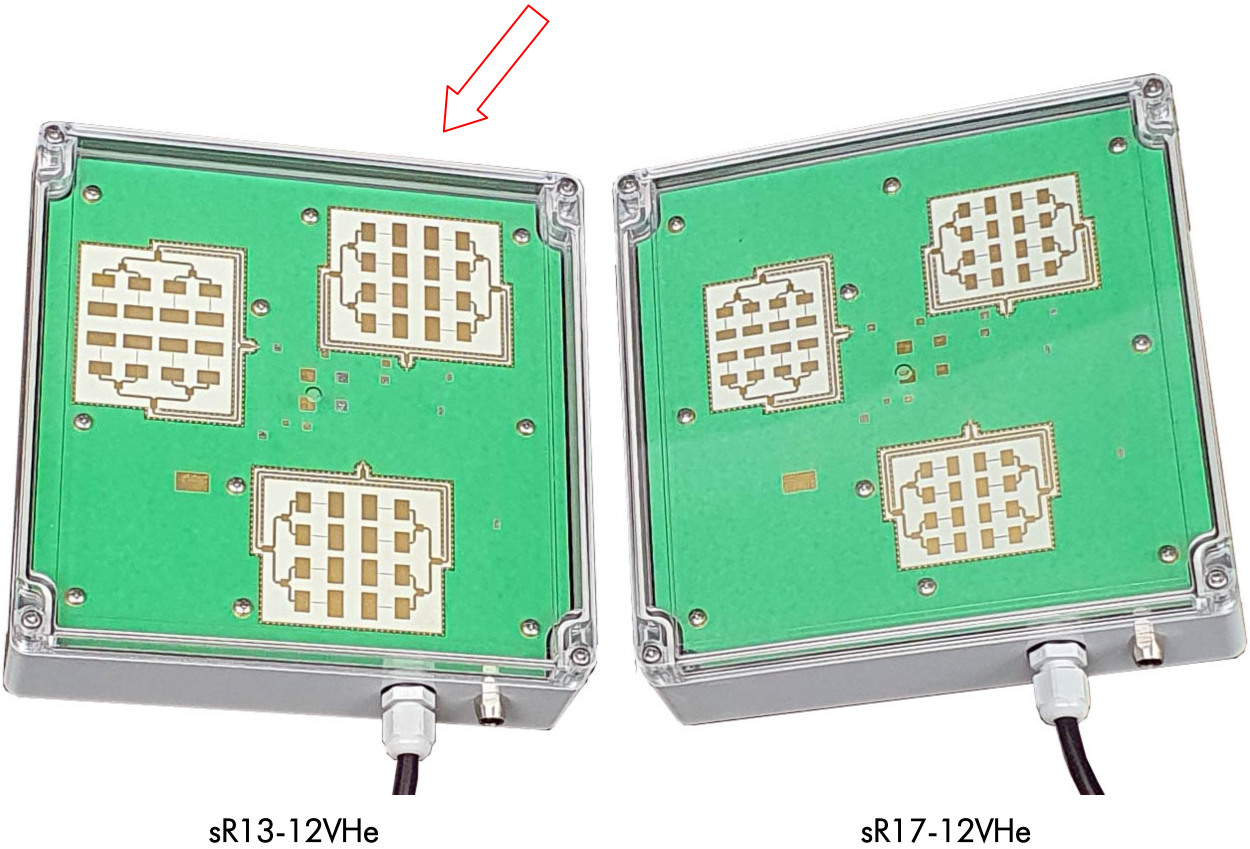
Development of 13.5 GHz and 17.5 GHz FMCW Radar Demonstrators with V-/H-Polarization

Final Report for 13.5 GHz Radar



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Note: All changes have to be mentioned here after the revision management has been initiated. This table describes all changes at the respective mentioned locations.

Table of Contents

1 Introduction

IMST has developed two radar sensors for University Sherbrooke for snow and ice thickness and properties measurements. The specified center frequencies were given at 13.5 and 17.5 GHz with a bandwidth of 2 GHz for precise distance measurements. Additionally, vertical and horizontal antenna polarization were realized for characterizing further material properties. The development started in December 2022 and a kickoff meeting was held on Jan. 17, 2023. MS-1 was reached on June 30, 2023. A Milestone MS-1 report was written and delivered followed by an online presentation to report and discuss the progress and achievements. The two radar sensors could be successfully finished and evaluated in October 2023. A final meeting and presentation are scheduled for October 26, 2023 at IMST GmbH in Kamp-Lintfort, Germany. Two final reports, one for the 13.5 GHz sensor and the other for the 17.5 GHz sensor were written. Each report contains the following tasks and achievements:

- Antenna simulation results,
- Initial outdoor measurements for co- and cross-polarization characterization of Rx-channels,
- Target distance accuracy and separation measurement,
- Tx antenna characterization in anechoic chamber to determine EIRP and antenna characteristic, comparison of simulated and measured antenna diagrams,
- Radar characterization at operating temperatures from -40°C to +30°C, extraction of parameters for fitting function to stabilize output power over temperature,
- Compliance matrix comparing requirements with verification results.

The radar modules are given the names **sR13-12VHe** and **sR17-12VHe**. "sR" stands for "sentire Radar", a brand name of IMST, "13" and "17" are the frequencies in GHz, "12" stands for one transmitter and two receivers, "V" means vertical and "H" horizontal polarization and "e" indicates the Ethernet interface.

2 Antenna Simulations

All passive RF structures (antennas and circuits) have been simulated and optimized with IMST's high performance 3D time domain EM modelling tool for RF applications (https://empire.de/). As an example, the simulation result of one of the 13.5 GHz patch antennas is presented in Figure 2-1. The structure shows a 4 by 4 patch array with feeding networks and shielding frame. Via fences increase the de-coupling to feeding lines and neighbored antenna arrays. The picture does also show the transparent radome. Material properties, thickness and distance to the patches are influencing the antenna performance. These parameters are included into the simulation. The farfield pattern is a result of the 3D simulation. The main-beam and sidelobes are visible. From these simulations the antenna gain and directivity can be derived for specific frequencies. A comparison of simulation and measurement results are presented in chapter 4.

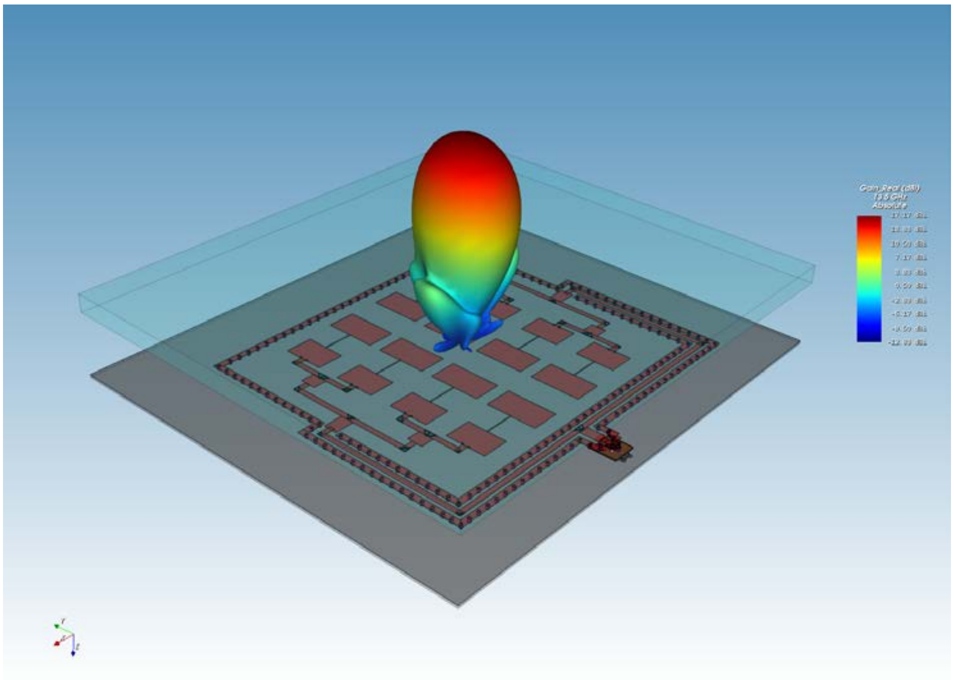


Figure 2-1: Farfield simulation of antenna array with radome, 17.2 dBi gain at 13.5 GHz

3 Outdoor measurements

3.1 Selection of measurement method

An FMCW method with one measurement ramp was chosen in order to perform optimal distance measurements, as aimed for ice- and snow-thickness determination. A fast-chirp-sequence mode, as specified in the Statement-of-Work was finally not implemented. This method allows a range-doppler evaluation including distance and velocity determination simultaneously. However, since this method requires significantly more signal processing effort and thus more time, this extends the measurement cycles. In addition, the radar heats up faster because the power amplifiers for the chirp sequence remain switched on longer. This would lead to a reduction of the duty cycle and thus further increase the measurement time. Therefore, the following FMCW mode with one ramp has been implemented:

The measurement starts with a short configuration **Delay** followed by initializing the FMCW ramp. At the end of this up-ramp (**Ramp Time**), a short down-ramp followed. The processor records the measured radar data in parallel and calculates the Range-FFT. When all data from this measurement is acquired, the Rx and Tx power amplifiers will be switched off (**Pulse** time). The radar is now in idle mode. The next measurement cycle starts when the **Interval** time has finished. Figure 3-1 illustrates one measurement cycle.

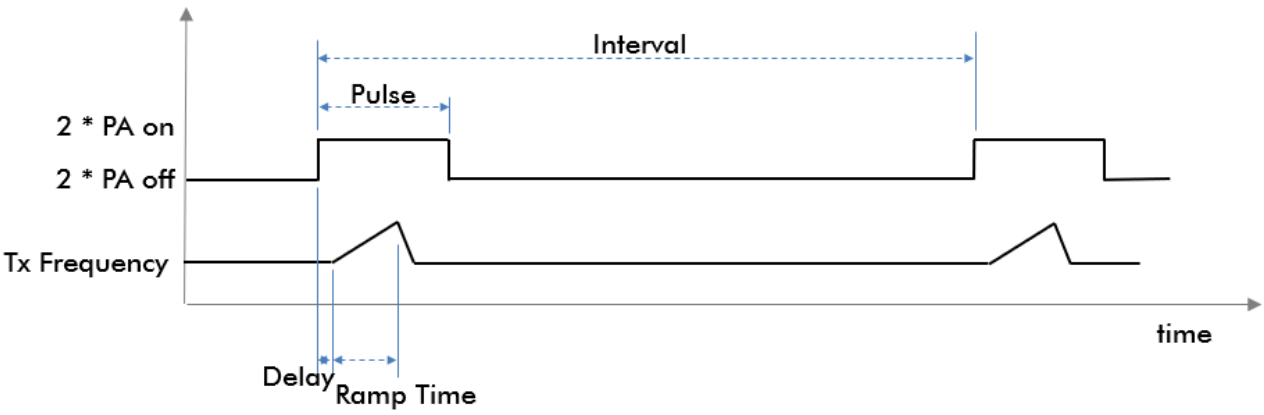


Figure 3-1 Time diagram of FMCW measurement cycle

The following numbers show example values for a typical measurement interval:

Interval = 1 ms, can be increased by the user: ≥ 1ms

Ramp Time = 104 μs (= 1024 bins, sampling rate = 10 MHz), these bin numbers can be selected by the user: 256, 512, 1024, 2048 (Ramp time doubles, when 2048 bins will be selected)

Pulse length = 200 μs, varies depending on bin number selection and signal processing time

Delay = 22 μs, is a fix time duration

3.2 Distance measurements with target reflector

After commissioning and testing in the lab, outdoor radar measurements have been carried out with the 13.5 GHz radar in the backyard behind the company building of IMST. The radar was mounted on a turntable and connected via Ethernet to a Windows PC (see Figure 3-2). Parameter settings and data visualization were made with SenTool. The bandwidth was set to 2 GHz (12.5 – 14.5 GHz). A corner reflector was placed at 10m distance in front of the radar. The turntable was rotated manually in 5-degree steps in azimuth direction and the magnitudes of the target reflections from co- and cross-polarized channels (Rx2 and Rx1) were recorded.

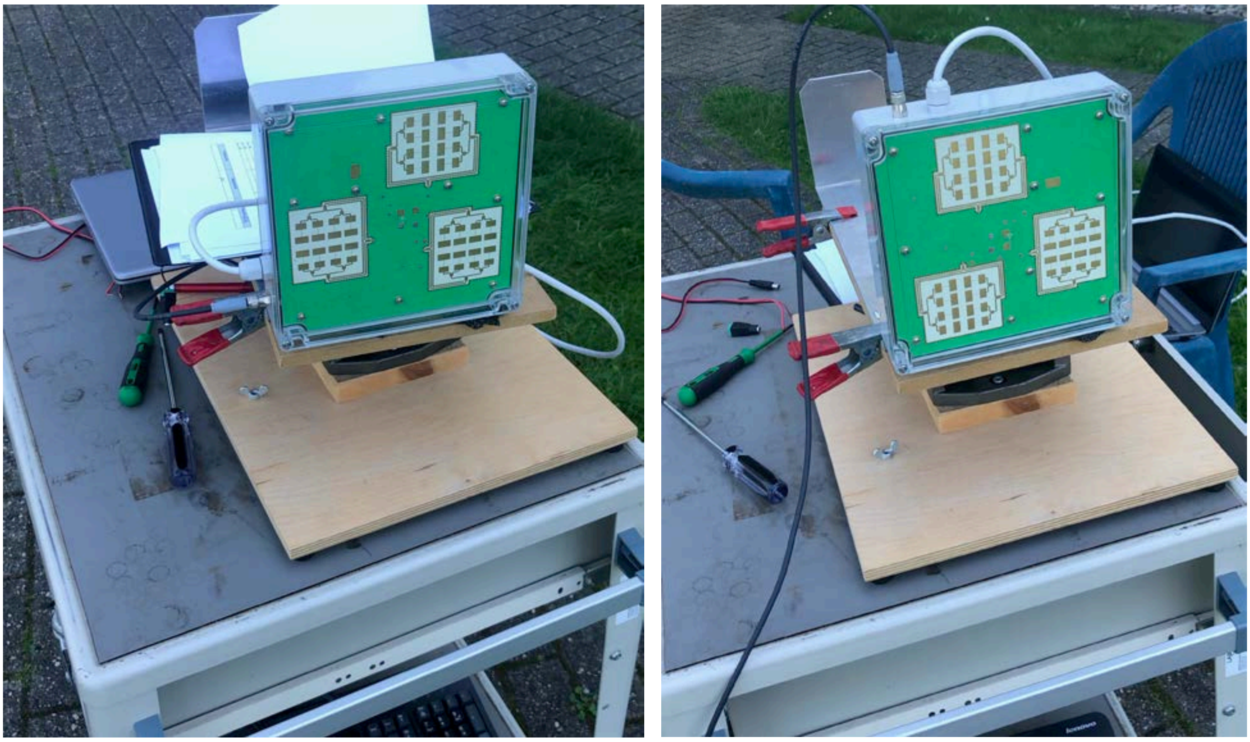


Figure 3-2: Outdoor measurements with 13.5 GHz radar mounted on a turntable in azimuth (left) and elevation (right) orientation

For V-/H-polarization, co-/cross-polarization, azimuth and elevation, the following definition could be made for the two measurement setups in azimuth and in elevation. Figure 3-3 and Figure 3-5 show the configurations, while Figure 3-4 and Figure 3-6 show the corresponding measurement results.

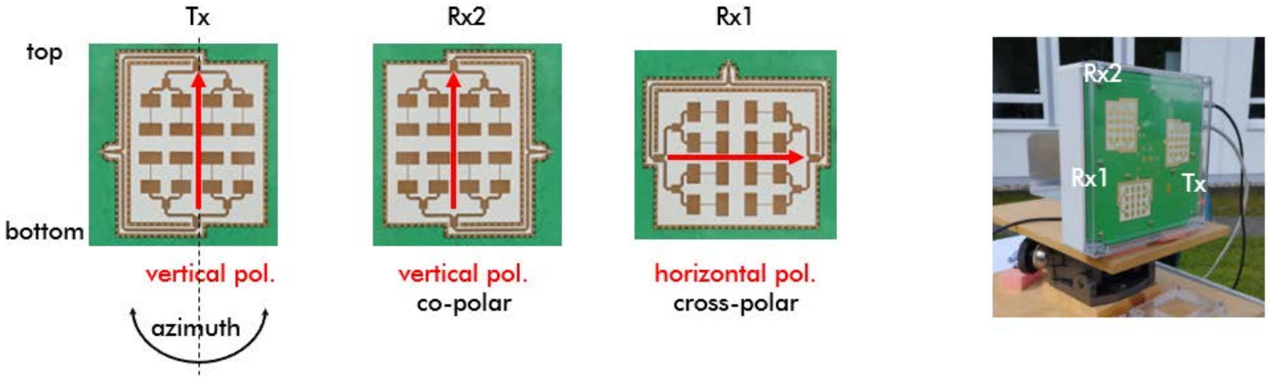


Figure 3-3: First measurement setup: azimuth configuration

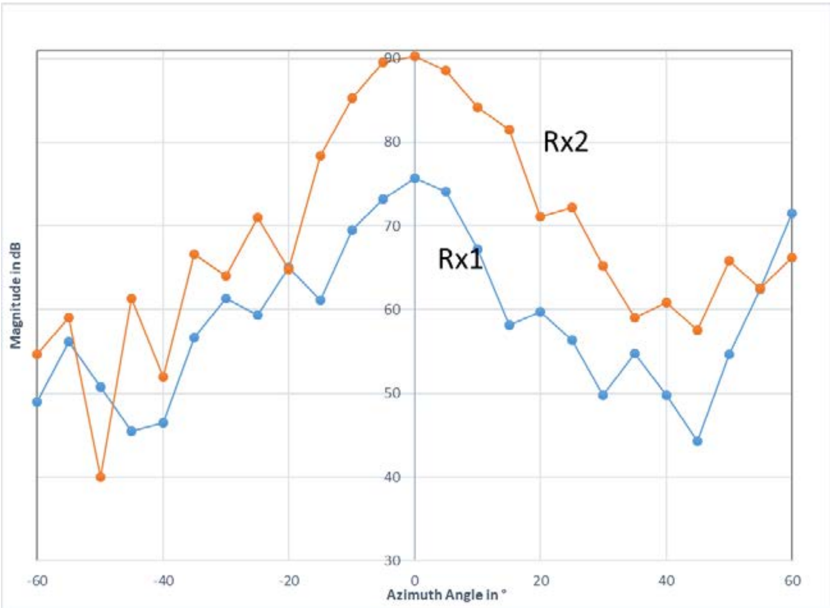


Figure 3-4: Magnitude measurement of target reflector in azimuth configuration

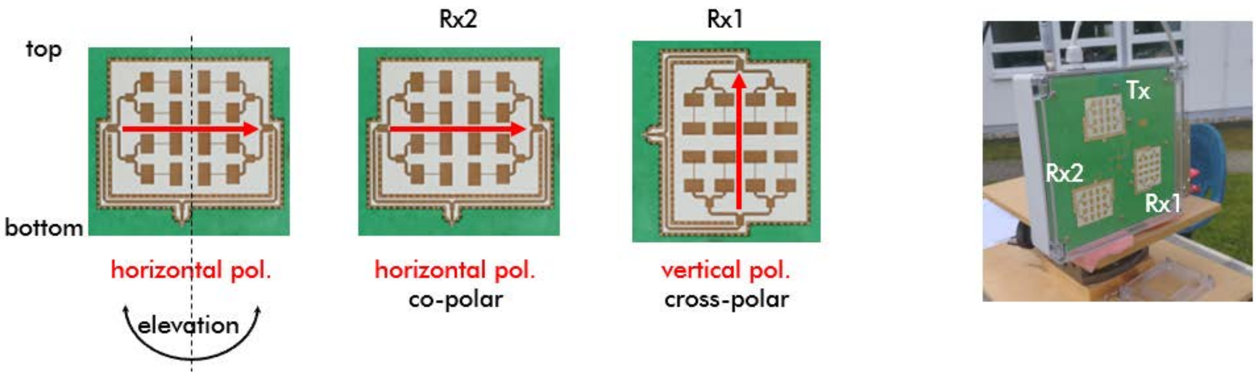


Figure 3-5: Second (rotated) measurement setup: Elevation configuration

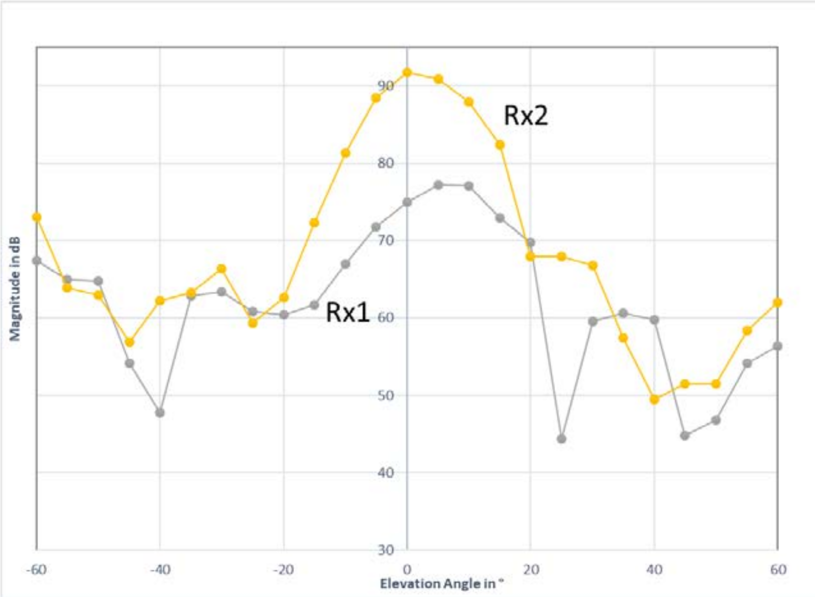


Figure 3-6: Magnitude measurement of target reflector in elevation configuration

Further precise measurement results have been achieved, when the radar and antennas was characterized within IMST's anechoic chamber, see chapter 4.

Outdoor and anechoic chamber measurements are comparable only to a limited extent. Outdoor measurements are influenced by the environment, where reflections from the surrounding and clutter from the ground affect the radar signals. Furthermore, the antenna characteristic from the transmit AND the receive antennas are present, while in the anechoic chamber only the transmit antenna was characterized at one single CW frequency. The outdoor measurements were made in FMCW mode with the full 2 GHz bandwidth. The antenna performance degrades especially at the edges of the frequency band.

With the 13 GHz module it is noticeable that the cross polarization (Rx1) is less attenuated than at the outdoor measurements compared with the 17.5 GHz sensor. Reasons for that might be, that the outdoor environment and the measurement setup changed slightly, or that the influence of the antenna characteristic at the band-edges has more influence. As predicted, a 2 GHz bandwidth at 13.5 GHz center-frequency cannot be as good as at 17.5 GHz. However, the cross-polarization suppression of the 13.5 and the 17.5 GHz are comparable at center-frequency and 0 deg boresight, which is shown in chapter 4 as comparison between simulated and measured data (13.5 GHz sensor ~22 dB and 17.5 GHz sensor ~25 dB suppression at boresight).

3.3 Distance accuracy and resolution measurements

Distance accuracy measurements were made outdoor mounted on a polymer sliding scale with an aluminum tube as radar target, which is shown in Figure 3-7. The physical distance was measured between the surface of the transparent radome and the target. The distance measured by the radar has a specific offset, which is 33.2 cm for the 13.5 GHz radar at a frequency bandwidth of 2 GHz. This offset results from the distance between the antenna and the radome plus an internal electrical length resulting from microstrip waveguide lines from the mixer to the antennas. This measured offset is used in the firmware to correct the distance measurement.

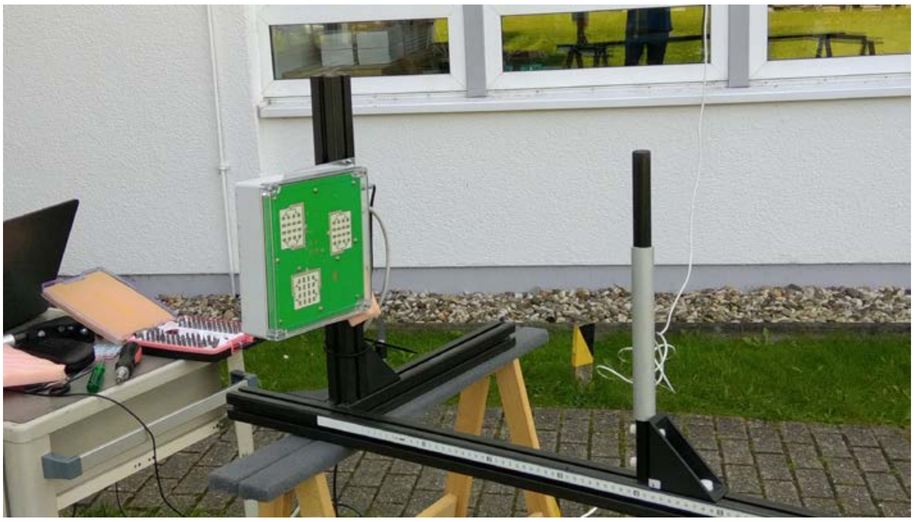


Figure 3-7: Distance measurement set-up with scale

Figure 3-8 plots the radar distance measurements as a function of the target distances. The measurement accuracy is within a tolerance of +/- 3cm.

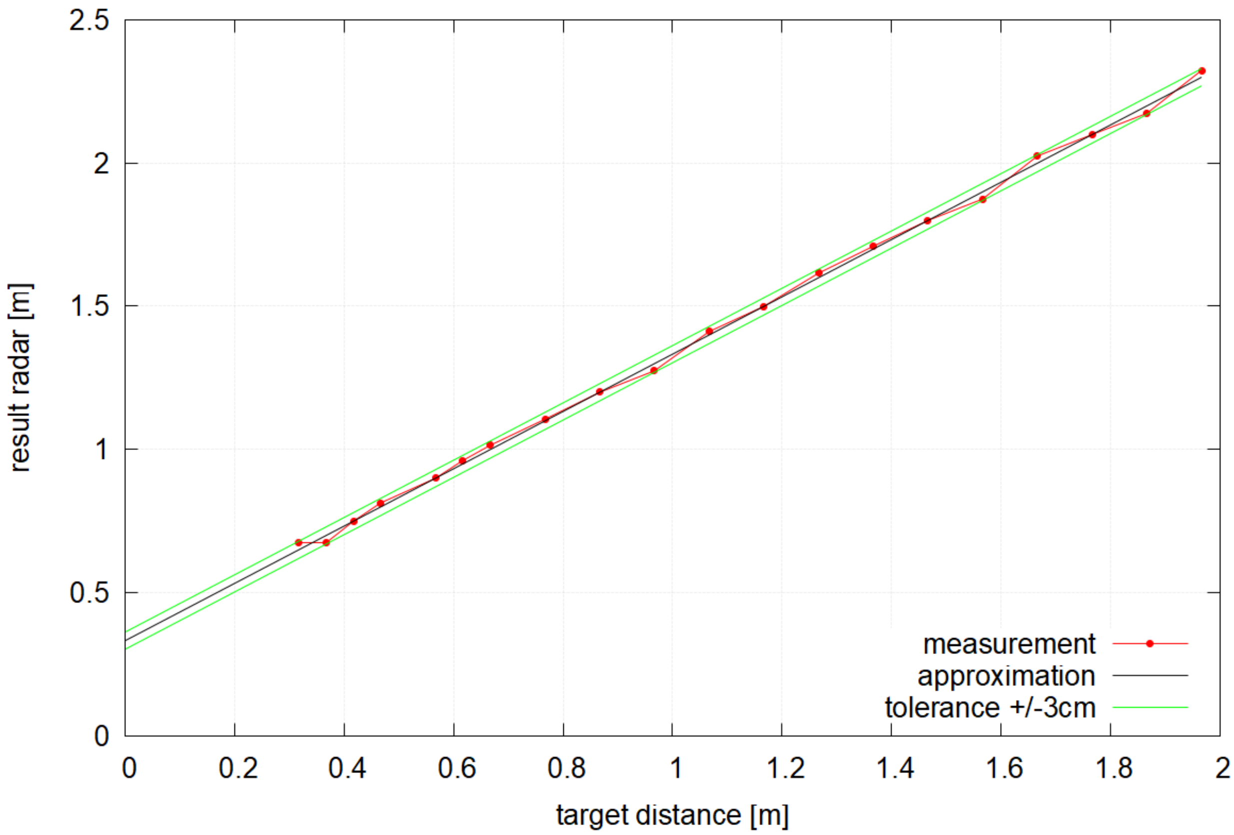


Figure 3-8: Distance measurement without offset correction

The distance accuracy measurements are summarized by these parameters:

- Reference plane is the radome surface (outside)
  (radome thickness = 3.36mm, antenna to radome distance = 11.2 mm)
- Measurement with the estimation curve

- 2 GHz bandwidth
- Distance offset: 33.2cm
- Distance accuracy: +/-3cm

Radar resolution is defined by $c_0/(2*\Delta f)$. "c_0" is speed of light, "Δf" is the bandwidth = 2GHz.

Therefore, the resolution results in 7.5 cm for the following measurement campaign. The radar distance measurement is divided into **bins**. One bin is equal to one resolution cell. The maximum range therefore results into the number of bins multiplied by the resolution. E.g., 512 measurement bins result into a max. distance measurement of 38.4 m.

If a target is detected in a specific distance bin, the next target must be in the next but one bin in order to distinguish or separate it from the previous target. This target separation has been tested in the setup, which is shown in Figure 3-9. Two targets with a distance of approximately 20cm ($\approx$ 3 * resolution) can be detected as 2 separate targets. This result is plotted in Figure 3-10. The selectable "Window"-function as part of the radar signal processing does also influence the separation properties of two neighbored targets.

Figure 3-9: measurement set-up with two targets for range resolution

Figure 3-10: FFT data of two targets at 21.5cm distance

The target separation properties are by these parameters:

- 2 GHz bandwidth
- Target separation: 21.5cm

4 Antenna measurement chamber

The 13.5 GHz radar sensor was characterized in the anechoic chamber of IMST. The module was mounted on a turntable to measure the EIRP parameter from -90° to +90° in Vertical and Horizontal Polarization at different center frequencies (in CW mode). The photos in Figure 4-1 illustrate the measurement setup.

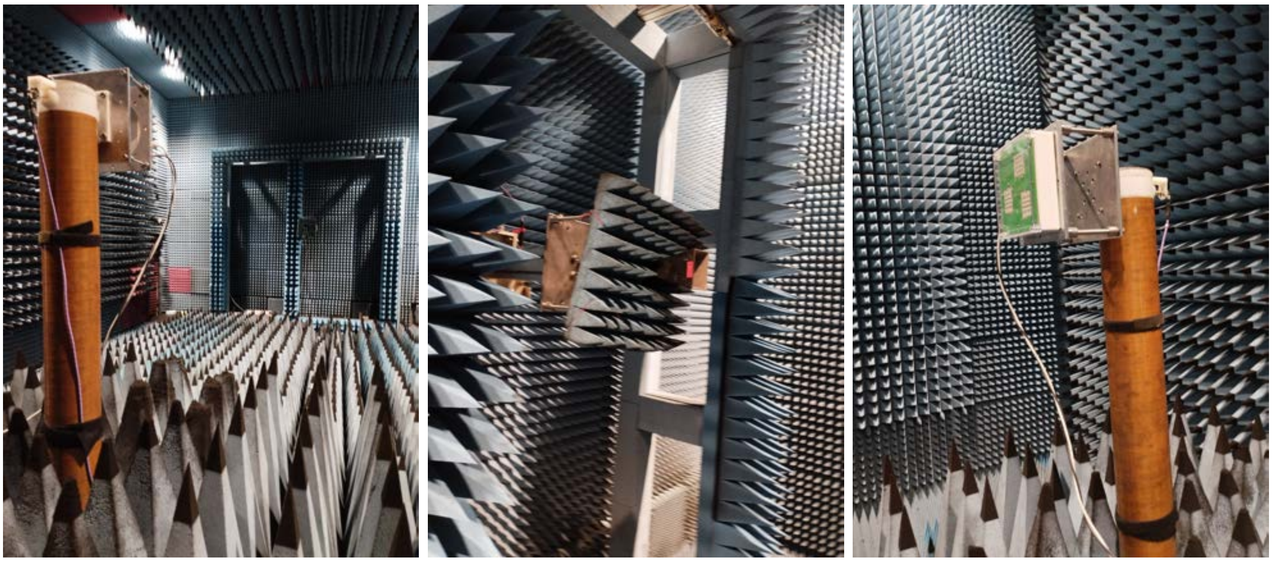
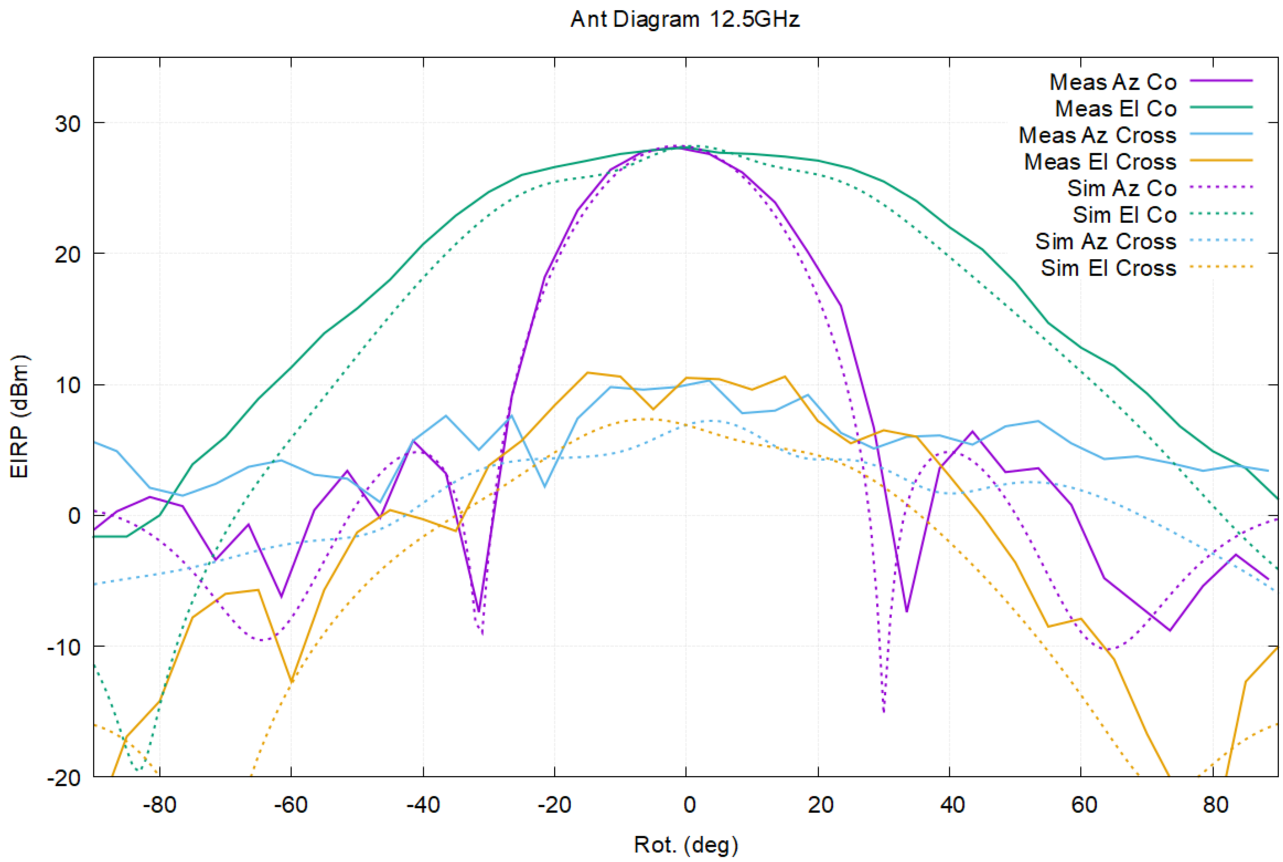
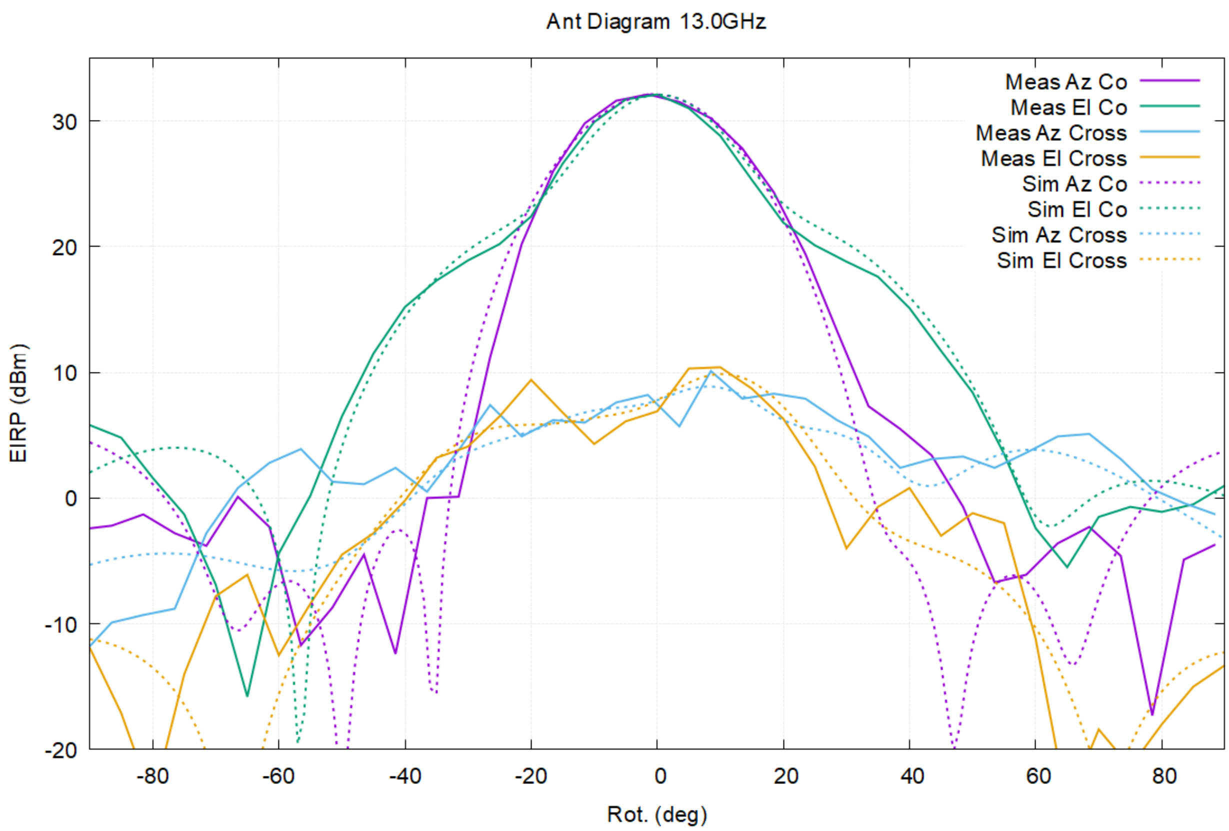


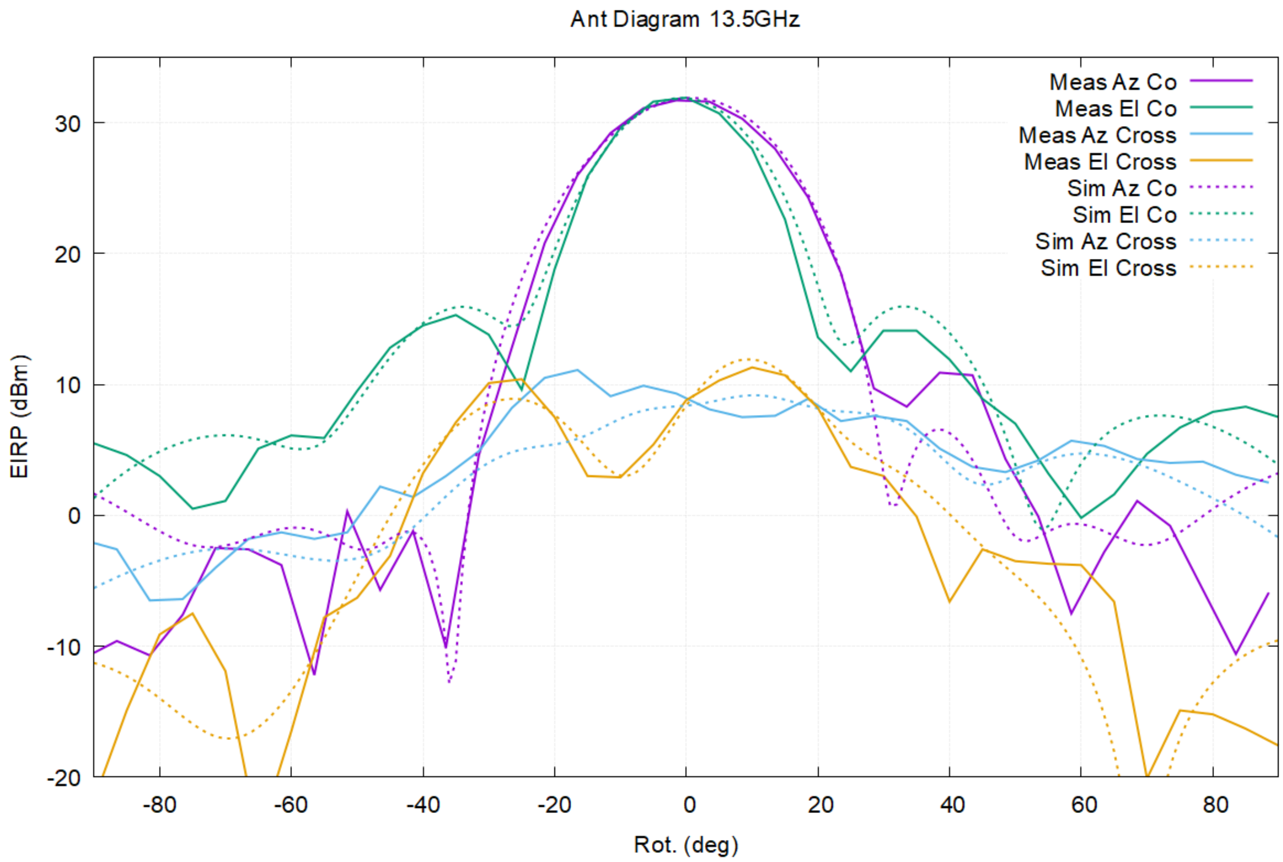
Figure 4-1: from left to right: antenna measurement chamber, receive antenna and radar module

The diagrams in Figure 4-2 present the EIRP measurements at different frequency points with these properties:

- Solid lines are measurement data, dashed lines are simulation data
- Az=azimuth, El=elevation, Cross= cross polarisation, Co=co polarisation
- Sim = simulation, Meas = measurement
- Calibrated measurement
- RF output power: **EIRP = 31.9 dBm** at 13.5 GHz, Az = 0 deg, El = 0 deg and 23.5 °C environmental temperature
- Measured 3 dB beam width at 13.5 GHz:
  24.5 deg in azimuth and 19.5 deg in elevation
- Cross polarisation suppression >= **22 dB at 13.5 GHz**
- An antenna gain of 17.2 dBi was simulated at 13.5 GHz.
  Simulations and measurements match very well.


Ant Diagram 12.5GHz
Meas Az Co
Meas El Co
Meas Az Cross
Meas El Cross
Sim Az Co
Sim El Co
Sim Az Cross
Sim El Cross
EIRP (dBm)
30
20
10
0
-10
-20
-80
-60
-40
-20
0
20
40
60
80
Rot. (deg)


Ant Diagram 13.0GHz
Meas Az Co
Meas El Co
Meas Az Cross
Meas El Cross
Sim Az Co
Sim El Co
Sim Az Cross
Sim El Cross
EIRP (dBm)
30
20
10
0
-10
-20
-80
-60
-40
-20
0
20
40
60
80
Rot. (deg)


Ant Diagram 13.5GHz
Meas Az Co
Meas El Co
Meas Az Cross
Meas El Cross
Sim Az Co
Sim El Co
Sim Az Cross
Sim El Cross
EIRP (dBm)
Rot. (deg)
30
20
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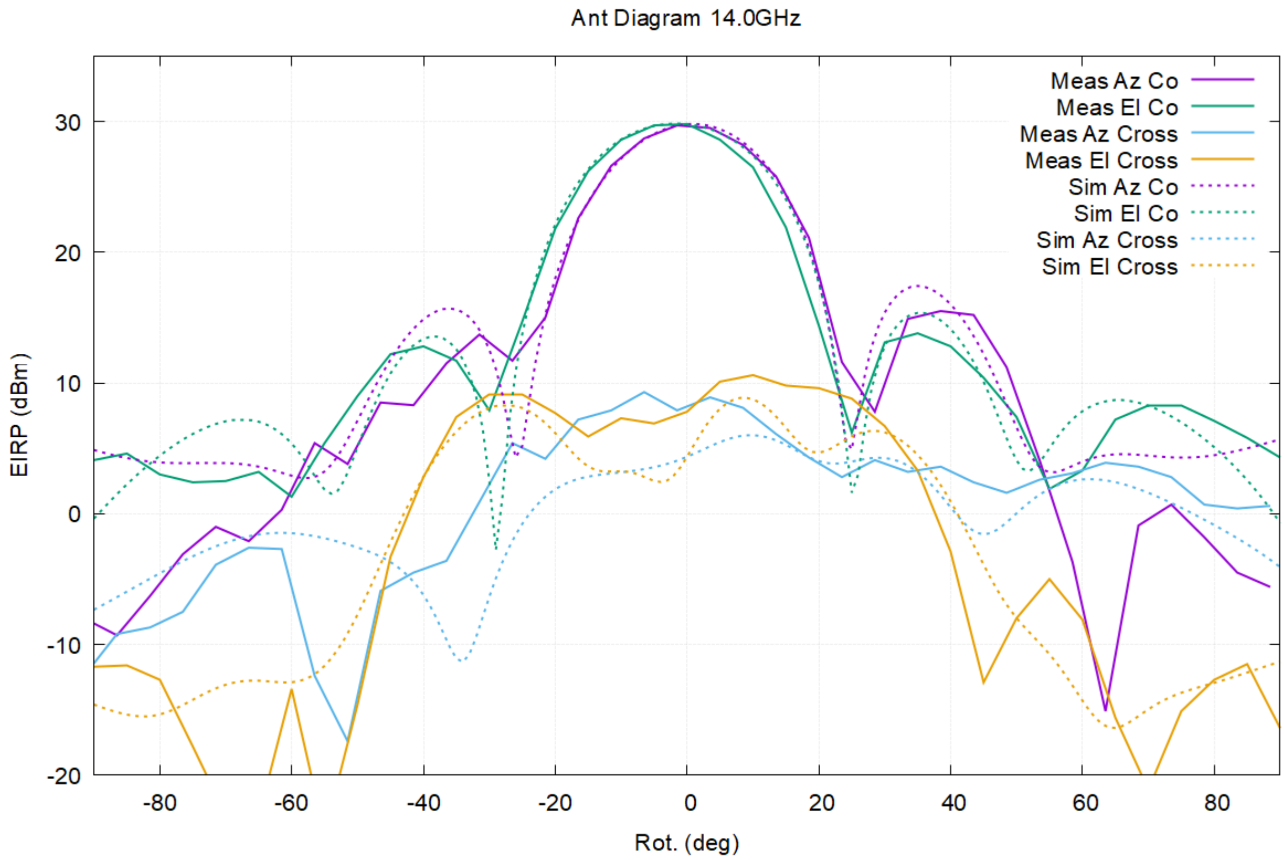
0
-10
-20
-80
-60
-40
-20
0
20
40
60
80


Ant Diagram 14.0GHz
Meas Az Co
Meas El Co
Meas Az Cross
Meas El Cross
Sim Az Co
Sim El Co
Sim Az Cross
Sim El Cross
EIRP (dBm)
Rot. (deg)
30
20
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0
-10
-20
-80
-60
-40
-20
0
20
40
60
80

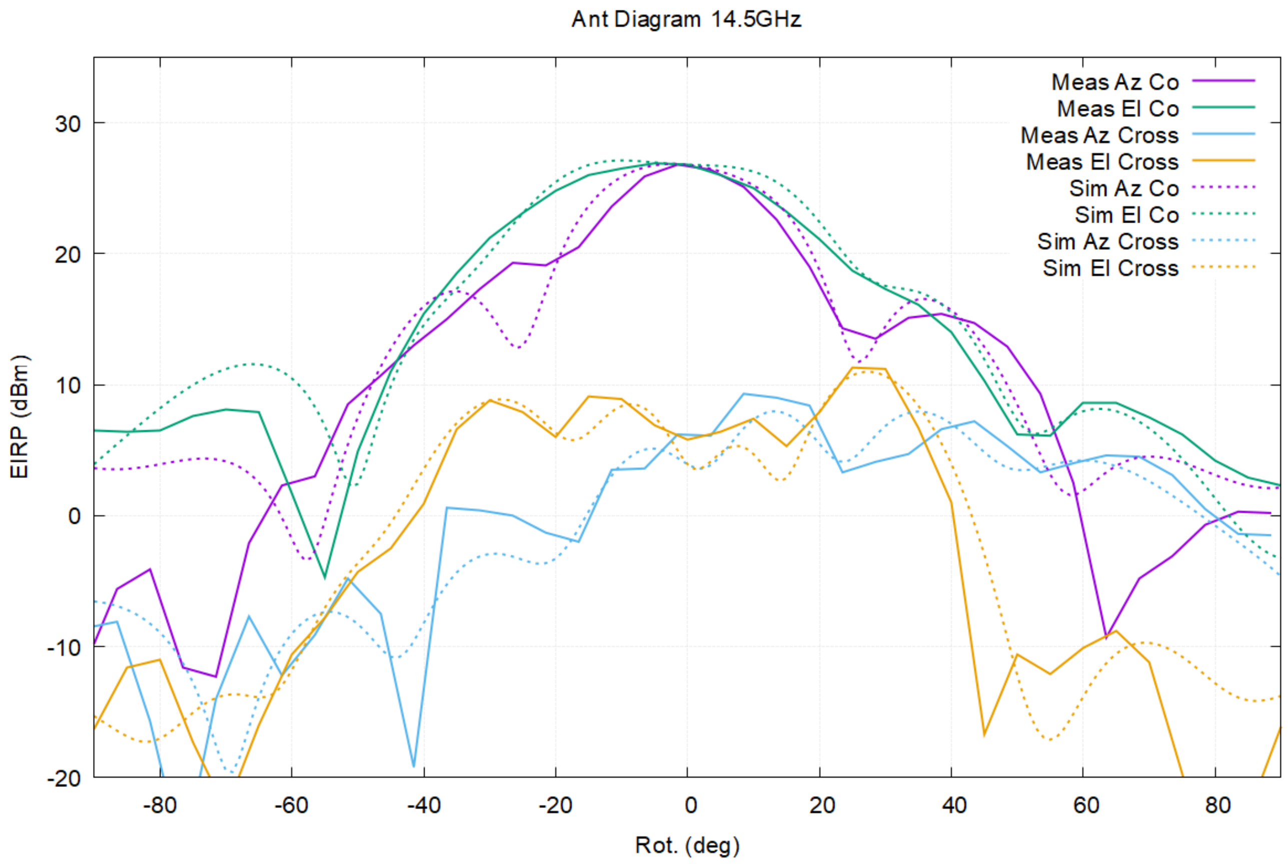


Figure 4-2: Tx Antenna diagrams at 12.50 GHz, 13.00 GHz, 13.50 GHz, 14.00 GHz, 14.50 GHz

5 Operating environmental temperature

The radar sensor was placed into a temperature cabinet. The antennas are facing the cabinet door, while the transmit antenna was aligned in opposite from the door's window. When the door was closed, an antenna was mounted in front of the door – surrounded by absorber material – directly in opposite to the radar's transmit antenna.

The measurement antenna was connected to an amplifier module, followed by a peak-power sensor and a peak-power analyzer. A PC controlled the temperature cycling and recorded the measurement data. The temperature within the cabinet was varied between -40°C and +30°C. Figure 5-1 shows the measurement setup.

The uncalibrated output power was measured at different chamber temperatures and different settings of the Voltage Control Amplifier (VGA). This VGA was controlled by a DAC to modify the amplifier attenuation. A DAC voltage of 0V is equal to a control voltage of 0V with the lowest attenuation. A DAC voltage of 1V is equal to a control voltage of -0.8V with an attenuation of about 11dB at 20°C environmental temperature.

Figure 5-1: Radar module in temperature cabinet on the left side, measurement set-up on the right side

The temperature cycling started at -40°C. The temperature inside the radar module was measured with an NTC thermistor, which was mounted close to the power amplifier of the transmitter. When the ambient temperature has stabilized at -40°C, the NTC thermistor measured 6°C in transmit mode. At +30°C the NTC thermistor measured +65°C inside the radar housing. The uncalibrated measured output power is plotted in Figure 5-2 as a function of the amplifier attenuation and the intrinsic temperature. These curves have been normalized to 0dBm, which is presented in Figure 5-3.

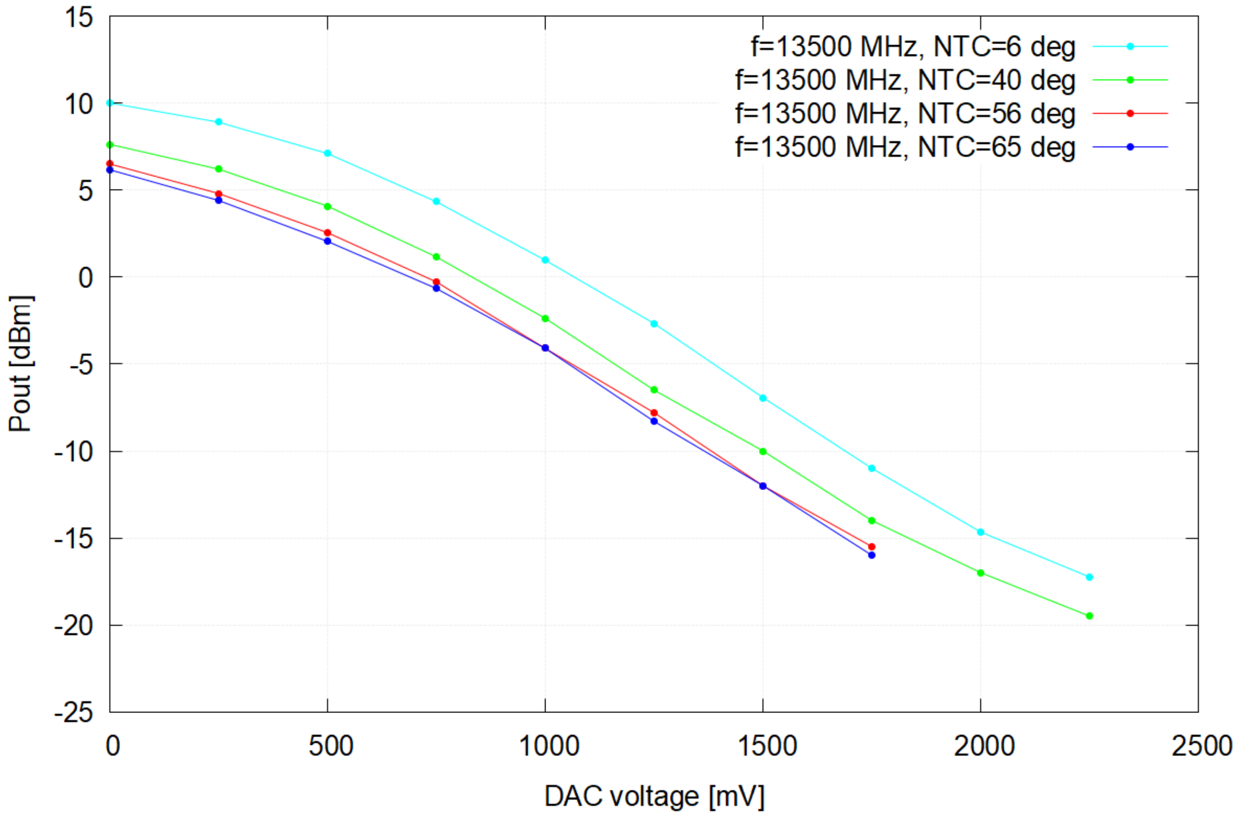


Figure 5-2: Measured output power over DAC voltage for different NTC temperatures.

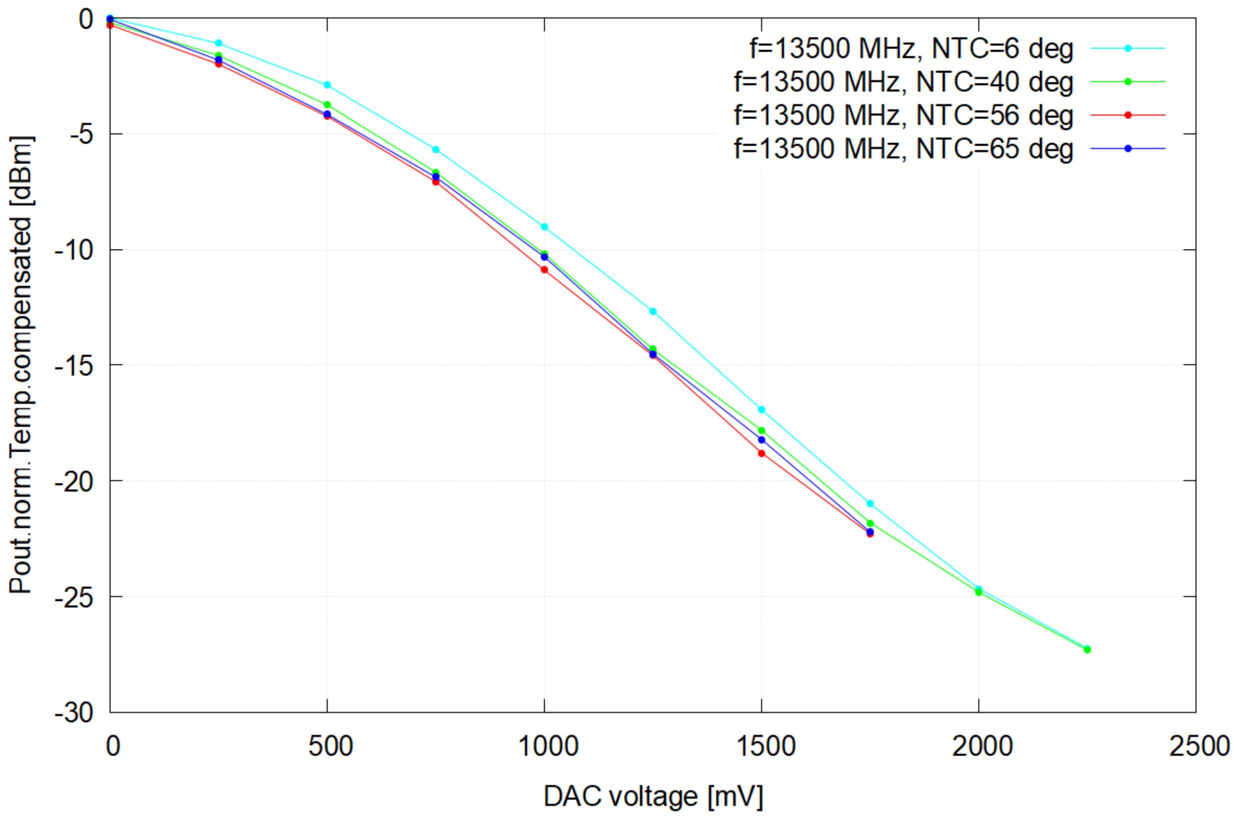


Figure 5-3: Measured output power (normalized) over DAC voltage for different NTC temperatures with linear temperature compensation.

At each ambient temperature a given attenuation requires a specific DAC setting. This is demonstrated in Figure 5-4 for NTC = 6°C and 65°C. A fitting function is needed to get a defined EIRP output power over the entire ambient temperature range. A fourth-degree polynomial was chosen to emulate this functionality. The coefficients have been derived for the 13.5 GHz radar as:

a(NTC)=(155.7-220.9)/(65.0-6.0)*(NTC-6.0)+220.9

b(NTC)=(-7.52+16.4)/(65.0-6.0)*(NTC-6.0)-16.4

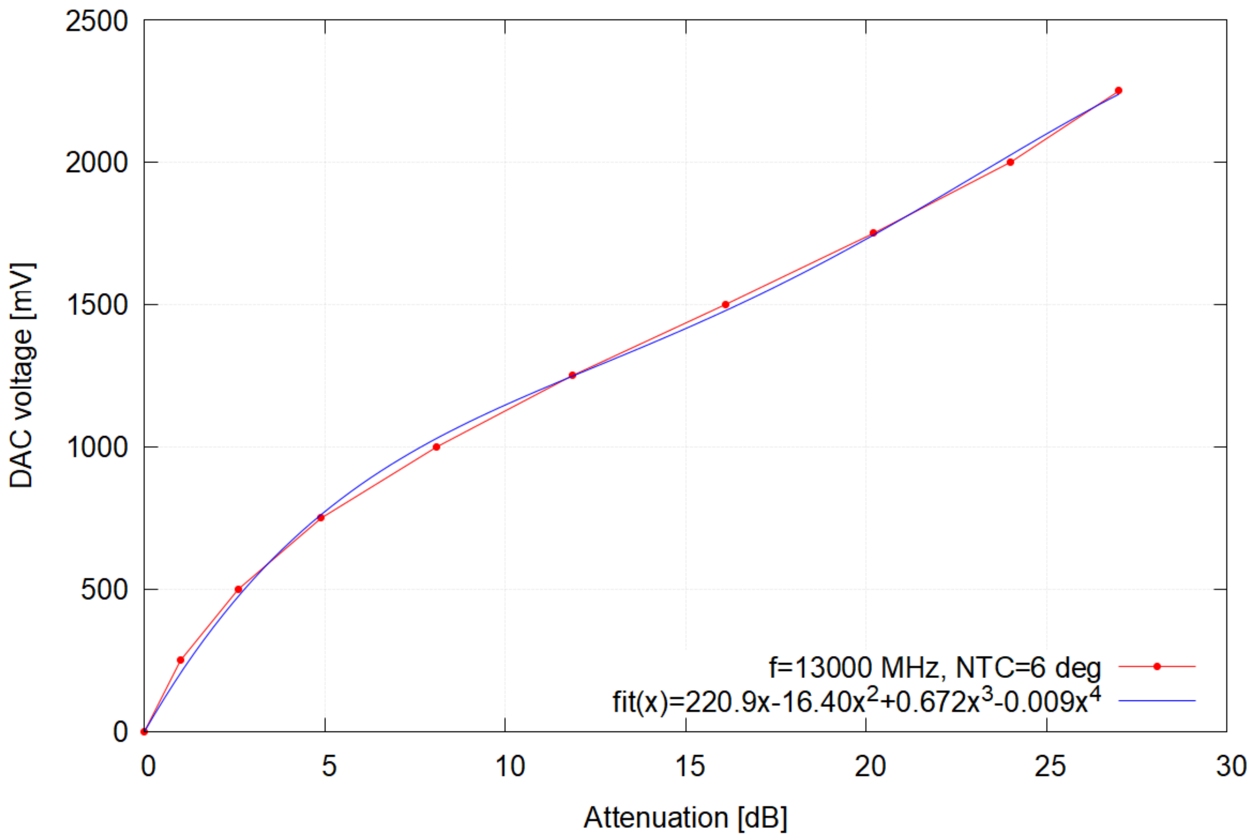
c(NTC)=(0.216-0.672)/(65.0-6.0)*(NTC-6.0)+0.672

d(NTC)=(-0.00135+0.00941)/(65.0-6.0)*(NTC-6.0)-0.00941

The following function delivers the DAC voltage for a given attenuation in dependency from the NTC temperature:

$$DAC(att,NTC)=a(NTC)*att+b(NTC)*att^2+c(NTC)*att^3+d(NTC)*att^4$$

This function was implemented in the radar's firmware. The user selects the desired EIRP output power and the attenuation setting will be made automatically as a function of the measure NTC temperature.



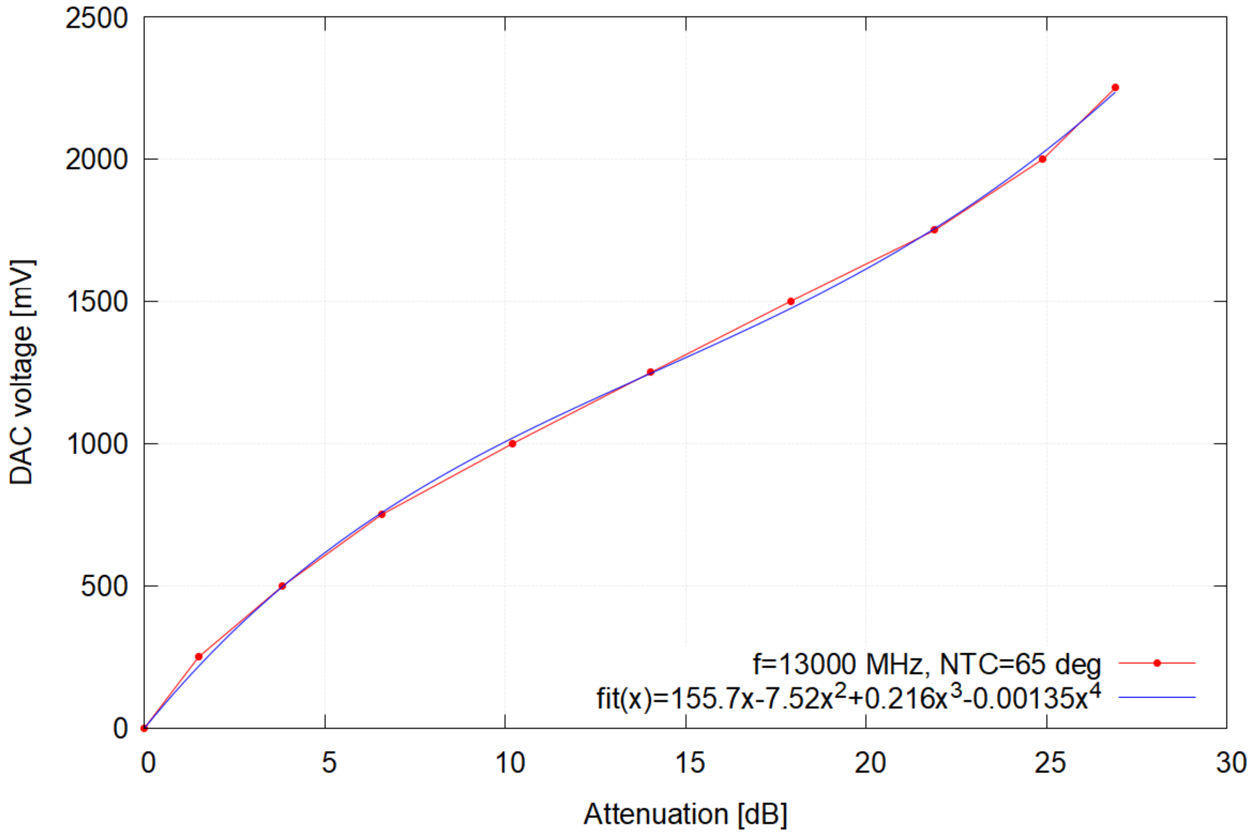


Figure 5-4: Measured dependency between attenuation and DAC voltage and fitting curve with 4th grade polynomial at NTC temp.=6 and 65deg (env. temp.=-40 and 30deg).

This behaviour has been tested with the radar sensor. Figure 5-5 shows the test results. The dotted curve indicates the maximum available power without taking the temperature dependency into account. The solid lines show the output power at different EIRP stetting as a function of the ambient temperature. A maximum of 30 dBm can be achieved over the entire temperature range. The RF power stability is better than ±0.7 dB for EIRP settings from 10dBm to 30dBm.

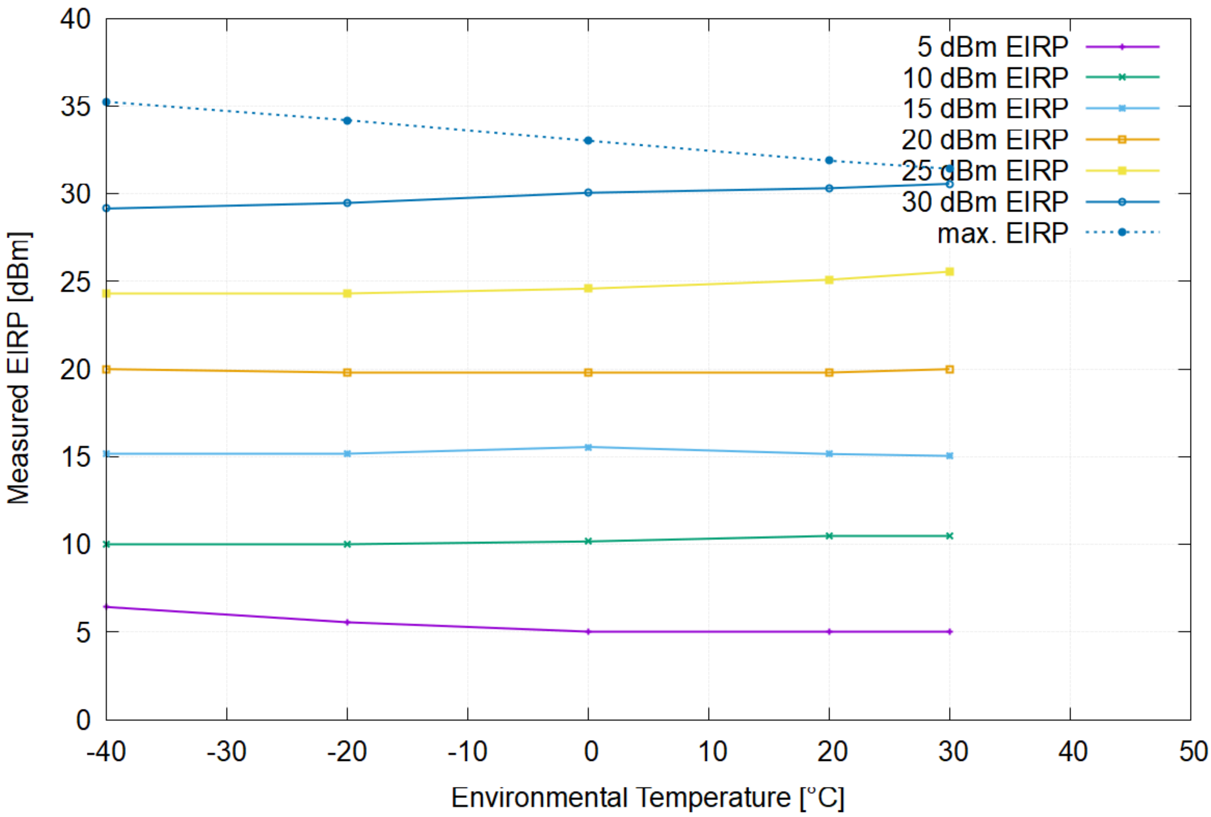


Figure 5-5: RF output power with stabilization, the legend shows the set power, max. EIRP without stabilization

The following list summarizes the RF power stability parameters:

- Radar settings:
  - Interval 1ms
  - Pulsed RF power amplifier
  - 200us pulse length
  - 1024 Samples
  - Continuous measurement
  - 13.5 GHz
- Operating environmental temperature from -40 °C to 30 °C
- **the radar works within the operating environmental temperatures**
- Verification measurement for integrated stabilization functions
- Stabilization via software functions in the firmware
- **RF power stability better than ±0.7 dB**
  (at 10 dBm to 28 dBm EIRP and -40 °C to 30 °C environmental temperature)

6 Compliance Matrix for 13.5 GHz FMCW-Radar

The following compliance table compares the requirements from the SoW with the achieved results from the 13.5 GHz sensor:

Parameter	Requirement	Verification (T/A/I/D/S)*, Comment
FMCW Radar	Distance and velocity measurements	(T) Only range measurements are implemented for optimal distance determination
Weight	≤ 800 g	(T) 949g with 2m Ethernet cable and connector plus 122g for DC cable with connectors
Board dimensions	150 mm x 170 mm	(T) 178 mm x 178 mm
Housing dimensions		Standard Housing “RND 455-00143” 190 x 190 x 55 mm without connectors; (T) 211 x 190 x 55 mm incl. bushing
Housing protection code	IP65	(D) compliant; housing, DC-connector and bushing have IP65 protection rating
DC power supply	+ 24 V	(T) DC Supply +20 V minimum voltage +24 V nominal voltage +28 V maximum voltage Power Consumption @ 24 V 5.9 W Mode 1 ** 7.1 W Mode 2 ** 7.8 W Mode 3 ** 8.5 W max. (estimated)
Integrated Tx and Rx patch antennas	Txv: 4*4 patch array for transmit with vertical polarization	(I) compliant
	Rxv: 4*4 patch array for receive with vertical polarization	(I) compliant
	Rxh: 4*4 patch array for receive with horizontal polarization	(I) compliant
Antenna 3dB beam width	approximately 25° in azimuth and elevation	(T) 24.5° in azimuth (T) 19.5° in elevation
Antenna gain	approximately 15 dBi	(S) 17.2 dBi @ 13.5 GHz

Receive channels	(RxV and RxH) with I/Q modulation	(D) compliant
Target bandwidth	approximately 2 GHz	(T) compliant; 2 GHz bandwidth achieved
Range resolution at 2 GHz bandwidth	7.5 cm	(D) compliant
Distance accuracy at 2 GHz bandwidth	2 cm	(T) ±3 cm
Distance range (max) at 2 GHz bandwidth	1,000 range bins	(T) compliant, adjustable number of range bins are: 256, 512, 1024, 2048
RF output power (EIRP)	tunable from 10 to 30 dBm	(T) compliant (10 to 30 dBm)
RF output power measurable	Power detector integrated	(T+D) compliant
Operating environmental temperature	-40°C to 30°C	(T) tested in temperature cabinet
RF output power stability	0.5 dB over temperature range from -40 °C to 30 °C	(T) EIRP vs. stability range 10 dBm -> 0.5 dB 15 dBm -> 0.6 dB 20 dBm -> 0.2 dB 25 dBm -> 1.2 dB 30 dBm -> 1.4 dB
RF output power precision	1 dB over frequency range by signal processing (re-adjustment of output power over frequency ramp is not possible)	(A) Analyzed by comparing internal power detector values with EIRP power measurements at CW frequency points
Temperature measurement	Temp. sensors integrated	(T+D) compliant; temp. sensors integrated and tested
Ethernet Interface		(D) compliant
Communication/commands interface		(D) compliant; commands adapted to specific sensor
GUI software SenTool™	unlocked and customizable	(D) compliant; SenTool adapted to specific sensor

* Verification Methods:
(T)=Test, (A)=Analysis, (I)=Inspection, (D)=Demonstration, (S)=Simulation

** Radar Operation Modes:
Mode 0: Radar connected, Radar Transmitter turned off, no Measuring
Mode 1: Continuous Measuring, Measurement Cycle = 1ms, 1024 bins, max. EIRP
Mode 2: Continuous Measuring, Measurement Cycle = 1ms, 2024 bins, max. EIRP

Table 6-1: Compliance table for 13.5 GHz sensor

7 Annex

7.1 List of Figures

7.2 List of Tables