ETH
Eidgenössische Technische Hochschule Zürich
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Earth Observation and Remote Sensing

Robustness of Radar Reflectors at Ku Band Microwaves

Implications for Interferometric and Polarimetric Radar Calibration

Master Project Thesis in Environmental Engineering

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Abstract

This Master project thesis investigates the robustness of newly developed radar reflectors at the ETH Zürich for measurements with microwaves at Ku-band. These relatively small reflectors are very handy and can be installed quickly and easily by a special interlocking mechanism. It was to be identify, how these reflectors behave on different influences such as deformation of the side walls or misalignment with respect to the symmetry diagonal of the reflector. Special mountings had to be designed for these two experiments. On October 30$^{\text{th}}$, a series of measurements with a total of six reflectors and a KAPRI radar from *Gamma Remote Sensing* was carried out. In total, six different influences on the intensity of the backscattered signal as well as on the polarization were investigated. These were the rotation of a reflector through 360° around its body diagonal, a deformation of one reflector panel, or filling a reflector with aluminum chipping. Furthermore, the influences of a symmetrical deformation over the reflector corners, a misalignment of the reflector in azimuth direction, the coverage of a reflector with tarp, as well as the influence of leaves in a reflector were measured. The evaluation of the data showed that especially the deformation of the side panel, the aluminum chipping and the leaves have an extreme influence on the intensity of the backscattered radiation. On the other hand, it makes no difference at which angle the reflector is rotated, as long as the body diagonal points in the direction of the radar. Covering a reflector for protection against water or snow with 2 layers of tarp showed no influence on the intensity of the reflected signal, but is slowly decreased with more than 2 layers of tarp. Except for the experiment with the aluminum shavings, none showed an influence on the phase difference $\varphi_{co} = \varphi_{HH}$ - φ_{VV}. Therefore, the reflectors can be used as reference points and for calibration.

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Acknowledgements

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My deepest appreciation goes to Cornelius Senn for helping me designing and manufacturing the different reflector mounts and sharing his knowledge and experience with me.
Additionally, I want to thank Simone Baffelli for providing the script to correct the phase ramp and helping me with his knowledge about the KAPRI radar.

1. Introduction

Radar reflectors are very important tools in various fields of radar measurements because of their strong backscatter behavior. They are used as reference points for digital elevation models, for measuring glacier velocities, correction of atmospheric effects, or for calibration purposes, to just name a few. Radar reflectors come in different shapes and sizes. Traditional passive radar reflectors all consists of two (dihedral) or three (trihedral) panels that are perpendicular to each other. Because of their mechanical design, the incoming radar signal is reflected back in the direction where it came from [8].
Perfect radar reflector feature the following properties:

1. They are well visible in radar images
2. They can be absolutely fixed in space
3. They have a constant backscatter response, independent on environmental influences
4. They do not show any mechanical deformation
5. They are easy to transport and install

The fact that they are often installed in areas that are difficult to access, it is helpful to make them as small and light as possible. Furthermore, big reflectors are more likely to be influenced by strong winds, or even their own weight, which in the worst case scenario can lead to a deformation of the reflector. ETH Zürich recently developed a new kind of corner reflector with a special interlocking system, so that the single reflector panels can be transported separately[11]. The purpose of this work was to specify, how suitable these reflectors are to the listed points 1-4 above. From a previous study [8] it is known, that the backscattered signal decreases, if the reflector panels show some deviation from the orthogonal angle. Therefore, it was decided to specify the influence on backscatter intensity if one or two panels were deformed. Additionally, a rotation measurement should be conducted to show, that the backscatter signal of the reflector is stable in relation to rotation around its symmetry axis. The rotation shouldn't have an influence, hence because of the named scattering mechanism. Further, the polarization shouldn't be influenced by the rotation [2].
It is known that misaligning a reflector in respect to the line of sight direction of the radar, causes a loss on backscatter intensity [5]. Since there are simulations available that show the dependence of a deviation in azimuth angle according to the backscatter intensity for exactly the used reflectors, it was considered to validate these data. Because reflectors are mostly used outdoors, they are often covered with some tarp to protect them from water or snow. This has to be done, because water has a big influence to dielectric loss[1], especially at the Ku-band frequency. Despite the fact, that protection foliage is commonly used, it is unknown if the coverage itself has a negative influence on the backscatter intensity.

2. Methods

2.1. Experimental setup

For measuring the robustness of radar reflectors at Ku-band, a real aperture radar (RAR) with slotted waveguide antennas, developed by *Gamma Remote Sensing AG* was used. The system called KAPRI (Ku-band Advanced Polarimetric Radar Interferometer), or also known as Pol_GPRI-2, can be installed with different antenna settings. A heavy-duty tripod from Leica with three rods assures a stable mount of the radar. With a stepper motor, the custom designed tribrach lever can be rotated. KAPRI uses an frequency at Ku-band of 17.2 GHz which corresponds to a wavelength of around 1.74cm and has an operational range of 30m up to 10km [4]. With an antenna length of 2.06m, the range resolution is 0.75m and 0.4 degrees in azimuth. The rotation causes the images to be in polar coordinates. In this experiment, two transmitting (upper) and two receiving (lower) antennas were installed (right figure 2.1) with an antenna elevation angle of 20°. The configuration settings were chosen in a way that the co-polarized phase centers lie in between of the antennas on the same point, in order to calculate the phase difference $\varphi_{co} = \varphi_{HH} - \varphi_{VV}$. The outer antenna pair transmits and receives the vertical polarized waves, while the inner antenna pair is for the horizontally polarized waves. Further informations about the polarimetry can be read in the subsection 2.2.

The reflectors to be tested were developed at ETH Zütich by Dr. Silvan Leinss and Cornelius Senn, containing a new and simply interlocking assembly mechanism (EP 17152977.9 (patent pending)). Two different reflector sizes with penta-squared sections were used with a edge length of 0.6m and 0.45m (figure A.12 in the appendix). For the deformation experiment, a reflector with thinner side plates was used, which allows an easier deformation. Table 2.1 below shows what kind of reflector was used for the different experiments.

Table 2.1: Reflectors used in the experiments

Reflector type	Reflector name			
40 cm	*CRref*	*CRrot*	*CRt1*	*CRt2*
60 cm	*CRdef*	*CRac*		

The experiment was conducted on the 30$^{\text{th}}$ of October 2017 at the ETH campus Hönggerberg in Zürich. The setup can be seen on the left in figure 2.1. The Kapri was placed on top of the HPP building. The reflectors were places next to a nearby country road. The nearest reflector *CRrot* was around 170m from the radar and the farthest reflector *CRt2* 230m. the KAPRI was roted from -10° to +15° from its initial position, in order to scan the area where the reflectors were placed. A total of 43 acquisitions were taken for 7 different experiments. The sequence of experiments can be seen in figure A.1 in the Appendix

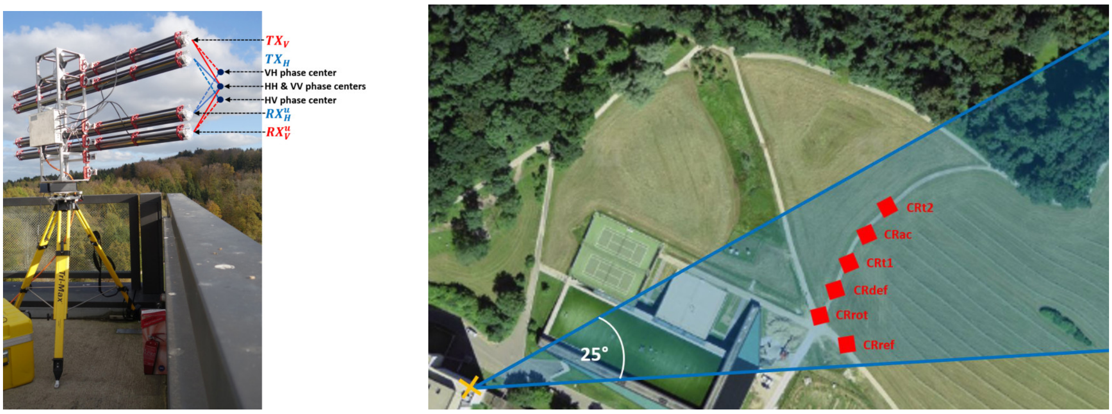

Figure 2.1: Left picture: Setup of the KAPRI radar. The upper 2 antennas (TX) are transmitting while the lower two (RX) are the receiving antennas (Photo: Silvan Leinss) **right picture:** Overview of the experiment setup on campus ETH Hönggerberg [10]. The position of the Kapri radar is illustrated through the yellow x on the lower left corner. The blue triangle markes the scanned area and the red squares indicate the position of the corner reflectors

2.2. Polarization

The behavior of a wave field vector in time at a fixed point in space is the polarization. A polarization HH means that the transmitted and received signal is in a linearly (horizontal) plane wave. VV on the other hand means that the wave is transmitted an received in vertical direction. These are the so called co-polarized (co-pol) phase and can be seen in figure A.13 in the appendix. Since there were 2 transmitting and receiving antennas used, also the cross-polarized (cross-pol) phase HV and VH can be measured. The scattering (or Sinclair) matrix 2.1 contains the four polarization.

$$Scattering\,matrix\; S = \begin{pmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{pmatrix} \tag{2.1}$$

Since different targets interacting differently with the polarization, some physical interpretations can be made. A single target like corner reflectors which are used for calibration, man-made objects or stones therefore should not change its polarization in time or space. The further approach how the calculation of the phase difference are proceed can be read in the section 2.10

2.3. Rotation

One of the main purposes of this project thesis was to show, rotating the reflector around its symmetry axis doesn't influence the backscatter intensity or the polarization significantly, as long as its oriented directly towards the radar. The assumption that rotation shouldn't have an influence, is based on the reflector geometry and how the incoming waves are reflected and returned to the radar. The reflecting mechanism of a trihedral corner reflector is illustrated in figure A.14 in the appendix.

To rotate the reflector around its body diagonal, a mounting had to be developed. Since the stand to tilt the reflector was already available, the rotation mechanism, the connection between reflector and rotation device, as well as the connection between the stand and the rotation device had to be engineered. The final solution was using the indexing head from a lathe to realize the rotation. It can be fully rotated around 360° and be locked in place at any angle. Figure 2.3**a)** shows the indexing head as the connection piece between the stand and the reflector.

To mount the reflector a solution had to be found where the corner of the reflector is on the rotation axis (body diagonal), so that it doesn't wobble during rotation. Therefore, the already existing flaps on the reflector were used. Three steel plates have been bent at angles of 45° and drilled in a way that the reflector lashes can be screwed on. Figure A.15 in the appendix shows the bended plates. The three plates then were welded to a piece of steel pipe. A round shape was chosen, because by connecting it to the indexing head, it centers by itself. This is based on the mechanism how the indexing heads holding fixture is working. The final missing part is the connection between the indexing head and the stand. To solve this problem, a plate was produced with holes to tight screw the indexing head on one side of the plate and the stand on the other side. The final assembly of the whole rotation experiment can be seen in figure 2.3**b)**.

(a) **(b)**

Figure 2.2: **a)** Mounting of the corner reflector with an indexing head on a tiltable stand
b) Installed and aligned corner reflector for the rotation experiment at initial rotation angle of 0°

During the measurement campaign, the reflector *CRrot* was rotated by 10° after each acquisition. The starting position was like the normal orientation of a corner reflector with the front side of the ground plate oriented parallel to the radar antennas. This position is set to an angle of 0° in the measurement protocol A.2. The measurement at a rotation of 40° was taken twice by accident. Additionally, the measurements at 250° and 320° were removed, because of a measurement error and a misunderstanding in communication.

2.4. Deformation

For this measurement, a bigger reflector than *CRref, CRrot, CRt1 or CRt2* with a side length of 60 cm, but made out of thinner plates was used. Before deciding how the deformation is done, a mount for the reflector had to be engineered to fix the corner of the reflector, so that the phase center is fixed absolutely in space. This was done by placing the reflector on a wooden, water resistant glued plate. To hold the reflector in place, 2 slats of wood were screwed onto the plate. The reflector itself afterwards was also screwed to the plate through its lashes to assure that its totally fixed in space.
Since the reflector was placed on a country way and the terrain wasn't flat, a base had to be designed to install the whole reflector with its front of the ground plate parallel to the radar antennas. Therefore, a square was built out of wood with some simply adjustable pedestals (left picture of figure 2.3). Afterwards, the whole plate with the reflector can be placed on this base. To align the body diagonal towards the radar, a wooden slat was screwed onto the base to get the needed angle. The whole mount can be seen in the right picture of figure 2.3.
Deforming a reflector can be done in different ways, referring on how the deformation is defined. The reflector has to be deformed in a way that can be described afterwards. For this it was decided to deform one of the reflector side plates center, by a screw. Thus, a wooden slat was attached diagonally to the reflector side (center picture of figure 2.3). With a screw through the middle of the slat, the center of the reflector wall can precisely be displaced. To avoid destroying the reflector by the thin, flat screw tip, a flat piece of aluminum has been sticked between the wooden slat and the reflector side.

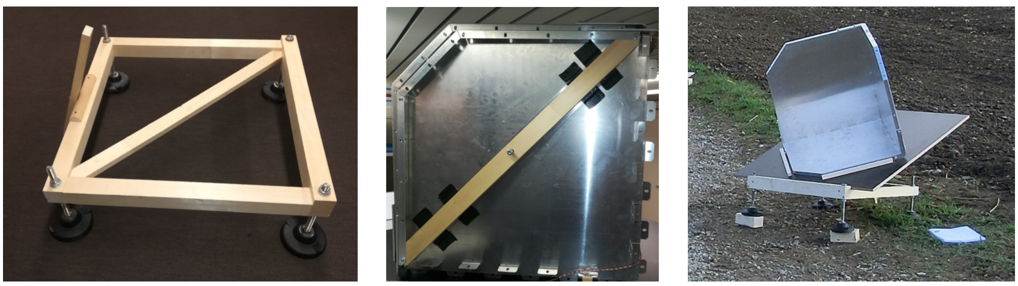

Figure 2.3: **left:** Base of the deformation experiment where the reflector can be placed on
middle: Deformation by a screw
right: Reflector *CRdef* during the measurement

During the measurement, the center of the reflector side has been displayed in steps of 2 mm towards the maximum displacement of 18 mm. The first measurement was a reference measurement with no deformation. Since the deformation of the center of the reflector wall caused an uneven deformation of the whole side, the horizontal, vertical and diagonal displacement of the reflector sides were measured and reported in row 4 to 7 in the measurement protocol A.2 in the appendix. At the maximum deformation, 2 measurements were taken, in order to see if the whole deformation is stable.

2.5. Aluminum chipping

Another goal was to see the influence onto the backscatter intensity and polarization if there were some metals inside the reflector. Mainly for further designs of corner reflectors, or if the reflector itself got damaged or the planes getting roughened. Therefore, reflector *CRac* was used. It has the same dimensions as *CRdef*, but is made out of thicker panels. As a filling, some leftover aluminum chipping from a workshop has been used. To prevent the chipping to slip out of the reflector (because of the tilting angle of the reflector towards the radar), the reflector base was covered with a paste and a radar image was taken. For the next few acquisitions, the reflector base was constantly covered with more aluminum chipping, reported in the measurement potocol A.2. Since it is hard to quantify the amount of clippings, pictures had been taken for each filling step. These photos (A.18 - A.20) can be seen in the appendix section A.3.2

2.6. Leaves

The main goal in this experiment was to evaluate the influence of leaves (or biomass in general) in a corner reflector on the backscattered intensity. The idea behind was, that especially in fall, the possibility of leaves blown into a reflector is high.
For this, two measurements with the reflector *CRdef* were performed. In the first acquisition, the ground plate of the reflector was covered with leaves that fell of a tree. Figure 2.4 shows the amount of leaves and how they were distributed in the reflector during the first measurement. In the second acquisition, the amount of leaves slipped out of the reflector or were blown out of it by wind.

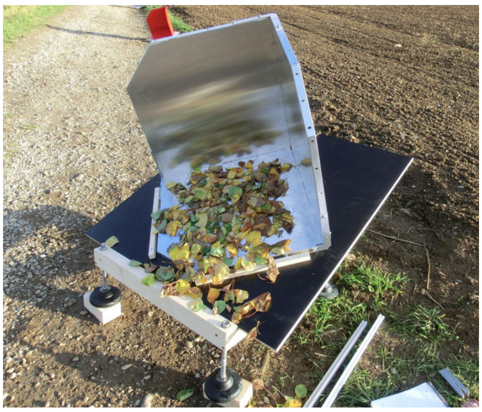

Figure 2.4: Corner reflector filled with leaves

2.7. Tarp

According to Chapplin[1], the dielectric loss caused by water at Ku-band reaches a maximum of around 40% (water at 0°). For this reason, water and snow in a reflector have a high influence on the backscatter intensity and the reflectors often are protected by covering them with tarp. It is assumed that the protection foliage itself doesn't have a big influence on the intensity of the received signal, but has never been proven before. Therefore, the reflector *CRrot* from the rotation experiment 2.3 was covered with a tarp that is normally used by radar experts. The rotation of the reflector has been set to its iniatial position of 0° to get the orientation how normally a reflector is arranged. The measurements were taken with 2, 4, 6 and 8 layers of tarp in order to see how strong the influence of the tarp is.

2.8. Tilt (misalignment)

Aligning a reflector not directly towards the radar causes a loss in the backscatter intensity[5]. Since enough reflectors were available, it was considered to compare the sidewards misalignment to computed models. Therefore reflector *CRt1* was tilted left and *CRt2* was tilted right. The tilting was measured by the displacement in mm of the front of the reflector. The different displacements and the according tilting angles are noted in table 2.2 below.

Table 2.2: Tilt distance of the different measurements and the calculated angles

measurement number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
tilt [mm]	0	10	15	20	25	30	35	40
tilt [°]	0	2.75	4.14	5.52	6.9	8.29	9.69	11.08

The measured losses of backscatter intensity then have been fitted by a second-power polynomial function. Afterwards the fitted curve was compared to the computed losses for a penta-squared corner reflector with a side length of 0.45m (data provision by private communication).

2.9. Symmetrical Deformation with a chord

The reason for this experiment was to see, if a symmetric deformation over the edges has a big influence on the intensity of the backscattered signal. It was a more of a short-term decision during the measurement campaign to conduct this experiment. Therefore, the reflector *CRdef* from the deformation experiment 2.4 was used. To simulate a symmetrical deformation, a chord was mounted on both angled edges of the reflector like in figure A.21 in the appendix.
First, a measurement with the installed chord but without tension was done in order to see if the chord itself already influences the backscatter intensity. After this, a series of measurements were conducted in which the chord has been shortened or extended again to displace the reflector edges towards each other. Shortening the chord was done in steps of 1cm towards a maximum of 4cm. The order of the measurements can be seen in the measurement protocol figure A.2 in the appendix.

2.10. Calculations with MATLAB

The whole experiment has been evaluated with MATLAB R2016b.

There were two main scripts written in MATLAB. The script *deformation_screw.mat* visualizes the difference in deformation of the reflector panel for the deforming experiment with the screw 2.4. Therefore, the measured deformation in horizontal, vertical and diagonal direction were loaded from a .txt-file. Since the length of the reflector side and the tilt are known, the angles were calculated by the following formula 2.2:

$$angle = sin^{-1}\left(\frac{opposite\,leg}{hypotenuse}\right) \tag{2.2}$$

The data from the KAPRI radar were evaluated With the main script *Projektarbeit_main.mat.* For each acquisition the 4 channels HH, HV, VH and VV were saved by the KAPRI radar in a single look complex format (slc) file. In a first step, the positions of the reflectors in the image had to be set. This was done by searching the reflectors in the provided .bmp images. The positions of the center of each reflector can be seen in table 2.3, which were validated with the data later.

Table 2.3: Coordinates of the reflectors in the SLC file

Reflector	Coordinates [range/azimuth]
CRref	177 / 86
CRrot	164 / 194
CRdef	181 / 233
CRt1	187 / 269
CRac	196 / 312
CRt2	206 / 359

Backscatter Intensity The single look complex files were edited with the function *evaluation.mat.* In a first step, the slc data were loaded with the provided function *readbincomplex.mat* by Silvan Leinss[6]. This function reads in the slc files from the KAPRI radar and saves it as matrice with complex values, so that they can be used in MATLAB. Every pixel of the image is given by the complex backscattering coefficient 2.3. This contains target properties, wavelength and propagation effects. $|A|$ is the scatter Amplitude, φ_r the propagation phase and φ_s the object scatter phase. The distance in line of sight between the radar and the object is defined as r.

$$A = |A| * e^{-i\varphi} = |A|exp[-i(\varphi)] \qquad \text{with} \quad \varphi = \varphi_r + \varphi_S \quad and \quad \varphi_r = 2\frac{2\pi}{\lambda}r \tag{2.3}$$

Afterwards, the average backscatter Intensity of each channel is calculated by equation 2.4 and filtered with an low-pass filter from the MATLAB internal function *fspecial* [7]. Therefore, the filter type "*gaussian*" was used with a size of 5x5 pixels and the standard deviation sigma of 0.5.

$$I = \frac{1}{2} \cdot (7|A_i|2 + |A_j|^2) \qquad since \quad A_i = A_j \Rightarrow I = |A_i|^2 \tag{2.4}$$

In order to quantify the backscatter intensity of each reflector, some averaging has been performed. Just in case the reflector center isn't really discernible. The averaging is done over the adjacent pixels, from one pixel in azimuth direction from the reflector center to one pixel in range direction.

Percentage Loss Since the backscatter intensity is expressed in the logarithmic decibel unit, a decrease of 50% in the received backscattering intensity isn't equally to a 50% signal loss. For example, a decrease of 3dB is equal to a signal loss of about 50%. Therefore, a MATLAB-function was written to calculate the percentage loss. Firstly, the backscatter intensity in decibel [dB] is converted to the power in milliwatts [mW] with the following formula 2.5:

$$\begin{aligned} &Backscatter\,intensity: && x = 10 \cdot log_{10}\Big(\frac{P}{1mW}\Big) \quad [db] \\ &Power: && P = 1mW \cdot 10^{\frac{x}{10}} \quad [mW] \end{aligned} \tag{2.5}$$

Then the maximum of the received power during the specific experiment is searched for. With this, the loss of every acquisition is computed, relating to the maximum of the observed experiment sequence like in equation 2.6.

$$loss = 100 \cdot \frac{1-P}{P_{max}} \qquad [\%] \tag{2.6}$$

Interferogram Since a total of 43 acquisitions were taken during the experiment, interferograms can be computed with the following formula 2.7:

$$A_i A_j^* = |A_i A_j^*| exp[-i(2\frac{2\pi}{\lambda}\Delta r + \Delta\varphi)] \tag{2.7}$$

Displacement The line of sight displacement between two acquisitions can be calculated by using the proportionality of the interferometric phase φ_{itf} with formula 2.8.

$$\begin{gathered} \Delta R_{||} = \frac{\lambda}{4\pi} * \varphi_{itf} \qquad with \qquad \varphi_{itf} = 2\frac{2\pi}{\lambda}\Delta r \\ assuming\,stationarity \quad r_1 = r_2,\, \varphi_{S1} = \varphi_{S2},\, \lambda = \frac{c}{f} \\ f:\, frequency\,[Hz] \\ c:\, speed\,of\,light\,[\frac{m}{s} \end{gathered} \tag{2.8}$$

Phase Difference The phase difference between the two co-pol (HH-VV) and the two cross-pol (HV-VH) channels were calculated by multiplying the data of one polarization with the complex-conjugated data from the other polarization. It's like formula 2.7 but instead of another acquisition, one multiplies different polarizations from the same acquisition. Normally, the phase increases in the azimuth direction over an reflector. This so called phase ramp is caused by the rotation of the radar, because the distance of the phase center to the reflector changes [9] This can be seen on the left side in figure A.3 in the appendix. To correct this phase, the slc files were processed by an phase correction script provided by Simone Baffelli[9] from the Chair of Earth Observation and Remote Sensing at ETH Zürich. The correction mainly takes place in the VV polarization. The corrected phases can be seen on the right side of figure A.3. It clearly can be seen, that in the VV polarization, the increase of phase over the reflector is flattened. In a next step, a 3x3 pixel window with the center of the reference reflector *CRref* as a center pixel was averaged over all acquisitions. This lead to a complex value which was used to correct the polarization of the different reflectors in relation to the reference reflector. The polarization of each single reflector for each acquisition then was averaged with the same window size used in the step before. In a last step, the averaged phase of the reference reflector *CRref* was substracted from the mean reflector phase.
To make an assumption if the reflectors of the experiments can be used for calibration, the measurements nr.1 to nr.36 were statistically evaluated. This range was chosen because the results showed some significant changes in in the phase. Therefore the phase distribution of each reflector was visualized by a boxplot that showd the median, the quantiles and also the outliers.

3. Results

3.1. Reference Reflector

Since a lot of parameters have an influence on the radar signal, one has to check first if any shifts or trends are appearing. Therefore, a so called reference reflector which stays untouched during the measurement campaign is needed. The backscatter signal over the whole experiment from *CRref* is showed in figure 3.1. It becomes clear, that the backscattered signal of the co-pol phase is stable during the whole experiment. There is a slight shift visible from acquisition number 36 to 37. According to the measurement protocol A.2 there is a time difference of almost one hour between these 2 acquisitions, where the further measurements have been discussed. Since the backscatter intensity is relatively stable, it was decided that no correction has to be applied to the other reflectors. On the other hand the cross-pol channels show a lot of fluctuations. This result was expected to be like this, since these channels are used for environmental parameters and nor for single (deterministic) targets. However, they can be used to validate the changes in the HV & VH channels in the experiments.

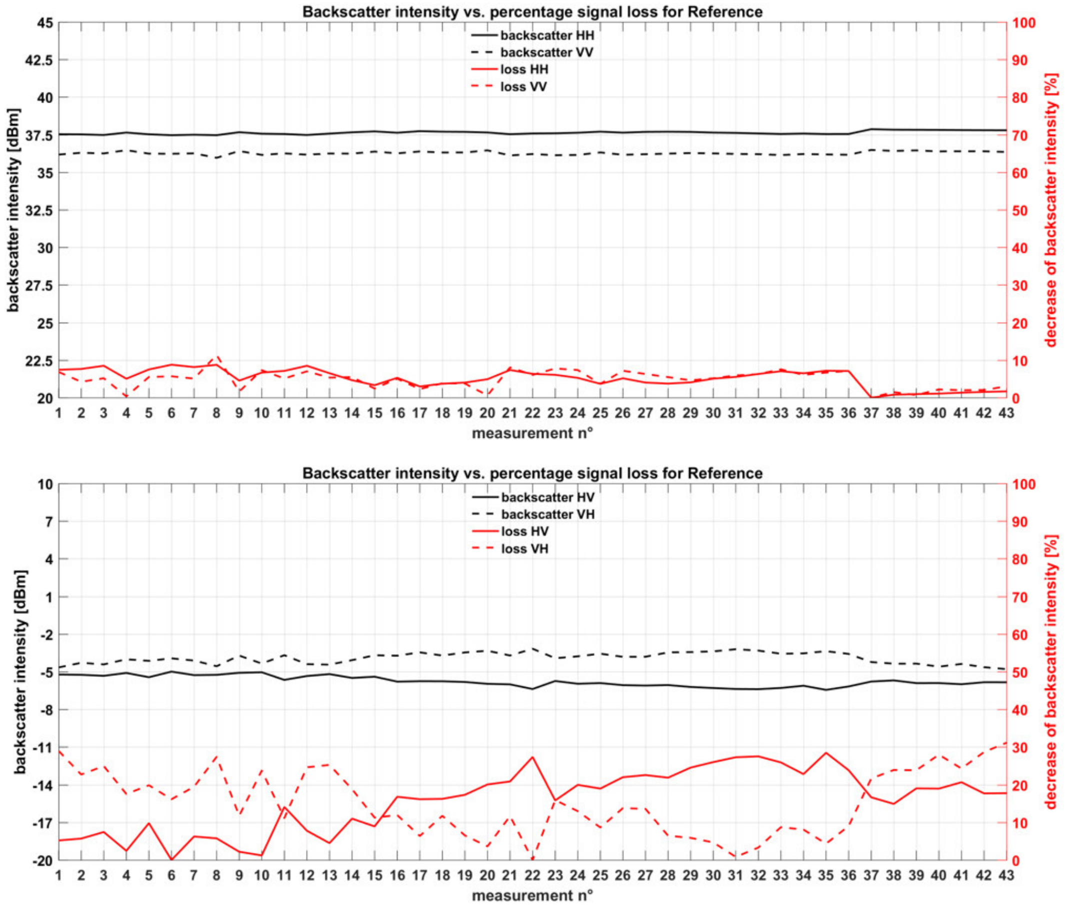

Figure 3.1: Backscatter intensity and percentage loss over the whole measuring campaign with *CRref* for all four channels

3.2. Rotation

The Evaluation of the backscatter intensity of the HH, VV, VH and HV channels for the rotation can be seen in figure 3.2. The co-pol channels have a similar trend and show a slight shift with a maximum at a rotation of 200° and 230°. This could be caused by the mount of the reflector, which was hard to center. So the body diagonal towards the reflector could show a small rotation. The cross-pol channels on the other hand show a very high fluctuation for the rotation. Especially, the HV channel shows an enormous cycle with a maximal signal loss of over 95%. Looking at the VH channel, the maximal loss of about 85% is also very high, but there isn't really a cycle recognizable. At a rotation arounf 50° and 280° the two channels HV & VH show an opposite direction.

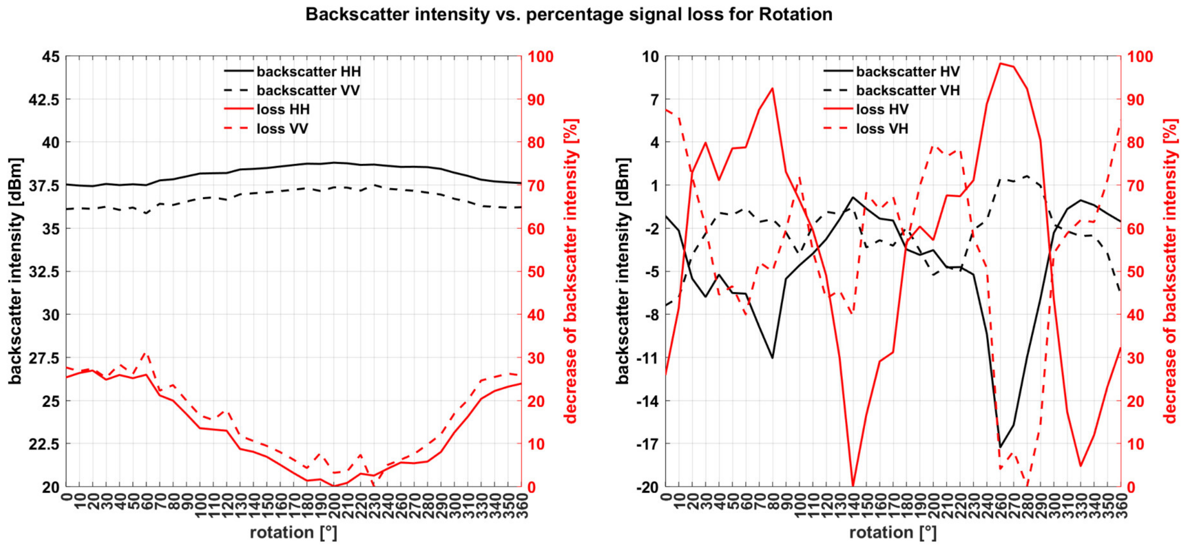

Figure 3.2: Backscatter intensity and percentage loss during rotating the reflector around its body diagonal.

3.3. Deformation

Deforming the center of one reflector side lead to the problem, that the whole side deformed uniformly. The uneven horizontal, vertical and diagonal displacement of the reflector side can be seen in figure 3.3. The deformations are shown in relation to the center displacement with the screw (x-axis). One can observe, that the reflector bends uneven witch a constant increase of the screw depth and it depends also on whether the screw direction is inwards or outwards. Additionally, it was attempt to visualize the bending of the reflector in 3-D. Figure A.4 in the appendix is the whole reflector side at a maximal deformation of the side plate center of 18 mm. The missing values have therefore been interpolated.

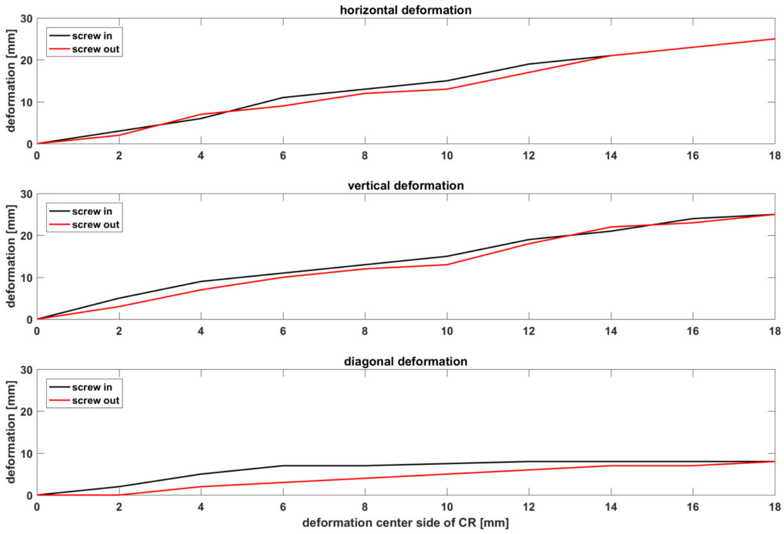

Figure 3.3: Actual deformation of the reflector side plate by push it in and out in the center of the side with a screw

Figure 3.4 shows the change of the backscatter intensity for HH and VV. The x-axis shows the plate deformation with the screw. It becomes clear that deforming the reflector has a huge influence on the intensity of the received signal. Both polarizations, HH and VV show more or less the same development in loss. The maximum loss of backscatter intensity is about 9.5 dB which is a percentage loss of about 90%. Although the whole reflector deformation is different, depending on the screw direction, the plot looks very symmetrical. Screwing out (going from maximal deformation to the initial state) shows a very linear increase of the backscatter intensity. This correlates with the more linear progression of the red line in figure 3.3.

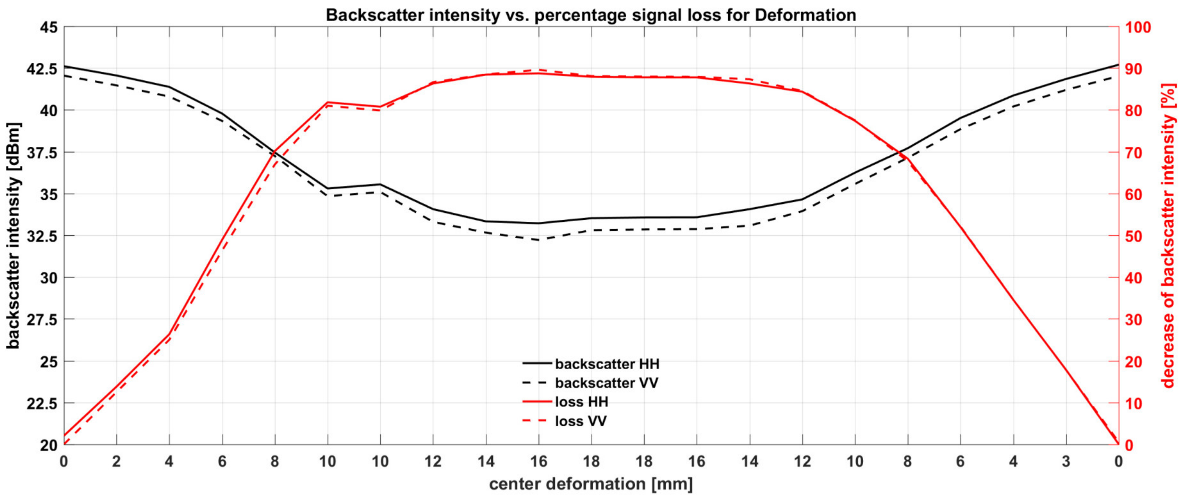

Figure 3.4: Backscatter intensity and percentage loss for HH & VV while deforming the center of one side of the reflector by pressing it in with a screw

Taking a look at the HV and VH channels in the left plot of figure A.5 in the appendix shows a very big difference between them. The curve in backscatter intensity of the VH channel shows nearly the identical progression like the one of the VV or HH channel in 3.4, but with other values. The loss in all three of them is almost the same (around 9.5 dB). The origin of this could be due to the electronics of the radar. It is possible, that some cross-talk between the channel is occurred.

3.4. Aluminum chipping

Figure 3.5 shows the backscatter intensity for channels HH & VV. Unlike in the experiments before, here it makes a difference if you look at the HH or VV channel. Although, the trend is the same with increasing the amount of aluminum clippings. There is a big difference in the total signal loss between the two channels. The VV channel shows a bigger loss of backscatter intensity of around 96% at the last two acquisitions, compared to a loss of 75% in the HH channel. Covering the reflector base with paste is causing a decrease in signal of about 18% in the VV channel in contrast of just a few percent in the HH channel.

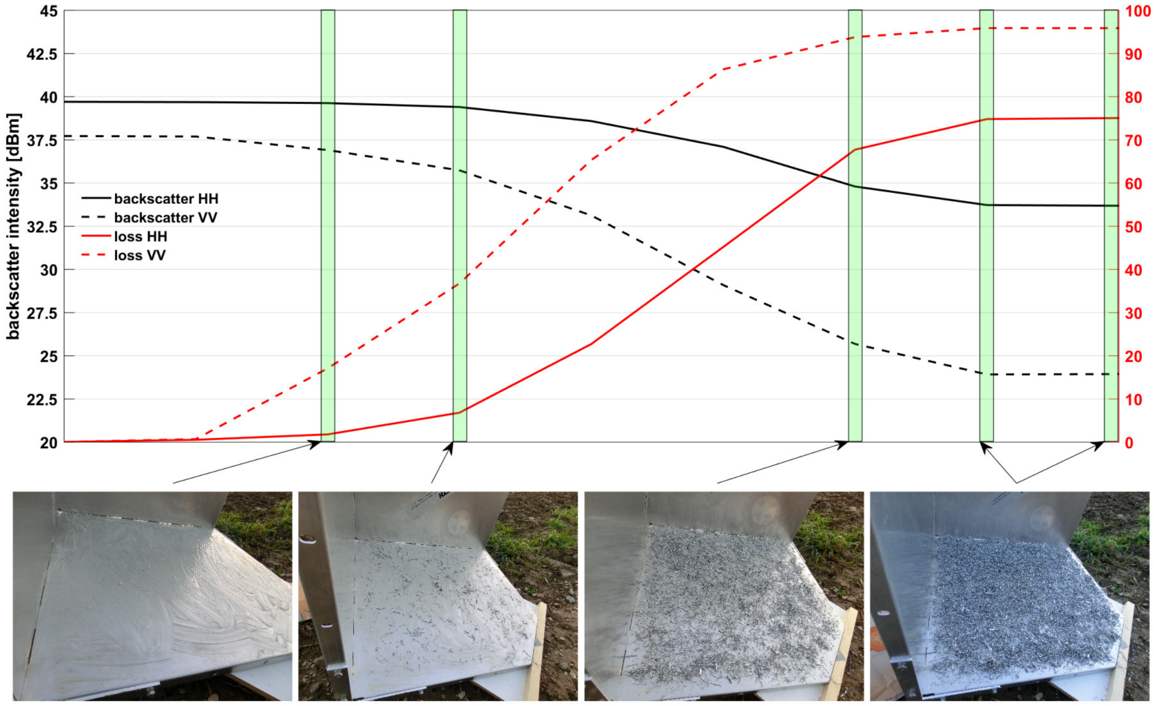

Figure 3.5: Backscatter intensity and percentage loss in HH & VV for covering the ground plate of the reflector with paste (1st picture) and adding aluminum chipping

Concerning the difference in loss between HH and VV, it's also recommended to take a look at the HV and VH channel. This is visualized in figure 3.6. The two channels show a slight difference the intensity, but a similar trend can be observed. Interesting is the fact, the backscattered signal increases by adding some aluminum chipping and dropping again for filling the whole base with chipping. Also the loss is more or less the same, whether the reflector is at is initial conditions or full of clippings.

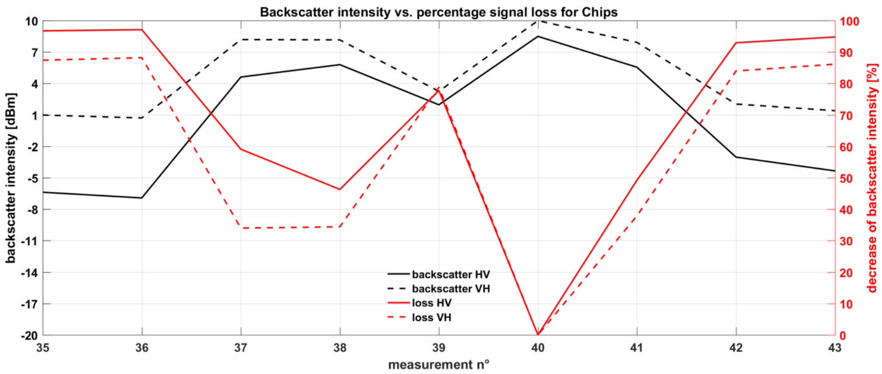

Figure 3.6: Backscatter intensity and percentage loss in HV & VH for covering the reflector base with paste and adding aluminum chipping

3.5. Leaves

For this experiment it's also interesting to look at all the channels. Figure 3.7 below show that biomass has an influence on the backscatter intensity. The diagram shows the biggest loss with about 8 dB in the HH channel. Both HH and VV show a similar progression as well as the HV and VH channel. More leaves result in a bigger loss in HH and VV where less leaves result in a bigger loss for VH and HV. However, the difference in maximum loss within the co-polarized channels and the cross-polarized ones are in the same magnitude.

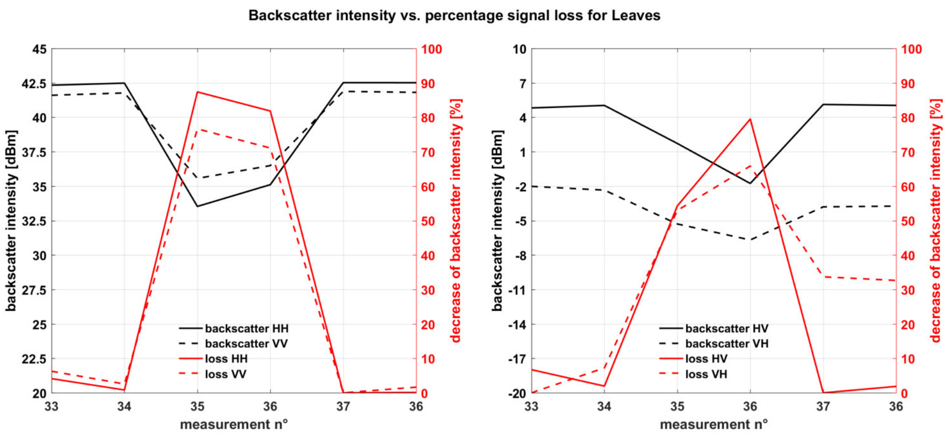

Figure 3.7: Backscattered intensity and percentage loss when leaves are in the reflector. At measurement nr.3, the reflector ground plate was filled with leaves and for the 4. measurement, some leaves were blown out because of the wind.

3.6. Tarp

Covering the reflector with different numbers of layers influences the backscatter intensity slightly. In figure 3.8 the effect can be seen. The 1st measurement already is with 2 layers of tarp. Comparing it to the 5th one, it becomes clear that this has no influence on the backscatter intensity, since the percentage loss is in both 0%. Measurement number 2, 3 and 4 are with 4, 6 and 8 layers of protection foliage. Here the percentage loss shows a linear increase with a maximum signal loss of about 25%. The cross-polarized channels are shown in figure A.6. The loss during the measurement is big, but mainly random. Compared to the results form the reference reflector 3.1 the trend is similar.

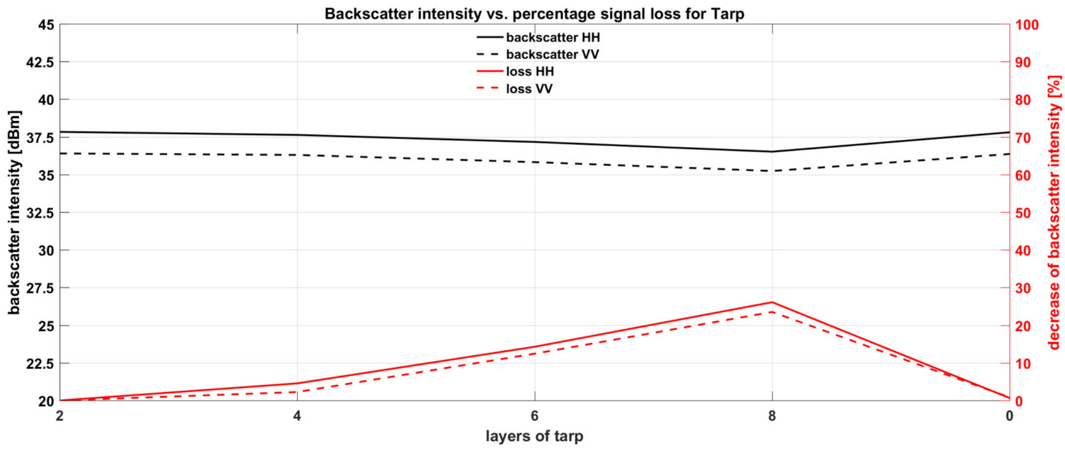

Figure 3.8: Backscatter intensity and percentage loss in HH & VV by covering the reflector with tarp.

3.7. Tilt (misalignment)

Tilting the reflector to one side causes a decrease in the backscatter intensity for both sides. The plots for tilting the reflector to the right side A.7 and left side A.8 can be seen in the appendix. The first measurement refers to the measurement with no tilt. According to the measurement protocol A.2 , one has to keep in mind, that this first measurement was taken 50 minutes before the first tilting measurement. This can be the cause of the decrease of loss in the co-pol channels in figure A.7 between the first two measurements. Another reason could be that the reflector wasn't aligned perfectly and with the first tilt the alignment was getting better. Between the 6th and 7th measurement both tilting experiments show a constant or decreasing loss in the HH channel. This was caused by the fact that the two reflectors had to be rearranged, because no further tilting was possible due to the placement of the reflector on the ground and therefore, the reflectors ha to be rearranged. The cross-pol channels both show an opposite trend depending on the tilting direction. The comparison between the loss in backscatter intensity of measured misalignment and the computed misalignment can be seen in figure 3.9. The black line indicates the second-power polynomial fit to the measured data (illustrated by blue dots). The simple fit meshes really good with the calculated losses.

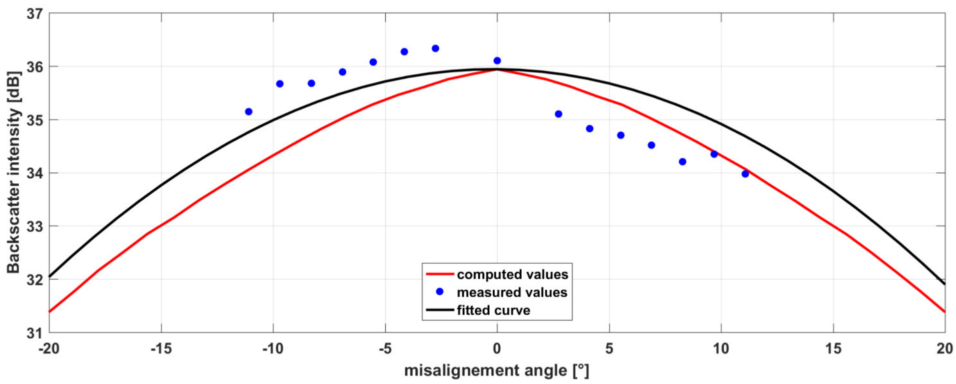

Figure 3.9: Comparison of measured versus computed loss of backscatter intensity in decibel caused by misalignment

3.8. Symmetrical deformation with a chord

The symmetrical deformation with a chord doesn't show a lot of differences in the backscattered signal for the HH & VV channel. Figure 3.10 shows a very similar , relatively straight development of the backscatter intensity. The maximal signal loss adds up to around 10% which is similar to the reference reflector. Table 3.1 gives a better overview of the independence of signal loss according to the symmetrical deformation. Taking a look at the cross-pol channels in figure A.9 shows a decrease of the percentage loss. This again is similar to the reference reflector.

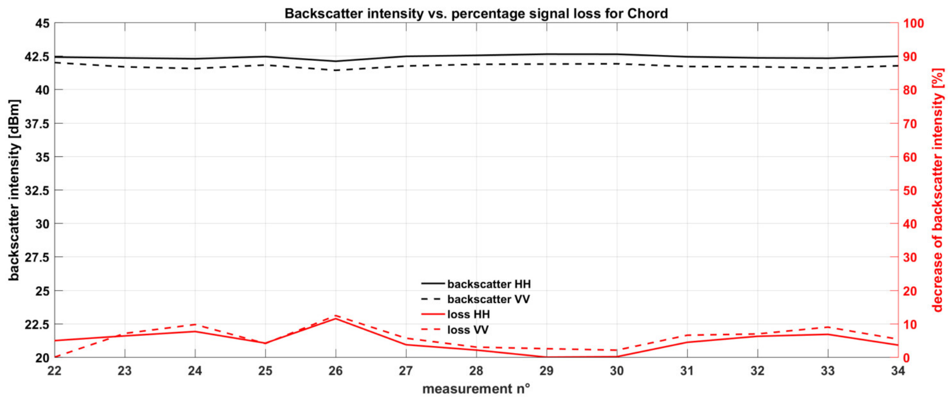

Figure 3.10: Backscatter intensity and percentage loss of the co-pol channels while deforming the reflector symmetrically over the edges with a cord

Table 3.1: Overview of the symmetrical deformation with the chord and the associated percentage losses in HH and VV

measurement nr.	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**
deformation chord [cm]	0	2	3	4	4	3	2	1	0	0	3	0	0
loss HH	5	6.4	7.7	4.2	11.5	37	2.1	0	0.1	4.4	6.2	6.8	3.6
loss VV	0	7.1	9.8	4.1	12.4	5.7	3	2.5	2.1	6.6	7	9	5.4

3.9. Polarization

Figure 3.11 shows the averaged phases difference for the HH and VV polarizations over each reflector for every acquisition. The phase difference of the reference reflector *CRref* shows a nearly straight line around a phase angle of 0°. The left tilted reflector *CRt2* contained a measuring error at the 25th acquisition and was removed in the plot. The phases of the different reflectors features a slightly different angle, but also are more or less straight except for *CRac* and *CRt1*. *CRac* shows an increasing phase during the experiment with the aluminum chipping 3.4 of around 55°. Furthermore the right tilted reflector *CRt1* also shows an increase in phase from measurement nr. 36 to nr. 37, but stays more or less the same for the subsequent acquisitions. Reflector *CRdef* from the deformation experiment (measurement nr.1 to 21) shows a slight change of the phase difference in order of under 5°.

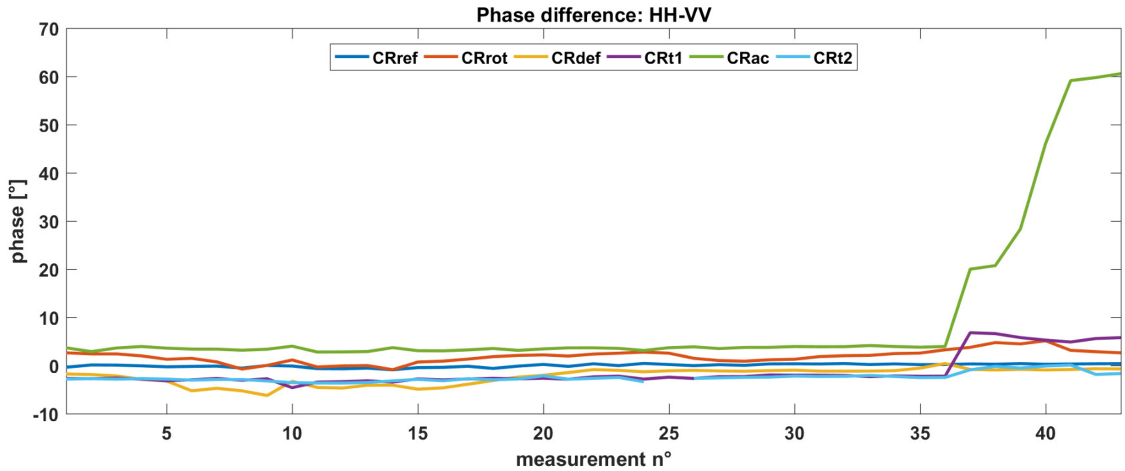

Figure 3.11: Averaged phase over each reflector for the corrected data.

Figure A.11 in the appendix shows the phase distribution of each reflector from measurement nr.1 to nr.36. The dashed red lines indicates the phase of -5° and 5°. In between these lines lays the accepted phase difference for reference reflectors to be used for calibration (Source: private communication). All the reflectors lie in the accepted range. The highest

3.10. Displacement

The result of the measured displacement in millimeters are visualized in figure 3.3. The measurement at the 25th acquisition has been removed due to an measurement error. Over the whole experiment, the displacements remain in a small range. Most of the time, nearly no displacement can be measured. The deformation experiment caused a displacement of at most 1.5 mm towards the radar. The biggest displacement was caused by the tilting the right tilted reflector *CRt1* of 9,5mm away from the radar. Reflector *CRt2* first shows a displacement towards radar, but afterwards also an movement in the opposite direction. Another visible displacement happened at the experiment with the aluminum chipping. Here, the reflector seems to move towards the radar, but the displacement in the HH channel (max 2.4mm) is more as twice of the measured displacement with the VV channel (max 1mm).

4. Discussion

Rotation Installing a corner reflector at any rotation angle doesn't influence the backscatter intensity very much, as long as the body diagonal of the reflector is pointing directly towards the radar. The shift that is visible in figure 3.2 which adds up to a maximum loss of 25% in intensity is likely to be caused by a wobble of the reflector body diagonal like described in section 3.2 above. The reason of this wobbling effect is assumed to be the not precisely centering of the steel ring onto the reflector mounting plates. This results in an small rotation of the body diagonal. The co-polarized phase-difference in figure 3.11 doesn't show a big difference over the rotation experiment. The cross-polarized phase on the other hand shows an extreme influence on the backscatter intensity. Especially the HV channel shows kind of a cycle where the intensity in- and decreases. The peaks are located around 180° away from each other. Compared to the reference reflector, the cross-polarized phases there doesn't show the cycle (right figure 3.2). This leads to the assumption that the rotation has an influence on the backscatter intensity in the HV channel and also in the VH channel. However, these channels aren't used for calibrating, for example displacement measurements.

Deformation The effect of deforming a reflector panel was way bigger than expected. Figure 3.4 shows, that an actual small deformation of just 2mm already causes a loss in backscatter intensity of about 15%. In reality, this can be caused for example by a rock hitting the side plane of the reflector. The fact, that the curve shows a relatively symmetrical progression, even of the unsymmetrical horizontal, vertical and diagonal deformation, is pleasing. The signal loss at a maximal deformation of 18 mm causes an extreme loss of backscatter intensity of about 90%. It seems, that the signal loss doesn't increase a lot after a deformation of 14mm. So the deformation in dimensions between 14mm and 18mm stays more or less the same. The two co-pol channels both show a very similar dependence on deformation. This leads to the assumption, that the reflector planes had to be very flat and even and should be checked from time to time if they are installed in regions where rockfalls are possible.

Interesting are the cross-pol channels. Figure A.5 shows, a very similar progression of the loss of the VH channel like the co-polarized ones. As already mentioned, this can be caused by a cross-talk in the electronics of the radar system, since the HV channel also shows kind of a decrease but not as symmetrical as the VH channel.

Aluminum chipping Adding aluminum chipping caused a big effect on backscatter intensity. First of all, just covering the reflectors ground plate with paste already shows an influence on the backscatter intensity. This isn't surprising by taking into account, that the paste consists mainly of water. Like described in Section 2.7, according to [1], the dielectric loss caused by water is high, especially at the operation frequency of the radar. Besides, it can be seen that water mainly influences the vertical polarized signal which can be described by the interaction of the vertical oriented waves with water. Adding just a few chipping already caused a measurable decrease in backscatter intensity of about 5% in HH and 20% in VV if the loss of water is neglected. By adding more chipping, the received intensity logically decreases. Filling the whole ground plate of the reflector with chipping and neglecting the proportion of paste ends up with a loss of around 75%. It seems like the curve of percentage loss tends to converge to a limit. The assumption is, that because of the random orientation of the chipping, still some signals are reflected to the other panels, or are backscattered directly.

Leaves The occurrence of leaves or biomass in a reflector is a problem that should not be underestimated. Especially at measurements in fall, the leaves can lead to a problem when they fall off trees and be blown into the reflector. It is also observed, that corner reflectors some times are a preference resting place for birds. The right plot of Figure 3.7 in the appendix showa a big loss of backscatter intensity. One has to consider, that the amount of leaves in the experiment is relatively big, but it is assumed that also a "normal" amount of leaves causes a significant backscatter intensity loss. This thought is based on the not so big decrease between measurement nr.35 and nr.36, where some leaves were blown out of the reflector.

Tarp The popular solution to protect corner reflectors from water or snow by covering them with tarp doesn't have that big of an influence on the backscatter intensity. Normally, the coverage is just with one or maximal two layers of protection foil. Figure 3.8 shows that the tarp becomes an issue, if there are six or more layers used. Additionally, there is no influence on the polarization visible. This are good news and encourage to continue this protection method.

Tilt (misalignment) The validation of the decrease in backscatter intensity due to a misalignment of the reflector away from the line of sight direction towards the radar, showed the expected reaction. The comparison between the computed curve and the fit through the measured values in figure 3.9, show that the curves follow a similar progression. Since the fit function is just in order of a second-power polynomial, it was expectable that the fitted curve won't overlay correctly with the computed curve. Additionally, the maximum misalignment in the experiment was just 11°, and may show a steeper decrease towards bigger misalignment angles. A full turn with one reflector from -45° to +45° from the line of sight towards the radar would probably result in a better fit.
Taking a look at the co-polarized phase difference in figure 3.11 shows a jump between the first and second measurement of the right tilted reflector. The time step between measurement nr.36 and nr.37 is almost an hour and could also be seen in the backscatter intensity in the left side of figure A.7 in the appendix. Since the phase-difference after these measurements is more or less stable, the reflector may have experienced a small movement.

Symmetrical deformation with a chord Deforming the reflector symmetrically with a chord led to a relatively small maximal signal loss of 10%. A recent study showed the dependency on orthogonality errors on the backscatter intensity [8]. Therefore, it was expected that moving the reflector edges towards each other has a bigger influence on the backscatter loss. The study just provides results for an orthogonality error for all 3 panels together, but not if just 2 panels weren't perpendicular. One possibility is, that a "small" symmetrical deformation of the reflector panels

really doesn't have a big influence on the backscatter intensity and the deformation is compensated. Through the symmetry of the reflector, it is possible, that the signal still is reflected onto another reflector side and back to the radar. Another possibility is, that the measured chord length doesn't transmit the same distance to the reflector edges. Measuring the actual change in distance between the two reflector side edges, could have given an answer to this uncertainty. Unfortunately, this wasn't done, since conducting this experiment was a short-term decision.
Interesting to know would be, what happened if the deformation was in the opposite direction or the deformation was bigger.

Polarization Figure A.13 shows, that the phase difference φ_{HH} - φ_{VV} isn't influenced by deformation, rotation, misalignment, tarp, or leaves. The only experiment that changes the phase, was the one with the aluminum chipping. It was expected that the chipping would change the polarization of the wave because of the spiral form of the clips. Normally a trihedral reflector doesn't change the polarization based on the principle how the radiations are reflected inside a reflector but with the aluminum chipping, the reflectance principle is changed. Taking in account, that the spirals were randomly oriented, it gets unknown how many times the signal gets reflected inside the reflector itself.

Comparing the mean phase change over the first 36 acquisitions in figure A.11), corrected in respect to the mean phase change of the reference reflector shows, that the different reflectors lie within an acceptable phase difference relating to the reference reflector. Thus, all the reflectors could be used as calibration reflectors in polarimetry.

4.1. Conclusion and Outlook

A wrong orientation of the reflector in meaning of rotation doesn't deteriorate the backscatter intensity, as long as the body diagonal is oriented towards the radar. An exact alignment in line of sight is lot more important!

The presence of spiral aluminum chipping has a big influence on the backscatter intensity as well as on the polarization. Therefore, it's important to keep the reflector panels clean. Also the paste had a influence on both (more in the polarization). Since the paste has a very high water content and reduces the backscatter intensity (especially in VV), it is highly recommended to cover the reflectors. This should avoid rain or snow to accumulate in the reflector and the experiment with the tarp showed, that one or two layers of protection foil doesn't change the backscatter signal a lot. An open question still is, if the choice of different kinds of protective foliage could influence the backscatter intensity. With the coverage one also avoids leaves or biomass in general to get into the reflector.

The last conclusion is, that for polarimetric measurements, it doesn't matter how bad the reflectors are aligned (at least for azimuth angles up to 11°) or rotated about its body diagonal for polarization measurements. All phase differences lie in an acceptable range to be used as calibration reflectors.

The outlook contains some thoughts about what would e interested in further experiments. Since the symmetrical deformation experiment didn't have the expected outcome, it would be interesting to know if larger deformations of the reflector edges also don't have a big influence. If this case occurs, further calculations have to be done to validate, that a symmetrical inwards deformation of two edges compensates itself. Also a deformation in the opposite direction would be interesting. This could also be said about the deformation experiment with a screw, if the direction of the center displacement is inverted.

Another open question is, what happens if the inner side of the reflector panel is scratched. For example, this case could occur at reflectors that are installed in an arid area, where sand is transported by wind and roughens the reflector panels. This leads to the next question, what would happen, if sand is accumulating in the reflector. It is clear that this would lower the backscatter intensity, but by how much. And also if and how the polarization is depending on the grain size.

Since even little aluminum chips had an influence on the backscattered signal, as well as on the polarization, the influence of bigger objects like screws or screw heads should be measured. Further the influence of rivets will be interesting, especially because this could be a simple and light way to mount reflectors or add stabilization plates. As one can see, all these these suggestions are important for developing new reflectors. Another interesting measurement for designing reflectors would be the influence of a cross beam over the reflector edges, in order to get more stabilization.

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A. Appendix

A.1. Measuring Campaign

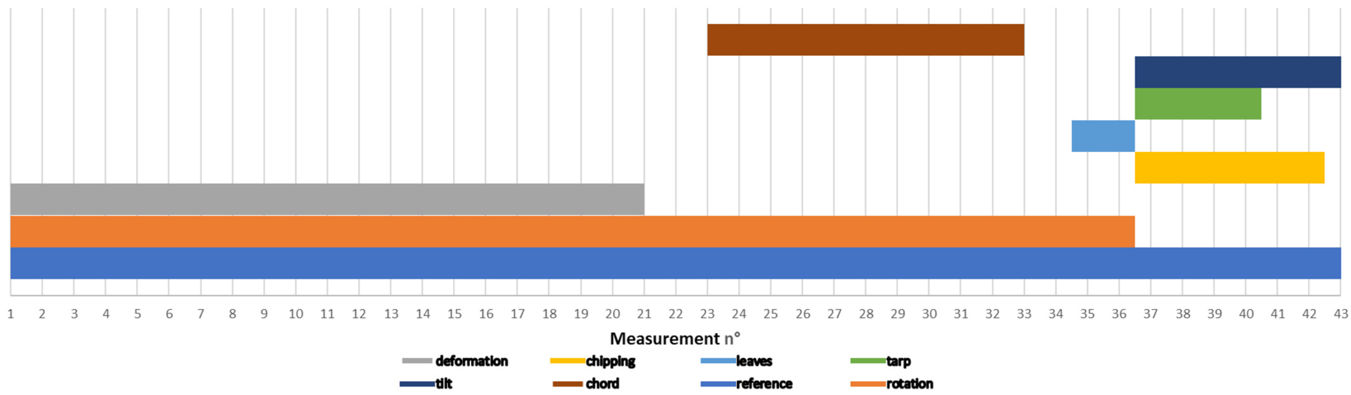

Figure A.1: Overview of the measurement campaign

		CRref	CRrot	CRdef					CRt1	CRac	CRt2
date	time		rotation [°]	deformation screw	deformation horizontal [mm]	deformation vertical [mm]	deformation diagonal [mm]	comments			
30.10.2017	14:23:59	Reference Reflector	0	0	0	0	0		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	14:26:42	Reference Reflector	10	2	3	5	2		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	14:29:21	Reference Reflector	20	4	6	9	5		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	14:31:57	Reference Reflector	30	6	11	11	7		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	14:35:01	Reference Reflector	40	8	13	13	7	forgot arc change	Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	14:36:47	Reference Reflector	40	10	15	15	7.5		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	14:39:46	Reference Reflector	50	10	15	15	7.5		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	14:42:20	Reference Reflector	60	12	19	19	8		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	14:45:09	Reference Reflector	70	14	21	21	8		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	14:48:00	Reference Reflector	80	16	23	24	8		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:50:28	Reference Reflector	90	18	25	25	8	from here screw back	Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	14:51:59	Reference Reflector	100	18	25	25	8		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	14:54:48	Reference Reflector	110	16	23	23	7		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	14:57:25	Reference Reflector	120	14	21	22	7		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	14:59:42	Reference Reflector	130	12	17	18	6		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:02:55	Reference Reflector	140	10	13	13	5		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:05:30	Reference Reflector	150	8	12	12	4		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:08:50	Reference Reflector	160	6	9	10	3		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:11:21	Reference Reflector	170	4	7	7	2		Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:13:40	Reference Reflector	180	2	2	3	0	deformation inwards 2 mm	Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:16:58	Reference Reflector	190	0	0	0	0	deformation inwards 3 mm	Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:18:52	Reference Reflector	200	0	0	0	0	deformation inwards 3 mm	Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:22:04	Reference Reflector	210	installation cord 0 cm				no tension	Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	14:24:21	Reference Reflector	220	cord 2 cm					Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:27:53	Reference Reflector	230	cord 3 cm					Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:30:16	Reference Reflector	240	cord 4 cm					Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:32:54	Reference Reflector	250	cord 5 cm					Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:35:27	Reference Reflector	260	cord 4 cm				relaxing	Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:38:03	Reference Reflector	270	cord 3 cm				relaxing	Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:40:28	Reference Reflector	280	cord 2 cm				relaxing	Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:44:47	Reference Reflector	290	cord 1 cm				relaxing	Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:46:29	Reference Reflector	300	cord relaxed (0 cm)					Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:48:27	Reference Reflector	310	cord relaxed (0 cm)					Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:49:00	Reference Reflector	320	cord 3 cm					Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:51:25	Reference Reflector	330	cord relaxed (0 cm)					Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:53:13	Reference Reflector	340	without cord					Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:55:41	Reference Reflector	350	leaves -> Photo					Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	15:57:05	Reference Reflector	360	leaves					Reference Reflector	Reference Reflecor	Reference Reflector
30.10.2017	16:50:57	Reference Reflector	2 layer protevtive foil	Reference Reflector					10 mm right	thin film of paiste	10 mm left
30.10.2017	16:55:46	Reference Reflector	4 layer protective foil	Reference Reflector					15 mm right	aluminium chippings	15 mm left
30.10.2017	17:02:34	Reference Reflector	6 layer protective foil	Reference Reflector					20 mm right	few aluminium chippings	20 mm left
30.10.2017	17:07:25	Reference Reflector	8 layer protective foil	Reference Reflector					25 mm right	medium aluminium chippings	25 mm left
30.10.2017	17:11:37	Reference Reflector	10° Rotation	Reference Reflector					30 mm right	a lot aluminium chippings	30 mm left
30.10.2017	17:16:41	Reference Reflector	20° Rotation	Reference Reflector					35 mm right	all aluminium chippings	35 mm left
30.10.2017	17:20:07	Reference Reflector	30° Rotation	Reference Reflector					40 mm right	all aluminium chippings	40 mm left
30.10.2017	**ab 17:21**						**Interferrence**				

Figure A.2: Measurement Protocol. The gray textured row wasn't measured, the orange line indicates the acquisition, where *CRt2* had an error and the orange row with texture included also an measurement error of the radar

A.2. MATLAB

A.2.1. Matlab Scripts

Main MATALB script

Name: Projektarbeit_main.m

Information: All calculations that were conducted to evaluate the data

Visualizing Deformation

Name: deformation_screw.m

Information: Visualizes the uneven deformation of the reflector panel caused by deform it with a screw.

A.2.2. Matlab Functions

Dataprocessing

Name: evaluation.m

Information: Loads the data and processes them

Manual: This function loads the .slc files from the repository and converts them into a format that can be used by MATLAB. This function takes as an input the the size in azimuth and range, as well as the coordinates of the reflectors.

Call up: Projektarbeit_main.m

Calculating interferometric coherence

Name: coherence.m

Information: Computes the interferometric coherence between two SLCs

Manual: This function takes as an input two SLC images and the averaging window. The averaging window contains the size of the rectangular window that is used for averaging (in the form [x,y]).

Call up: Projektarbeit_main.m

Calculating the backscatter power and the percentage loss of intensity

Name: dbm_convert.m

Information: This function computes the power of the backscatter signal and also the percentage loss of the backscatter intensity relative to the highest backscatter intensity of this section.

Manual: This function takes as an input a matrix with the backscatter intensities.

Call up: backscatter_master.m
bs_chipping.m

Plot of backscatter intensities and percentage loss

Name: backscatter_master.m

Information: Generates plots with the backscatter intensity and the percentage loss relating to the maximum intensity for the different experiments.

Manual: This function required no input. If the function is called, a window opens where one of the experiments can be chosen (deformation, rotation, leaves, aluminum chipping, tarp, tilt, chord or just the reference reflector). After that a new window opens where you can choose between different polarizations like HH & VV, HV & VH or HH,VV & HV,VH.

Call up: Projektarbeit_main.m

Visualize the displacements

Name: displacement_plot.m

Information: This function visualizes the displacement in all four channels

Manual: This function takes as an input a matrix with the displacements and the names of the corner reflectors.

Call up: Projektarbeit_main.m

Dialog to choose experiment

Name: choosedialog_reflector.m

Information: Generates the window on which the different experiments are listed and one can be chosen.

Manual: This function requires no input

Call up: backscatter_master.m

Dialog to choose polarization

Name: choosedialog_polarisation.m

Information: Generates the window on which the different polarizations (HH & VV, HV & VH or HH, VV & HV, VH) can be chosen

Manual: This function requires no input

Call up: backscatter_master.m

Plot of backscatter intensities and percentage loss for aluminum chipping

Name: bs_chipping.m

Information: Generates plots with the backscatter intensity and the percentage loss relating to the maximum intensity for the experiment with aluminum chipping including some images.

Manual: This function has to be called with the struct of backscatter intensities.

Call up: Projektarbeit_main.m

Visualize backscatter intensity over all acquisitions

Name: bscat_loss.m

Information: Creates a plot of each channel showing the backscatter intensity over all acquisitions.

Manual: This function has to be called with the struct, containing the backscatter intensities for all acquisitions measured with all channels and the reflector names.

Call up: Projektarbeit_main.m

Create RGB image

Name: RGB.m

Information: Creates a RGB-image of an acquisition.

Description: This function has to be called with the SLC and a number. A single number shows the RGB of this acquisition while 0 shows an animation over all acquisitions.

Call up: Projektarbeit_main.m

A.2.3. MATLAB Figures

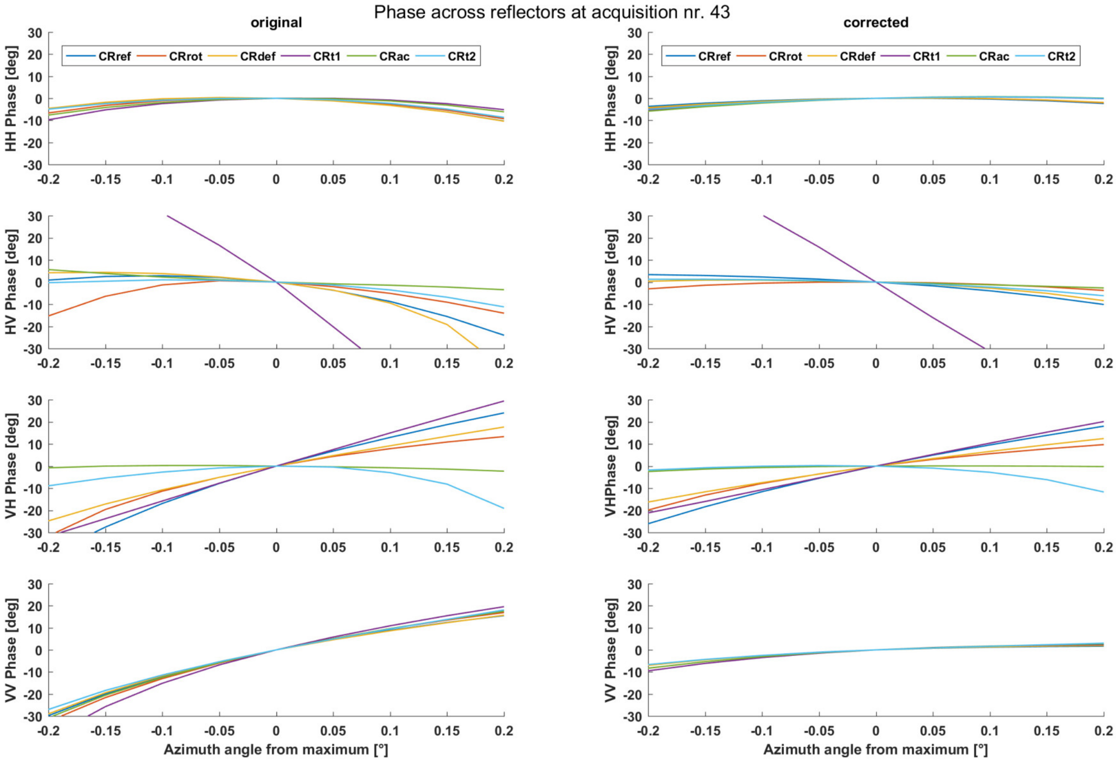

Figure A.3: Azimuth phase correction over reflector according to [9]

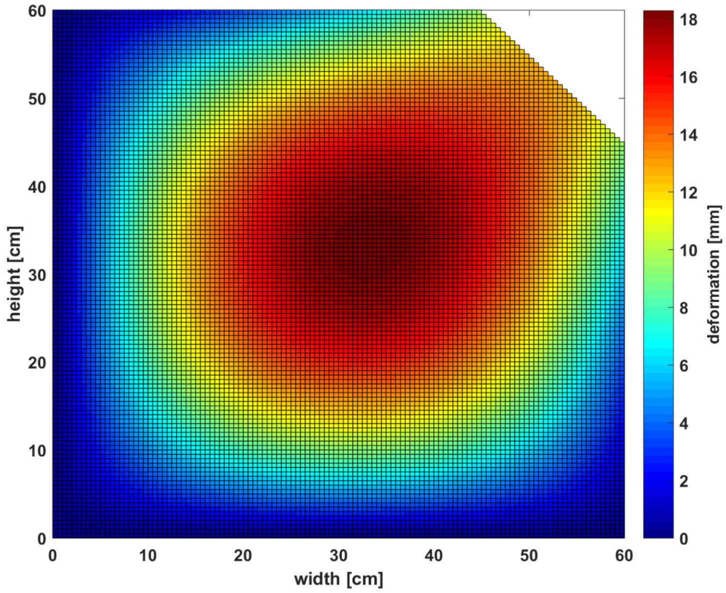

Figure A.4: Visualizing the deformation of the reflector side at maximal deformation with interpolated values

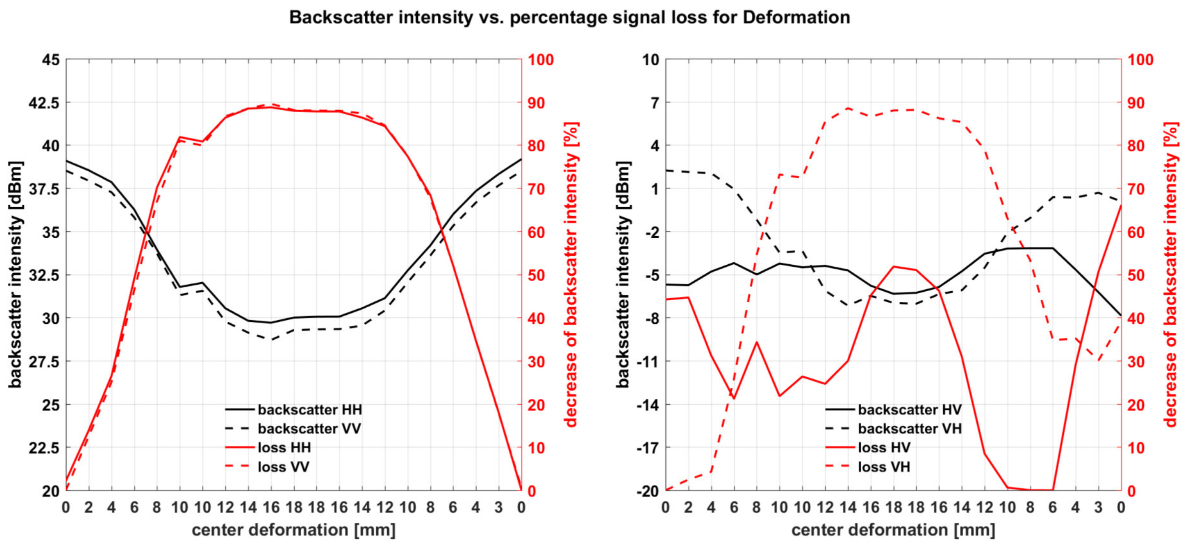

Figure A.5: Backscatter intensity and percentage loss of the deformation experiment

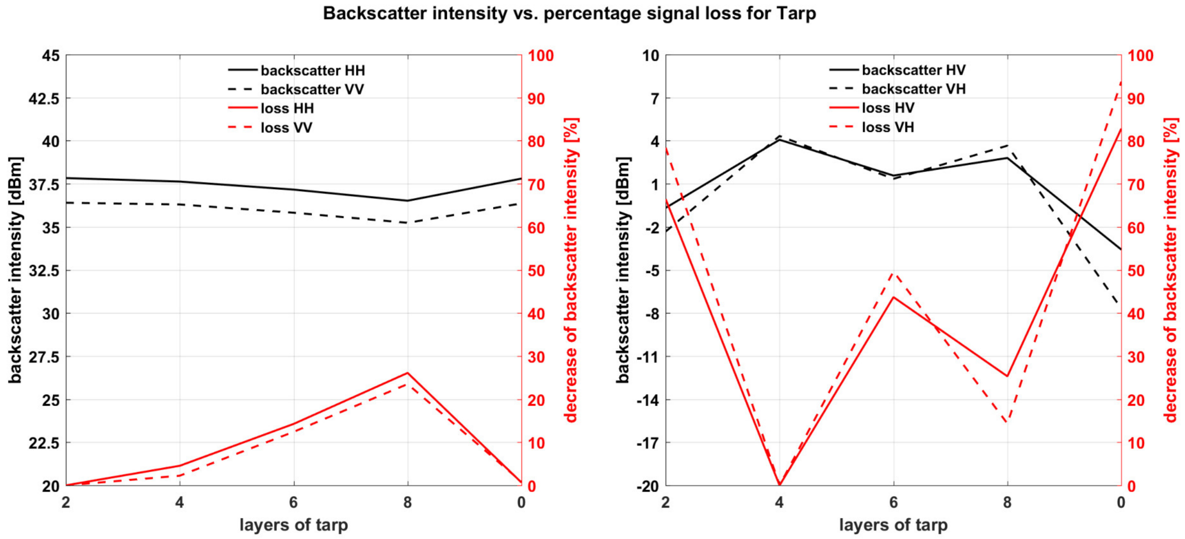

Figure A.6: Backscatter intensity and percentage loss for covering the reflector with 2, 4, 6 and 8 layers of tarp. Measurement n° already is with 2 layer of protective foliage

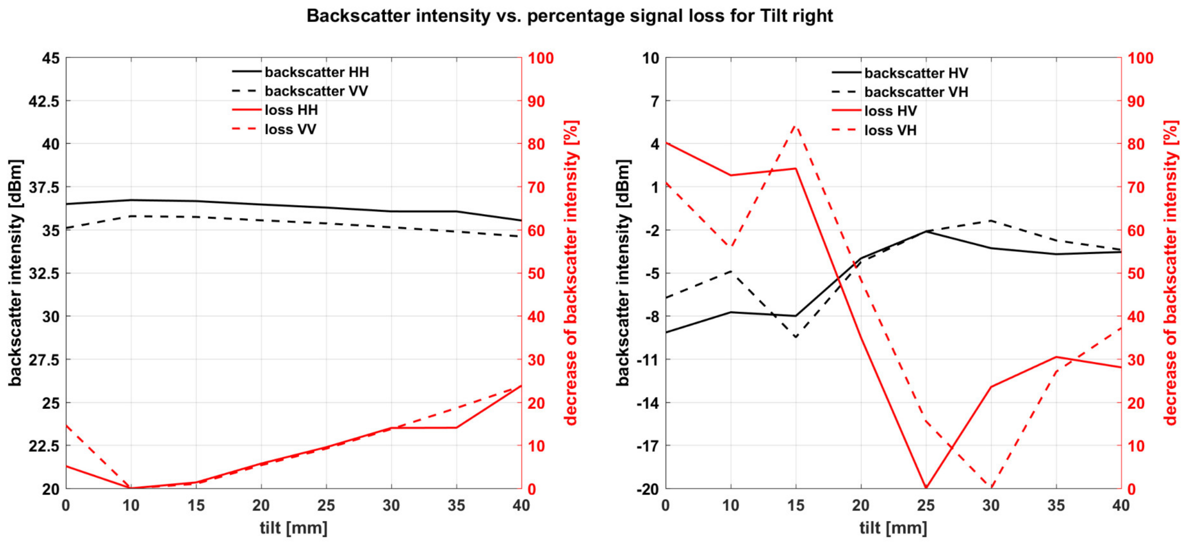

Figure A.7: Backscattered intensity and percentage loss for tilting the reflector to the right side. The first measurement was without any tilt.

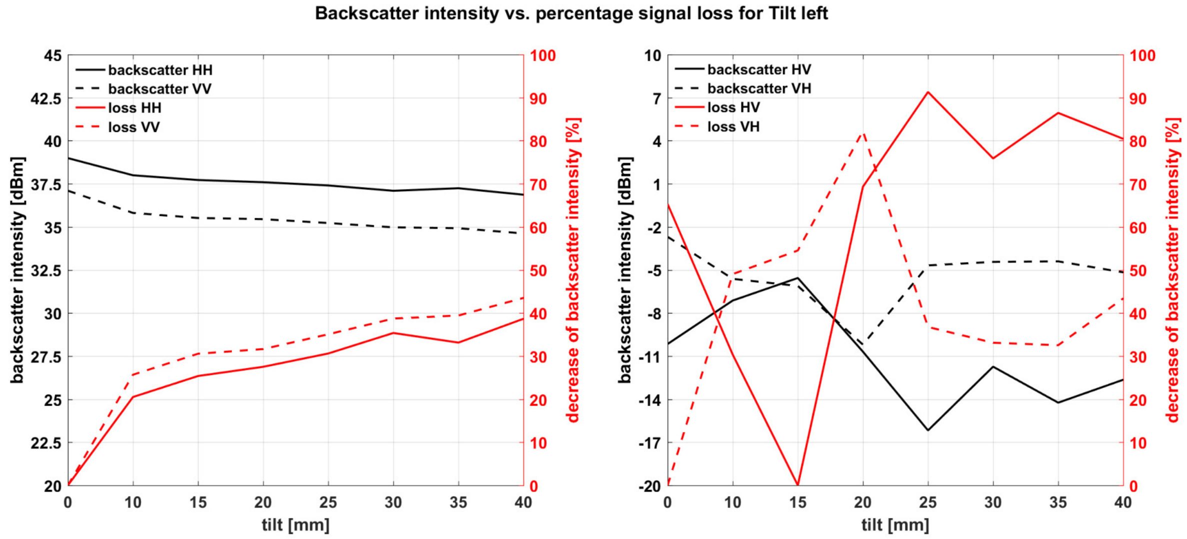

Figure A.8: Backscatter intensity and percentage loss for tilting the reflector on the left side. The first measurement was without any tilt.

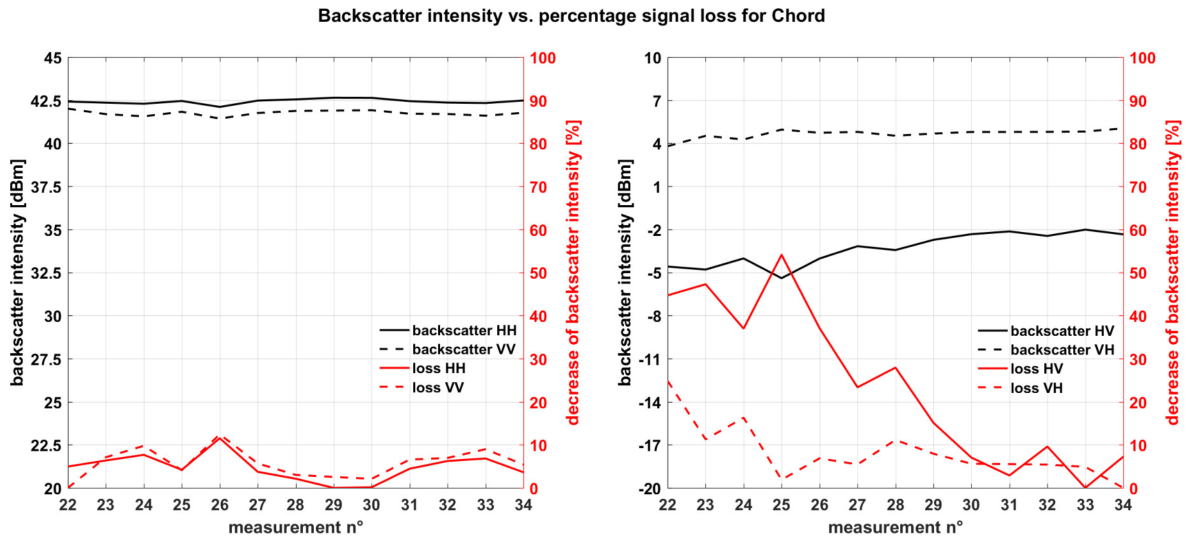

Figure A.9: Backscatter intensity and percentage loss while deforming the reflector symmetrically over the edges with a cord

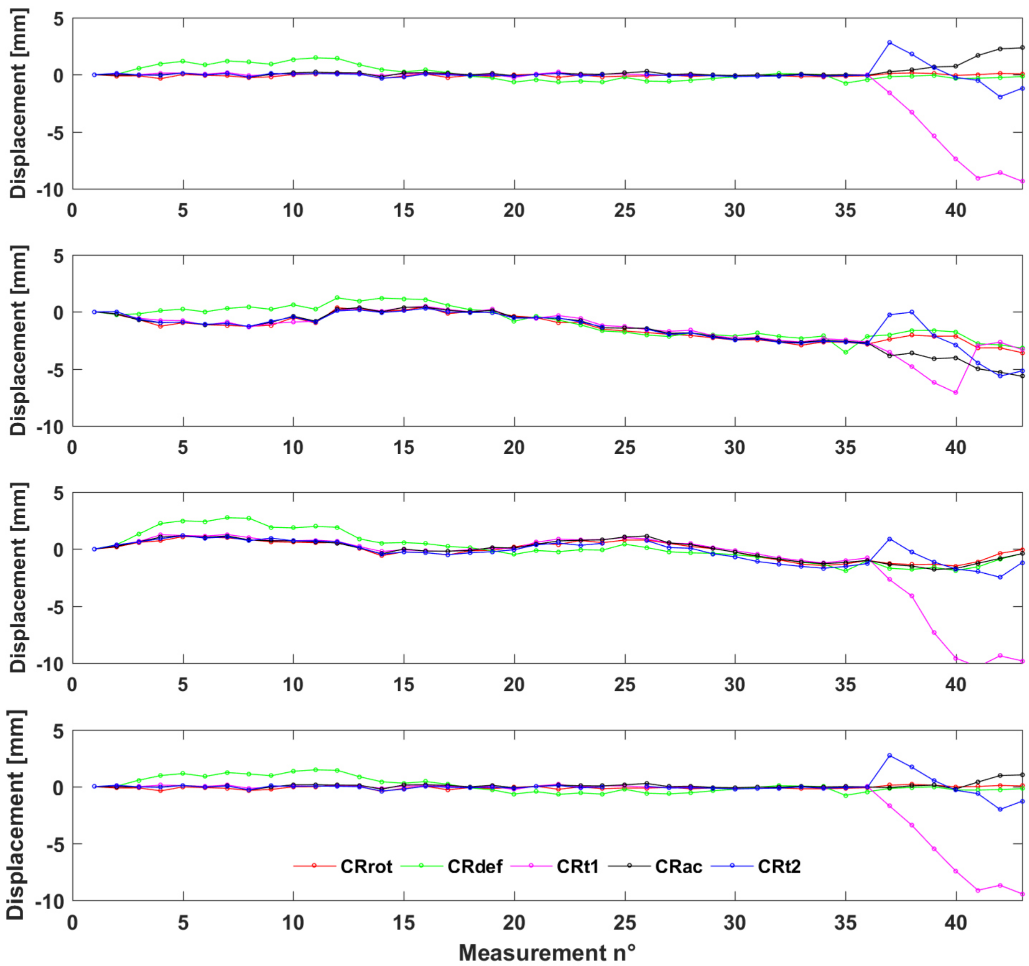

Figure A.10: Calculated displacements of the different reflectors. The first plot shows the displacement, calculated with the HH channel, the second with the HV channel, the third with the VH channel and the lowest one with the VV channel.

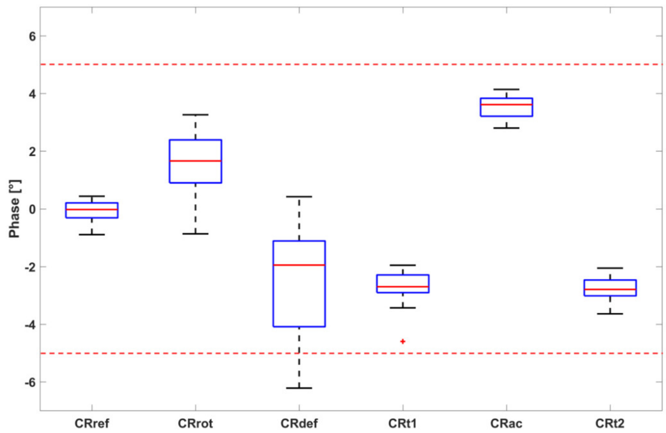

Figure A.11: Distribution of the phase for each reflector

A.3. Photos

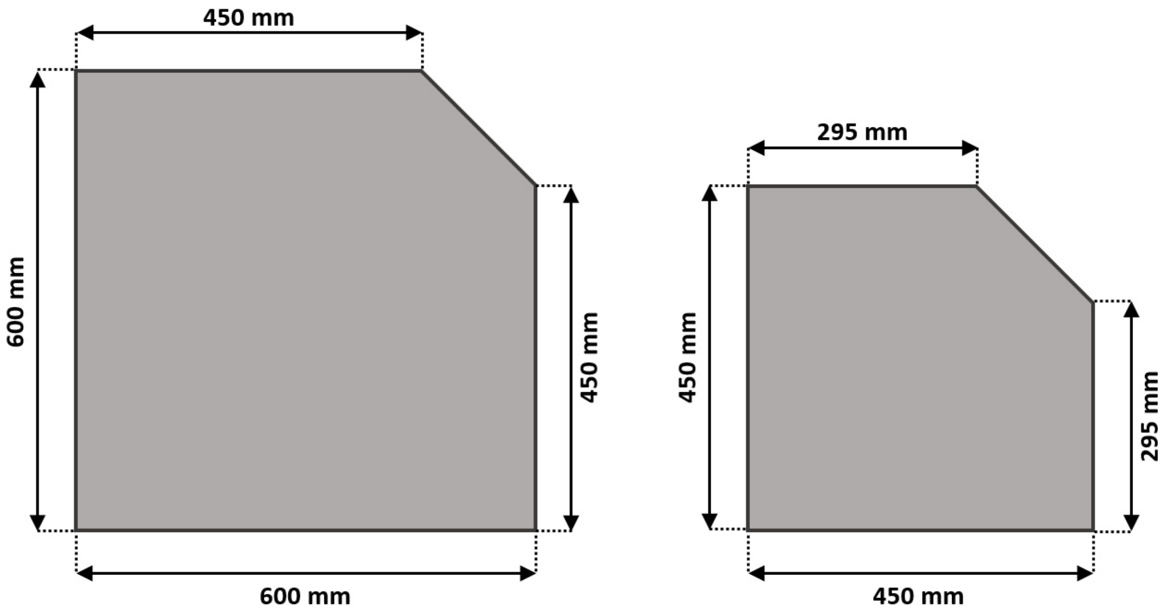

Figure A.12: Dimensions of the used corner reflectors

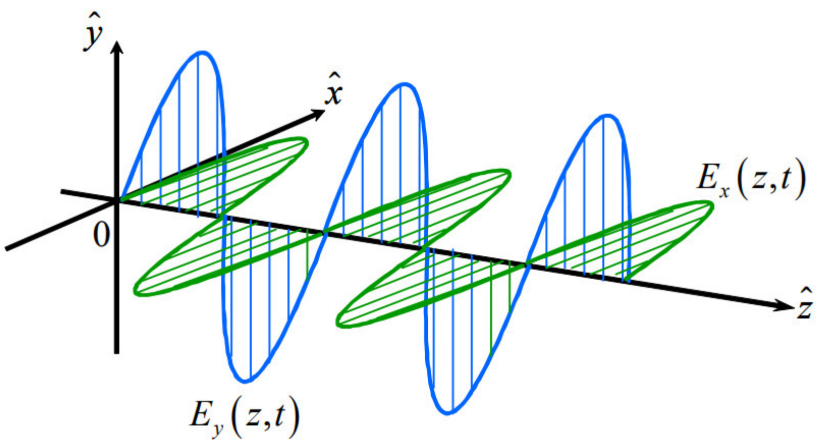

Figure A.13: Spatial evolution of a monochromatic plane wave. E_x(z,t) is the horizontal (H) polarization while E_y(z,t) is the vertical (V) polarization (Image: ESA PolSARPro Tutorial [3])

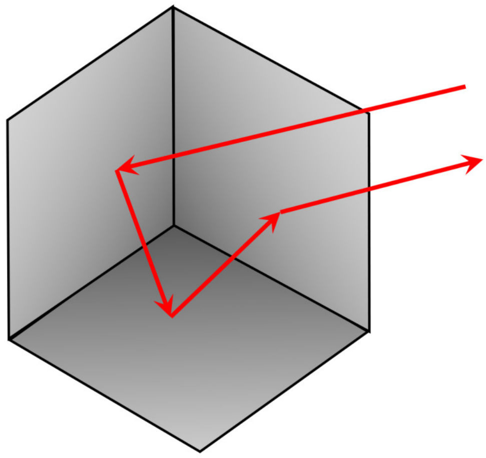

Figure A.14: Scattering mechanism of a trihedral corner reflector

A.3.1. Rotation mount

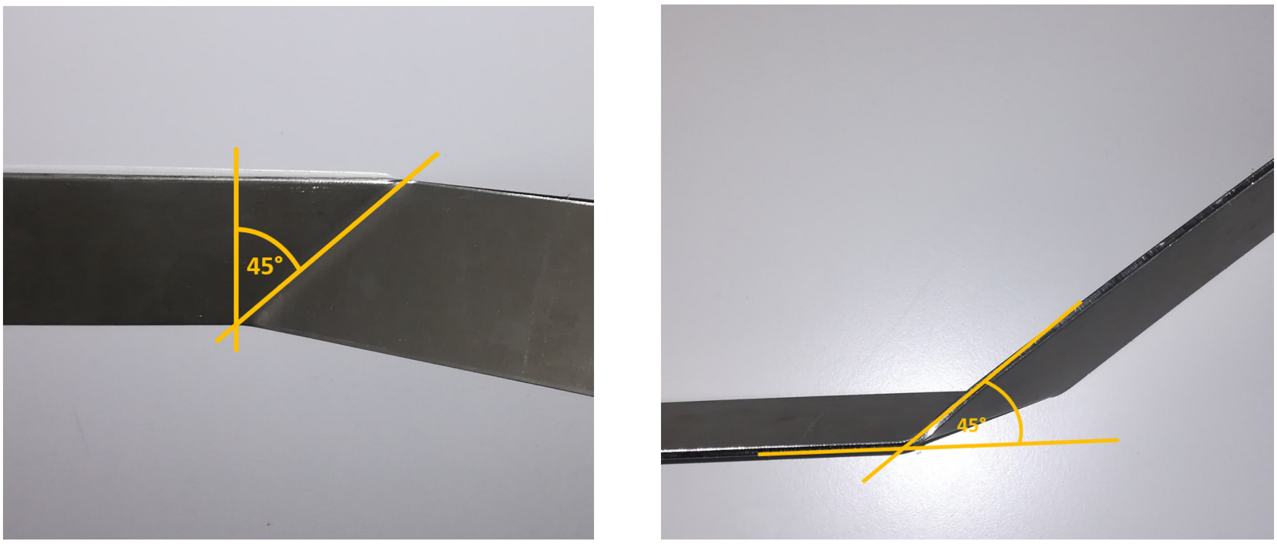

Figure A.15: Bent steel plates at an angle of 45° to mount the reflector. Left side: view from top. Right side: side view

Figure A.16: Orienting and fixing the steel plates for the reflector mount to see if the angles are right and set position for wholes to connect the lashes with screws and nuts

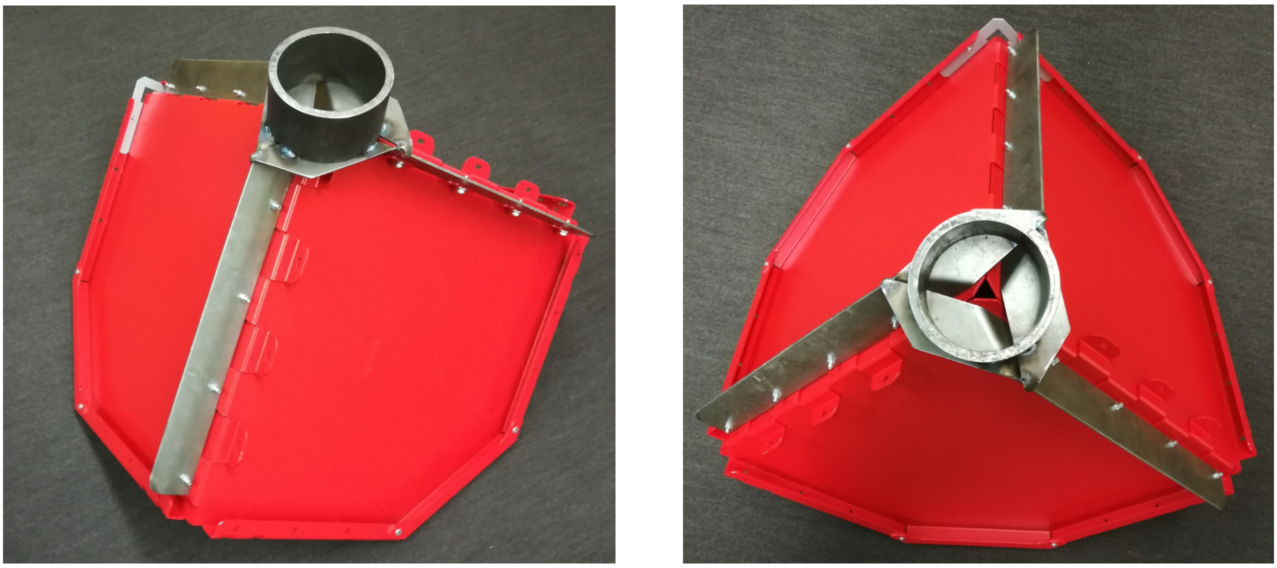

Figure A.17: Mount of the corner reflector for the rotation experiment. The indexing head is connected to the steel pipe part

A.3.2. Aluminum chipping

Figure A.18: Aluminum chipping in the reflector according to the measurement protocol A.2 for *thin film of paste* (left photo) and *aluminum chipping* (right photo)

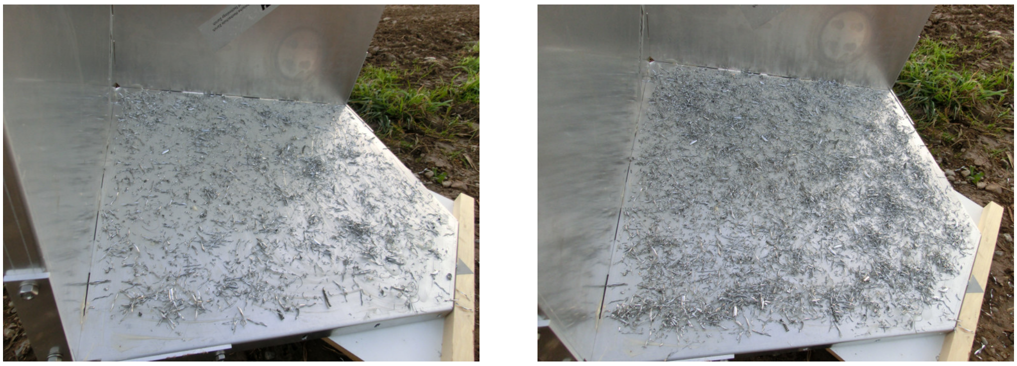

Figure A.19: Aluminum chipping in the reflector according to the measurement protocol A.2 for *few aluminum chipping* (left photo) and *medium aluminum chipping* (right photo)

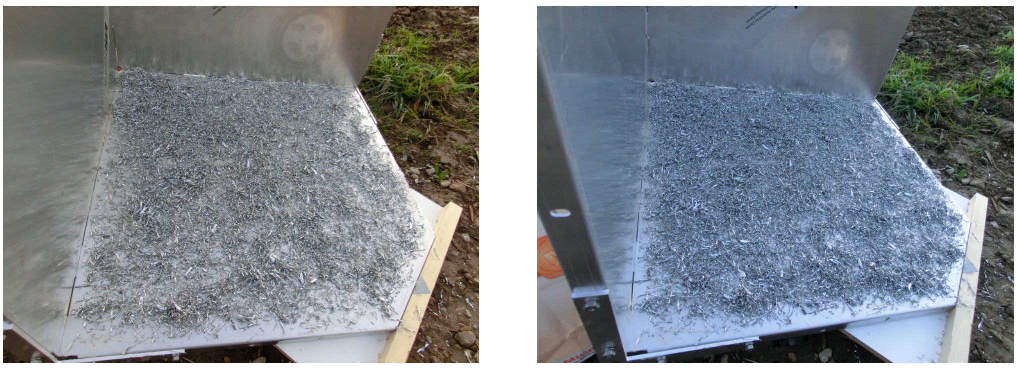

Figure A.20: Aluminum chipping in the reflector according to the measurement protocol A.2 for *a lot aluminum chipping* (left photo) and *all aluminum chipping* (right photo)

A.3.3. Symmetrical deformation with a chord

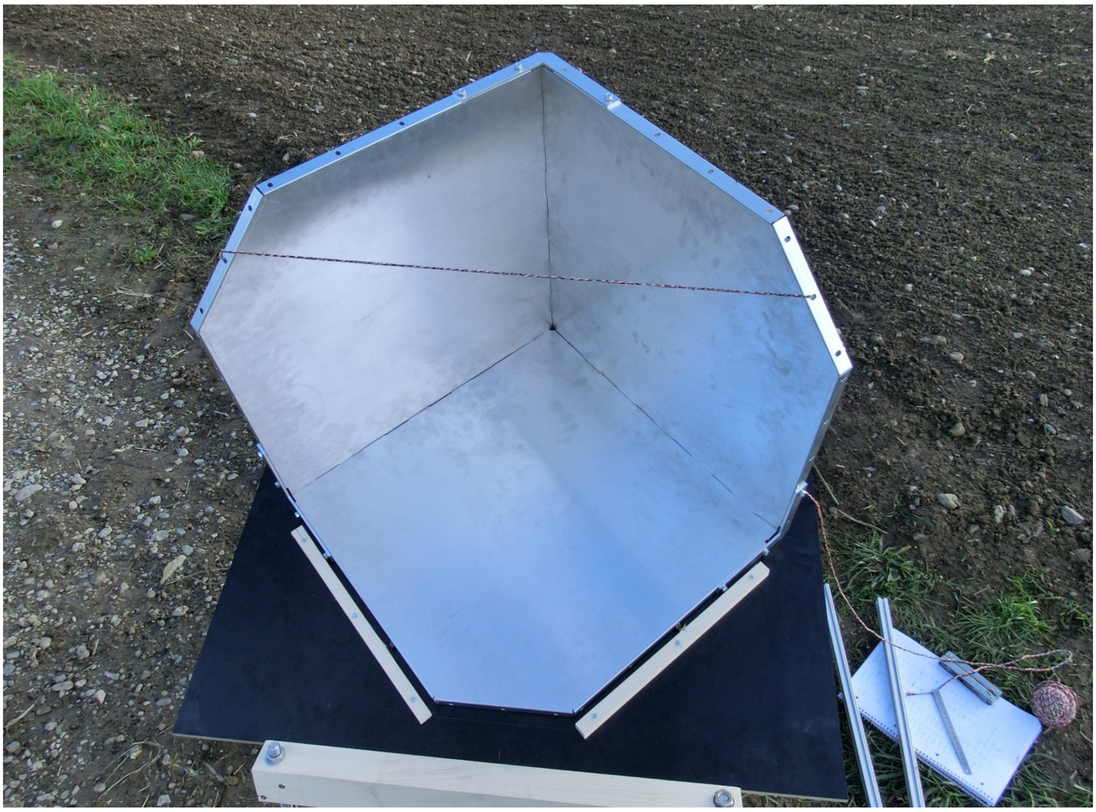

Figure A.21: Symmetrical deformation with the chord spanned from one angled reflector edge to the other

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