Absolute Radiometric Calibration of Broadband X-Band Transponders

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Abstract

Spaceborne synthetic aperture radar (SAR) systems are often used for earth observation capable for acquiring accurate high-resolution data. In order to ensure the quality of these SAR data, the SAR system has to be calibrated first. For this purpose active targets with well-known backscatter properties, called transponders, serve as an external reference. The enhancement of the operational bandwidth up to 1.2 GHz of future civil SAR systems requires the development of appropriate broadband transponders and their accurate calibration. In order to be well prepared for these missions, DLR has been developed a broadband X-Band transponder and an innovative technique for the frequency-dependent determination of the transponder's radar cross section (RCS) which promises an accurate measurement over the full transponder bandwidth. In this paper the calibration of a broadband transponder according to this new approach is described including the analysis of corresponding measurements. The derived results are verified with a second independent calibration method and finally evaluated.

1 Introduction

Over the last decades the steadily advancement of spaceborne SAR systems stresses the importance of precise and accurate geometric and radiometric calibration. For this external calibration passive (corner reflectors) and active (transponders) reference targets are used [1]. During measurements with the SAR instrument their well-known backscatter is recorded and the calibration parameters can be derived from this data. The parameter quality depends on the accuracy of the deployed reference targets because they act as an external, absolute reference. Any inaccuracy concerning the applied reference targets will later influence the quality of the derived SAR data.

DLR's Microwaves and Radar Institute has been developed and built a new broadband X-Band transponder with a center frequency of 9.80 GHz and 1.2 GHz bandwidth, shown in **Figure 1**. However, before acting as an external reference each target needs to be calibrated itself accurately. This radiometric transponder calibration requires an accurate measurement of its radar cross section. For this purpose different measurement methods are available [2].

Previous transponder calibration activities have shown that an external calibration with a spaceborne SAR system according to the "Comparison Measurement Method" will yield to the best result with respect to measurement accuracy and feasibility [3] [4]. For broadband transponders this fact requires the availability of a spaceborne SAR system with a corresponding large bandwidth. Unfortunately, up to now no civil X-Band SAR system in space provides a bandwidth of 1.2 GHz. Therefore the absolute radiometric calibration of the transponder over the full bandwidth requires a new calibration technique.

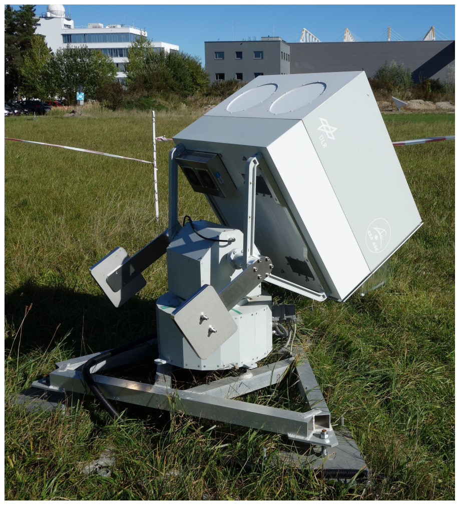

Figure 1 DLR's new developed X-Band transponder installed on an elevation-over-azimuth positioner.

DLR recently developed and patented an innovative strategy, called "Three Transponder Method" (3TM) [5] [6]. This new approach promises a more accurate transponder calibration and allows transponder RCS measurements without any bandwidth limitations [5]. Hence, DLR's novel broadband transponder has been calibrated by means of this 3TM. The first part of this paper describes the fundamentals of the 3TM followed by results of an executed calibration campaign. In order to verify these results a second measurement campaign according to the "Comparison Measurement Method" [7] was executed by means of acquisitions with DLR's X-Band SAR system TerraSAR-X (TSX). Although the bandwidth of TSX is limited to

300 MHz these measurements were suitable to verify the 3TM outcome for the overlapping frequency range of both strategies, shown in **Figure 2**. In the second part of this paper the results of the verification are presented and discussed.

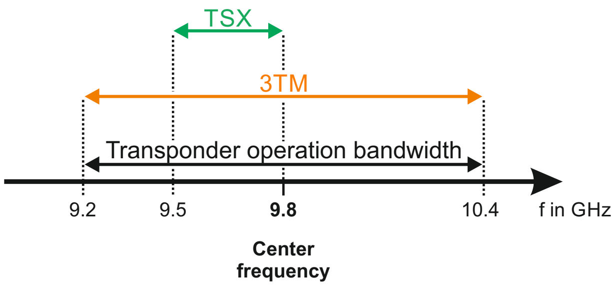

Figure 2 Frequency ranges for different calibration concepts: Whilst the "Comparison Measurement Method" is limited by the bandwidth of the SAR system (in this case up to 300 MHz by TSX), the RCS can be derived over the full transponder bandwidth (1.2 GHz) by means of the 3TM.

2 The Three Transponder Method

The innovative "Three Transponder Method" (3TM) has two crucial advantages: First a potentially more accurate transponder calibration can be achieved. The conventional method, described in **Section 3.1**, is based on the usage of a radar target as an external measurement standard. By using this approach the accuracy is dominated by the uncertainty of the RCS knowledge of this deployed reference [2]. In contrast the 3TM allows to determine the transponder RCS without knowledge of the RCS of any additional references, likely the well-known three antenna method allows to measure the antenna gain of three antennas with unknown gain [8].
The second advantage concerns the bandwidth of the transponder to be calibrated. As described in **Section 1** the "Comparison Measurement Method", performed with a spaceborne SAR system, is limited to the operational bandwidth of the SAR instrument. With the 3TM the RCS over the complete transponder frequency range can be derived.

2.1 Principle

The 3TM is derived from the principle of the three antenna method and is based on the threefold application of the radar equation by executing three independent RCS measurements with three transponders (devices A, B, and C). Each measurement is performed by two of the three transponders whereas one device is operated as a radar and the other device operates as a transponder. The three measurements results in three equations which ca be expressed as a linear set of equations. Further details about the 3TM are described in [5] [6].
During the measurements it is not important which transponder is operated as radar and which one as a target. In the set of measurements using transponder combinations AB, AC, and BC only devices A and B needed to be operated as radars, and devices B and C as targets. Consequently only transponder B needs to be operated as radar and target during one measurement campaign. Concurrently device A is only used as radar and device C only as a target. Due to this fact it is not necessary to execute the three transponder method with three transponders. Exemplary, if device A is represented by a simple radar system with gain ς_{rad} and device C by a trihedral corner reflector with the radar cross section ς_{cr} the unknown transponder RCS σ_{trsp} can be determined by solving the matrix [5]

$$\begin{pmatrix} \varsigma_{rad} \\ \sigma_{trsp} \\ \varsigma_{cr} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 & 1 & -1 \\ 1 & -1 & 1 \\ -1 & 1 & 1 \end{pmatrix} \begin{pmatrix} P_{rad,trsp} - C \\ P_{rad,cr} - C \\ P_{trsp,cr} - C \end{pmatrix} \quad (1)$$

with C as

$$C = -20 \log(4\pi R^2). \quad (2)$$

Figure 3 illustrates a possible setup with all necessary measurement combinations. For the calculation of the transponder RCS σ_{trsp} no knowledge about the radar gain ς_{radar} and the corner reflector RCS ς_{cr} is necessary. This fact relaxes the hardware requirements for realizing a 3TM campaign. Besides the power ratio P only the distance R between both devices must be measured in order to make the linear set of equations solvable. Exemplary $P_{rad,trsp}$ represents the ratio of receive to transmit power measured by the radar and using the transponder as target.

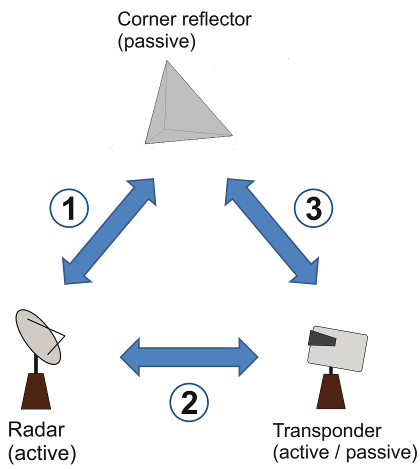

Figure 3 Exemplary setup for the three antenna method including all necessary measurement combinations.

Each measurement can be performed at a single frequency. In order to determine the RCS for the complete transponder bandwidth the measurement can be repeated with a stepped frequency technique.

2.2 Measurement Setup

A complete 3TM measurement campaign was performed for DLR's novel X-Band transponder (**Figure 1**). According to **Figure 3** measurements with three different device combinations were executed. Beside the transponder a

radar, provided by a vector network analyzer (VNA) with two horn antennas, and a corner reflector with an inner leg length of 0.9 m were used.
The measurements for all three device combinations were performed with an outdoor measurement range which yields to non-avoidable multipath scattering effects. In order to detect and characterize this uncertainty effect one device was mounted on a movable carriage and the measurements within each setup were repeated at varying carriage positions. **Figure 4** illustrates the applied measurement principle. During a complete measurement run several single measurements were performed and the target device was moved simultaneously. Parallel the distance R was measured automatically after each sweep. This procedure was repeated until the target has moved over a distance of several meters.

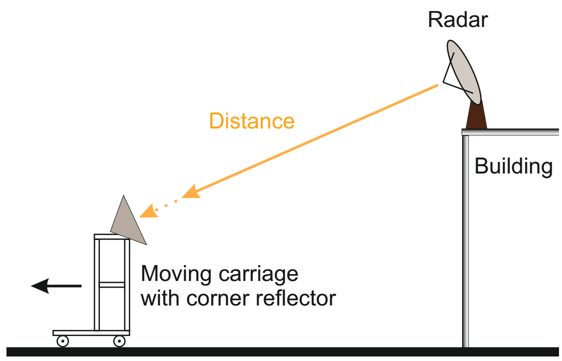

Figure 4 Principle of 3TM setup: One device (exemplary the radar) is placed on the roof of a building. In order to detect multipath scattering the target, placed on ground, is installed on a carriage. During measurements the distance is varied by moving the carriage continuously in one direction.

Figure 5 shows the setup of one measurement combination with a radar (emitter) and a corner reflector (target). The radar device measured the backscattering of the corner reflector in main beam direction. For aligning the radar antennas a sighting telescope was used.

2.3 Measurement Results

In **Figure 6** the recorded data of a single measurement sweep at one distance is presented. The upper diagram shows the range profile of the backscattered power. The clearly visible peak at a distance of approximately 68 m represents the corner reflector's echo and can be extracted by means of time-gating technique. The recorded data in frequency domain is shown in the lower diagram. From the results of one complete measurement run the distance-dependent power ratio P for each frequency of the emitted X-Band signal can be derived, as shown in **Figure 7**. With the resulting power ratios $P_{rad,trsp}$, $P_{rad,cr}$, and $P_{trsp,cr}$ the frequency-dependent transponder RCS can be determined according to Equation **Equation 1**.
The calculated transponder RCS according to the 3TM method is summarized in **Table 1**. The overall accuracy

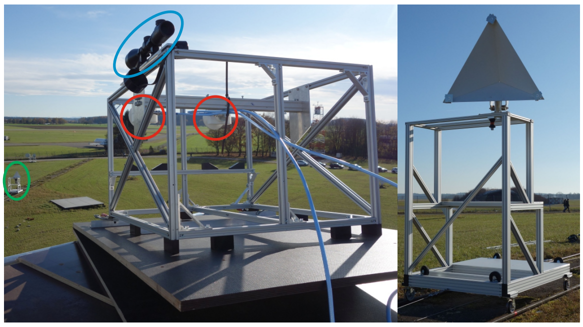

Figure 5 One setup of three measurement combinations of the executed 3TM campaign : The right picture shows a corner reflector mounted on a carriage. On the left picture the radar, placed on the roof of a building, is shown. Both antennas (red circles) are mounted on a frame and are aligned to the corner reflector (green circle) by using a sighting telescope (blue circle).

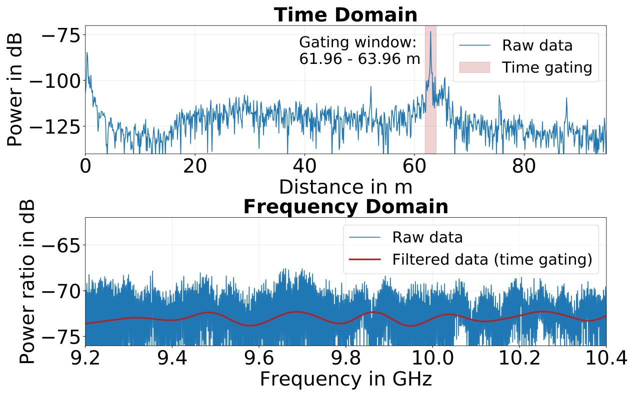

Figure 6 Results of one measurement sweep executed by the radar: The upper plot shows the backscattered power in time domain. After extracting the visible peak echo of the corner reflector by means of time-gating technique the filtered data are retransformed into frequency domain, shown in the lower plot.

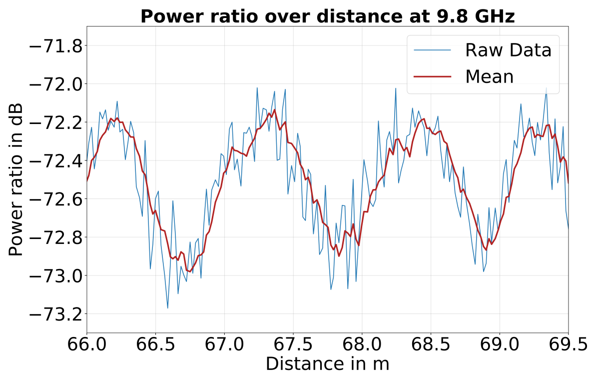

Figure 7 Diagram of determined power ratio over distance for a measurement run using radar and corner reflector at 9.8 GHz. The free space loss for the different distances is already compensated. For the presented data a mean power ratio of -72.6 dB can be derived.

is determined according to [9] and is derived from all executed measurements considering several error terms, e. g.

drift of the radar instrument, drift of transponder gain, and the uncertainty of distance measurements. A detailed analysis of the overall measurement uncertainty will be given in a separated publication, planned for 2021.

RCS	Uncertainty (1σ)
64.66 dBm^2	0.19 dB

Table 1 Calculated transponder RCS from 3TM measurement including accuracy estimation.

3 Verification with "Comparison Measurement Method"

As described in **Section 1** the 3TM results are verified with a second transponder calibrations strategy according to the well approved "Comparison Measurement Method". The campaign was realized from May till July 2019 by means of acquisitions with one satellite of DLR's X-Band SAR mission TerraSAR-X. In this Section the measurement principle, setup, and result is presented.

3.1 Principle

The described calibration method is based on a comparison of measurements between a transponder to be calibrated and a reference target with well-known backscatter properties. For both targets the receive power is measured with an external radar system within the same measurement setup. According to [2] the transponder RCS σ_{trsp} can be derived from the ratio of measured receive powers $P_{r,trsp}$ (transponder) and $P_{r,ref}$ (reference target) pursuant to the relationship

$$\sigma_{trsp} = (P_{r,trsp}/P_{r,ref}) \cdot \sigma_{ref} \tag{3}$$

where σ_{ref} is the known RCS of the reference target.
Figure 8 illustrates a possible setup where a spaceborne SAR instrument serves as external radar and measure the backscattering of both point targets within one acquisition. This setup was chosen for the executed transponder calibration campaign described in the next section.

3.2 Measurement Setup

For the measurements the X-Band transponder to be calibrated (**Figure 1**) was installed with ten additional trihedral corner reflectors (inner leg length of 1.5 m), serving as external reference, at the DLR site in Oberpfaffenhofen. At the beginning the transponder was aligned absolutely using a differential GPS device (for azimuth orientation) and an water level (for elevation adjustment). Thus it was possible to execute the overpass alignment of the transponder automatically using a high precision positioner. The corner reflectors were aligned manually with compass and inclinometer.

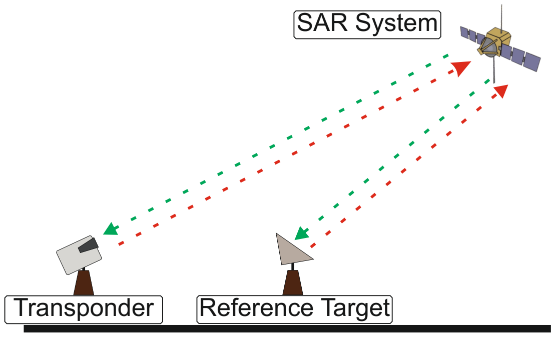

Figure 8 Measurement setup for the "Comparison Measurement Method" with transponder to be calibrated and a reference target. The external radar system is provided by a spaceborne SAR instrument and both targets are located within the same acquisition.

Figure 9 shows a TerraSAR-X image, containing impulse responses of the transponder and all corner reflectors. In order to reduce the overall uncertainty of the determined transponder RCS 13 SAR acquisitions were performed. In the past this approach was demonstrated successfully during several calibration campaigns [4] [7].

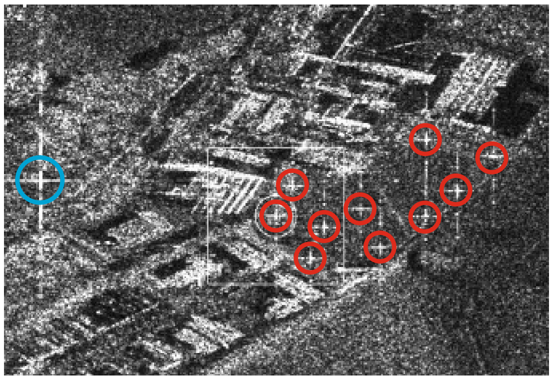

Figure 9 TerraSAR-X image: The impulse responses of ten corner reflectors are visible in the red circles and the transponder backscattering is marked with a blue circle.

3.3 Measurement Results

For calculating the transponder RCS two steps were conducted. First the backscattering power of all point targets' were derived from the image power by integrating over the impulse responses in the SAR images and substraction of the background clutter. In the second step the transponder RCS is computed according to **Equation 3** using the derived backscattering powers of transponder and corner reflectors [10].
In **Figure 10** the image power derived for each target is presented. For every overpass the average value of all corner reflector backscattering powers is computed. With this reference the final transponder RCS was calculated. The resulting transponder RCS is summarized in **Table 2** including an uncertainty estimation. The overall accuracy

was determined according to [9] from two error terms. The first one is the calculated standard deviation of the power ratio values derived for all overpasses. The second term is defined by the RCS knowledge uncertainty of the used reference targets. Based on the mechanical tolerances of the corner reflectors a value of 0.2 dB was assumed [11].

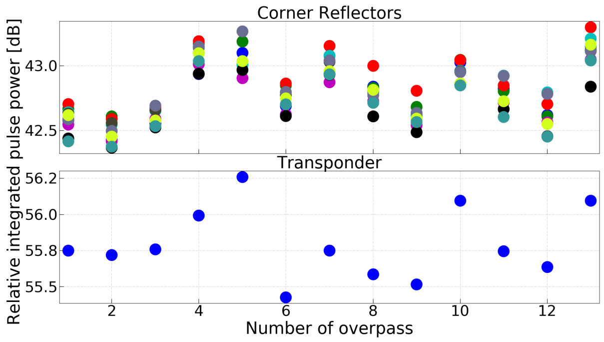

Figure 10 Extracted target power derived from each TerraSAR-X acquisition for transponder and corner reflectors.

After finishing the TSX campaign it turns out that the transponder was operated in nonllinear range during all overpasses. Several received SAR pulses were clipped by the receiver of the transponder. The calculated value from **Table 2** can be considered as too small. Hence the derived absolute pulse power values are not suitable for the verification of the transponder RCS derived by the 3TM. A new campaign with further TSX overpasses will be executed from December 2020 to January 2021 and the recorded data will be analyzed according to the procedure described above. The final results will be presented during the conference.

RCS	Uncertainty (1σ)
62.41 dBm^2	0.27 dB

Table 2 Transponder RCS derived from the "Comparison Measurement Method" campaign including derived measurement accuracy.

4 Conclusion

After an introduction of the challenges to determine accurately the RCS of a broadband transponder up to 1.2 GHz, an innovative concept covering the complete transponder bandwidth was described. From measurements executed for this "Three Transponder Method" a single value for the transponder RCS over the full operational bandwidth of 1.2 GHz and a corresponding uncertainty statement was presented. With another independent RCS measurement approach, called "Comparison Measurement Method", the results should be verified by means of TerraSAR-X. The discrepancy of the RCS derived from both approaches is sourced by a nonlinearity of the "Comparison Measurement Method" approach. Thus the verification will be executed once again and the new results will be presented at the conference. However, the Three Transponder Method is an innovative method to derive the RCS accurately, especially for high bandwidths, and has the potential to advance into new accuracy classes.

5 Literature

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