# The Three-Transponder Method: A Novel Approach for Traceable (E)RCS Calibration of SAR Transponders

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## Abstract

The radiometric calibration of synthetic aperture radar (SAR) systems is typically based on the known backscatter of calibration point targets such as transponders. Before a SAR calibration campaign can begin it is therefore necessary to determine the backscatter (radar cross section or RCS) of the transponder itself. Known methods suffer from unnecessarily high uncertainty contributions and therefore also affect the radiometric uncertainty of the calibrated SAR system. In this paper we present a novel calibration approach which neither requires to disassemble the amplifier path nor necessitates a separate RCS calibration target such as a corner reflector or a circular disk. Significant sources of measurement uncertainties can therefore be outright avoided. The method is not applicable to all transponders though, and a certain type of transponder design is assumed. Nevertheless, direct metrological traceability to a realization of the SI base unit "meter" can be achieved for the first time. The reduced measurement uncertainties of the novel approach will subsequently allow to reduce the radiometric measurement uncertainties of air- and spaceborne SAR sensors in the future.

## 1 Introduction

Transponders are, besides trihedral corner reflectors, the most commonly used measurement standards in radiometric SAR calibration. They allow signal recording for the reconstruction of the azimuth pattern of the SAR system, adjustments of the backscattering matrix for polarimetric applications, and radar cross sections (RCSs) which are potentially much larger than those of passive point targets. These advantages led DLR to develop, manufacture, and install three new, accurate C-band "Kalibri" transponders in South Germany. These transponders have been successfully used for the calibration and monitoring of the Sentinel-1A satellite [7, 8], and will be also used for the calibration of Sentinel-1B [9], the second Sentinel-1 satellite of the European Copernicus program scheduled for launch in April 2016.

Before the transponders could be used initially as radiometric measurement standards, they needed to be calibrated themselves. In an effort to find the most accurate RCS calibration approach for the given transponder design, several existing methods were compared [6], and a new, potentially highly accurate method, was devised which exploits the specific design of the Kalibri transponders [2]. The new *three-transponder method* (3TM) is similar in principle to the known *three-antenna method* [5], but is based on the radar equation instead of the Friis transmission formula. To conduct a complete measurement, three transponders and three measurements (with one transponder pair each) are required; refined measurement schemas are also possible. In comparison to existing methods, no additional radiometric measurement standard is needed, which so far has been one of the limiting factors in accomplishing lower calibration uncertainties. Measurement traceability is achieved by tracing a comparatively simple length measurement back to a national realization of the meter. Such a length measurement can be performed with high accuracy.

## 2 Requirements on Transponder Design

The proposed method requires a transponder device which can be operated both as a transponder (direct retransmission of received signal) as shown in Fig. 1 and as a radar (independent operation of the transmitting and receiving chains) as shown in Fig. 2.

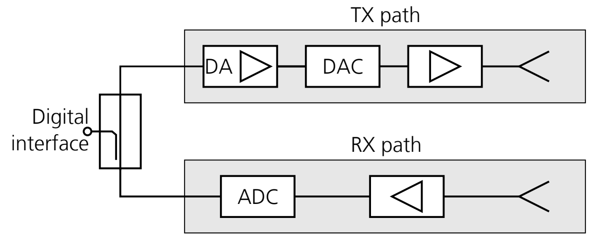


**Figure 1:** Transponder device operated as a transponder.

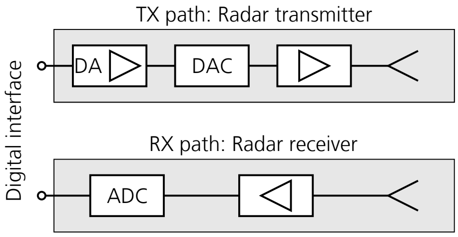


**Figure 2:** Transponder device operated as a radar.

Although this precondition limits the applicability of the new approach, the condition is often met by modern transponder designs. The digital sub-system, which connects the receiving and transmitting chains, is first of all used as a digital delay line to shift the impulse response in a SAR image. Such a digital sub-system is also part of DLR's C-band transponders.

# 3 Derivation of the 3TM Equation

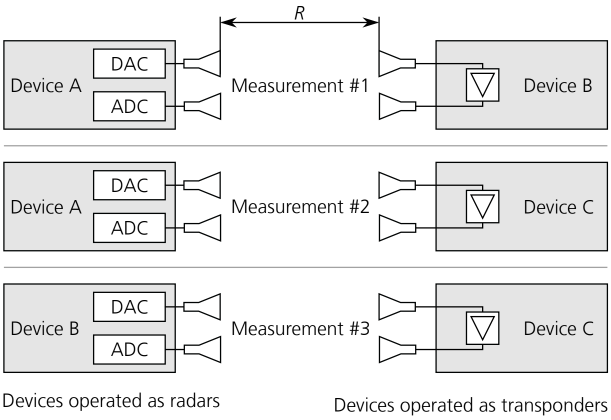


**Figure 3:** Three measurement pairs are needed for the novel three-transponder method in order to determine the RCS of transponders $A$, $B$, and $C$. The transponder's digital sub-system is exploited to operate the devices either as a radar or as a transponder.

The 3TM approach does not require an additional radiometric measurement standard like a corner reflector, thereby in principle eliminating a major source of calibration uncertainty. The method is based on three pairs of measurements, similar to the three-antenna method for the determination of the antenna gains of three unknown antennas [5]. For each of the three measurements, one of the transponders is operated as a radar and one as a "normal" transponder, which simply retransmits the received signal, see Fig. 3.

The ratio of the received to the transmitted power $P_r/P_t$ (measured by device $X$ which is operated as a radar) depends on the distance $R$ between the devices and on the RCS $\varsigma_Y$ of the device $Y$ operated as a transponder according to the radar equation

$$\left.\frac{P_r}{P_t}\right|_X = \frac{G_{\text{rx}} G_{\text{tx}} \lambda^2 \varsigma_Y}{(4\pi)^3 R^4}, \tag{1}$$

where $G_{\text{rx}}$ and $G_{\text{tx}}$ are the receive and transmit path gains of device $X$ (due to the radar antenna and amplifier gains), and $\lambda$ is the wavelength. Furthermore, the relationship between the transponder RCS and its amplification loop gain can be expressed as [1]

$$\varsigma_X = \frac{\lambda^2}{4\pi} G_{\text{rx}} G_{\text{tx}}. \tag{2}$$

Now Eqs. (1) and (2) can be combined to yield

$$\left.\frac{P_r}{P_t}\right|_X = \frac{\lambda^2}{(4\pi)^3 R^4} \cdot \frac{4\pi}{\lambda^2} \cdot \varsigma_X \cdot \varsigma_Y, \tag{3}$$

where the power ratio on the left is measured, $R$ is known, and $\varsigma_X$ and $\varsigma_Y$ shall be determined. This measurement can be repeated for three transponder pairs, e. g. $AB$, $AC$, and $BC$, where the first letter denotes the device operated as a radar, and the second letter the device operated as a transponder. The resulting three equations in the form of (3) can be converted to a system of linear equations by logarithmic transformation with $10\log(\cdot)$. Writing the system of equations in matrix form and inverting it yields the transponder RCSs (in dBsm):

$$\begin{pmatrix} \varsigma_A \\ \varsigma_B \\ \varsigma_C \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 & 1 & -1 \\ 1 & -1 & 1 \\ -1 & 1 & 1 \end{pmatrix} \begin{pmatrix} P_{AB} + C \\ P_{AC} + C \\ P_{BC} + C \end{pmatrix} \tag{4}$$

with

$$C = 20\log(4\pi R^2) \tag{5}$$

and the power ratios $P_{AB}$, $P_{AC}$, $P_{BC}$ expressed in decibels. Measurements can be repeated for different frequencies and alignment angles to determine the transponder RCSs depending on frequency and angle.

# 4 Demonstration Measurement Campaign

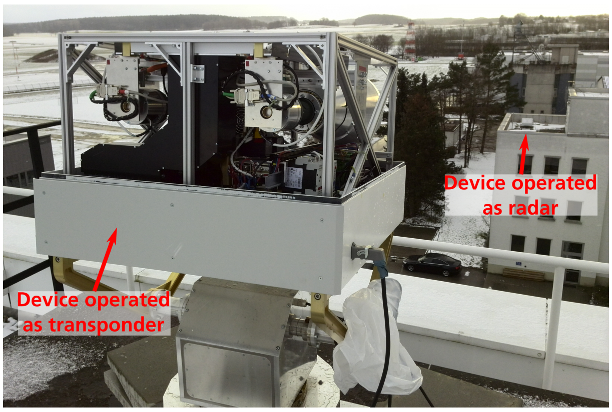


**Figure 4:** Measurement setup for the demonstration measurement campaign: The two devices were installed on the roofs of two adjacent buildings and were separated by about 50 m.

The applicability of the method was demonstrated in a first calibration campaign using DLR's three C-band transponders [2]. The measurement setup is shown in Fig. 4. One of the transponders was mounted on a slide which allowed to modify the distance ($z$ axis) between the devices in small increments for subsequent multipath suppression ($z = 0\,\mathrm{cm}$ denotes the slide position where the devices are closest to each other).

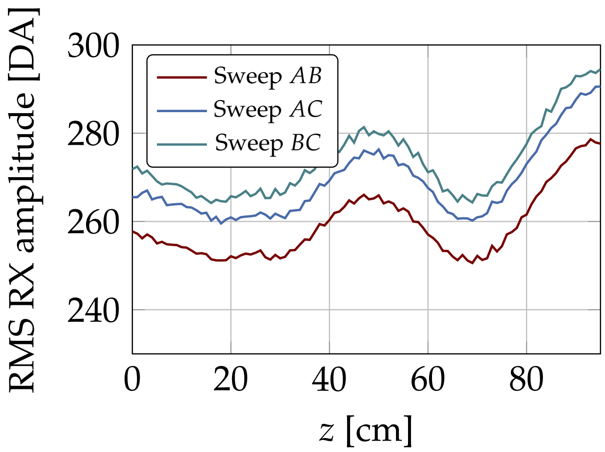


**Figure 5:** Received RMS amplitudes for an exemplary measurement triplet as shown in Fig. 3, at the center frequency. The data is normalized for a far-field distance $R$ at $z = 0\,\mathrm{cm}$.

Exemplary measurement results are shown in Fig. 5. It can be seen that the data is affected by a multipath effect, which explains the undulations over slide position $z$. The large undulations are mostly due to the *ad hoc* nature of the demonstration measurement campaign and it is expected that much lower multipath effects can be achieved if a dedicated measurement range (without metal ledges and proper use of absorbers) is set up.

The measurements were conducted with a stepped-frequency signal. The frequency-dependent RCS was therefore determined within the complete bandwidth of the transponders, so that the equivalent radar cross section (ERCS, the proposed novel radiometric measurement quantity for SAR images [4]) can subsequently be derived as well.

After data analysis and analysis of the measurement uncertainty, the transponder RCSs of each transponder could be determined with a remaining standard uncertainty of 0.4 dB [2]. To repeat, the major source for measurement uncertainty stems from the multipath effect which was attributed an uncertainty of 0.375 dB. Could this be suppressed due to a better measurement setup, the remaining standard uncertainty would have been only 0.08 dB, which is a significant improvement of the currently claimed transponder RCS uncertainty of 0.2 dB [3].

# 5 Conclusion

The radiometric uncertainty of calibrated SAR systems also depends on the radiometric uncertainty of the calibration targets. In this paper, we presented a novel RCS calibration approach for a special kind of SAR calibration transponders. For the first time, the novel 3TM approach allows the metrological traceability for radiometric calibration to be established directly through a length measurement. In practice, this length measurement can be accomplished with high accuracy, making the 3TM in principle a good choice for accurate transponder measurements, presuming that the transponders can also be operated as radars. Although measurement results acquired during a first demonstration measurement campaign were still considerably affected by multipath transmission, the method promises to become the most accurate transponder RCS calibration approach in the future. As a result, the radiometric uncertainty of calibrated SAR systems can be lowered which will benefit commercial and scientific applications alike.

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