Absolute Radiometric Calibration of the Novel DLR "Kalibri" Transponder

Daniel Rudolf, Sebastian Raab, Björn J. Döring, Matthias Jirousek, Jens Reimann, Marco Schwerdt

Microwaves and Radar Institute
German Aerospace Center (DLR)
Wessling, Germany
daniel.rudolf@dlr.de, tel. +49 8153 28 3087

Abstract—**The technological advancement of the synthetic aperture radar (SAR) principle leads to an innovative challenge for the calibration as well. In order to provide an active reference target for an accurate absolute radiometric calibration the knowledge of the target's backscattering characteristics is essential. For the recently developed DLR C-band transponder named "Kalibri" several strategies for an accurate determination of the radar cross section (RCS) have been analyzed. Based on a comparison with respect to accuracy and feasibility, several recommendations for the best transponder calibration strategy were established. The resulting RCS of the transponders retrieved from the most suitable measurement method is presented as well as a cross-validation to prove the plausibility of these results.**

Keywords—calibration; transponder; Kalibri; calibration strategies; RCS; SAR; absolute radiometric accuracy

I. INTRODUCTION

The ongoing improvement of spaceborne SAR systems in the last decades leads to stronger geometric and radiometric system requirements. In order to provide high quality SAR acquisitions the importance of a highly precise and accurate geometric and radiometric calibration is getting more and more important. This calibration is basically performed with passive (corner reflectors) and active (transponders) reference targets [1]. During the satellite overflight their well-known backscatter is recorded by the SAR instrument and the calibration parameters can be derived from this data. Hence the accuracy of the SAR data product depends at the end on the accuracy of the known backscatter of the deployed reference targets used as an external, absolute reference.

DLR recently developed and manufactured three novel C-band transponders [2] for the calibration of the Sentinel-1A system [3]. These "Kalibri" transponders need to be radiometrically calibrated prior to their first use as an absolute reference target. For this radiometric transponder calibration a highly accurate measurement of their radar cross section is required.

In the first part of this paper a comparison of four RCS measurement principles is executed, leading to a recommendation of one preferred calibration strategy. According to this advice the backscattering characteristics and the corresponding standard uncertainty of all "Kalibri" transponders were determined during a first measurement campaign. The results are shown in the second part of this paper. Finally a cross validation is performed with results of a second campaign according to the same strategy and with a new transponder calibration principle, which was developed and tested at DLR.

II. ANALYSIS OF TRANSPONDER CALIBRATION STRATEGIES

Four different methods for transponder calibration have been compared, leading to a recommendation for one calibration strategy. A more detailed analysis with respect to accuracy, feasibility, and costs is given in [4].

A. Complex Gain Measurements (Method A)

The radar cross section of the transponder can be derived by determining the total loop gain, which is composed of the receive antenna gain G_r, the transmit antenna gain G_t, and the gain of the signal path including the complete amplifier loop G_{sys} (see Fig. 1).
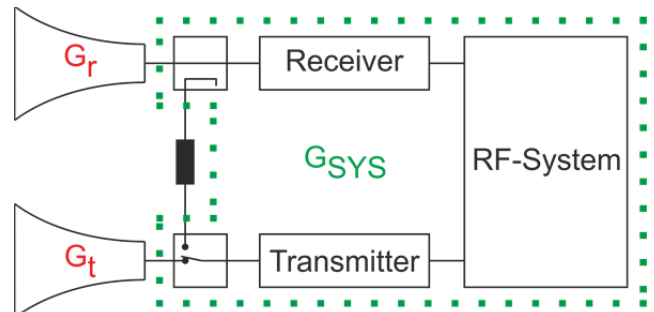

Fig. 1. Block diagram of the transponder with receive and transmit antennas, signal path, and internal calibration loop.

With three individual measurements for G_r, G_t, and G_{sys} the radar cross section of the transponder σ_{Trsp} can be derived at the given wavelength λ as [5]

$$\sigma_{Trsp} = G_r G_t G_{sys} * \lambda^2 / 4\pi . \qquad (1)$$

B. Transponder as Target – Radar Equation (Method B)

For this calibration strategy the transponder is considered as a point target and is illuminated by the beam of an external radar system. The RCS of the transponder σ_{Trsp} can be derived from the fundamental radar equation [6] as

$$\sigma_{Trsp} = (P_r*(4\pi)^3 *R^4) / (P_t*G_{t,rad}*G_{r,rad}* \lambda^2). \qquad (1)$$

It is necessary to measure the following unknown quantities: the receive and transmit power P_r and P_t, the gain of receive and transmit antenna of the radar instrument G_r and G_t at the given wavelength λ of the radar signal as well as the distance R. The measurement setup is shown in Fig. 2 (case A).

C. Transponder as Target – Comparison Measurement (Method C)

The third strategy is based on a comparison measurement between the transponder and a reference target with well-known backscatter properties. For both targets the receive power P_r is measured separately by the same setup with an external radar system.

Derived from the ratio of the measured powers $P_{r,trsp}$ and $P_{r,ref}$, the radar cross section of the transponder σ_{Trsp} is given by

$$\sigma_{Trsp} = (P_{r,trsp} / P_{r,ref}) * \sigma_{Ref} \qquad (2)$$

where σ_{Ref} is the known RCS of the reference target. Figure 2 (case B) shows the described measurement setup.
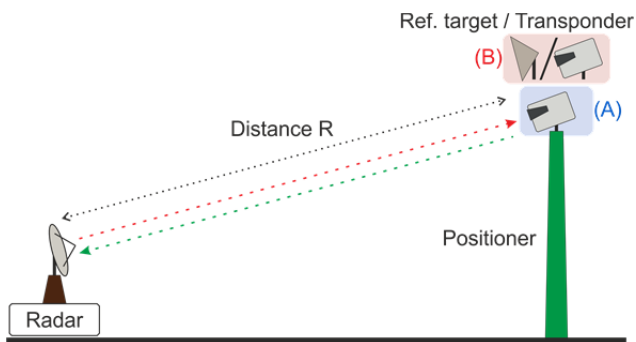

Fig. 2. Measurement setup with transponder as a point target for method A ("transponder as target – radar equation") and method B ("transponder as target – comparison measurement").

D. Transponder as Radar (Method D)

The DLR transponder can also be operated as a radar instrument, i.e., the transponder is able to generate and to receive a signal by opening the amplification loop. Hence, it is possible to determine the transponder RCS from a measurement with a known reference target. Figure 3 shows the measurement setup.

This method is based on the principle of the radar equation as well, but the transponder is seen as a black box, whereupon the gain of the receive and transmit antennas are part of the transponders' backscatter. The transponder RCS σ_{Trsp} is given by [7]

$$\sigma_{Trsp} = (P_{r,trsp} / P_{t,trsp}) * (4\pi)^2 R^4 / \sigma_{Ref} . \qquad (3)$$

According to this the transponder RCS can be derived from a measurement of the receive and transmit power P_r and P_t

with a reference target with known radar cross section σ_{Ref}. The distance R between radar and target has to be determined as well.
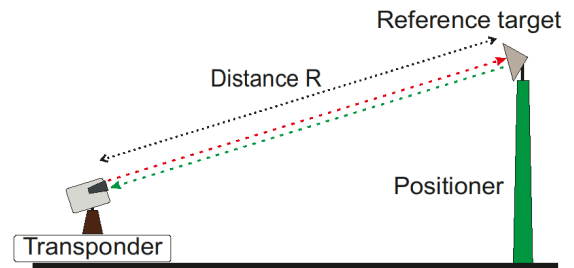

Fig. 3. Measurement setup for "transponder as radar" strategy.

E. Comparsion of Transponder Calibration Strategies

For all calibration strategies described above, a measurement uncertainty analysis has been performed according to the *Guide to the Expression of Uncertainty in Measurement (GUM)* [8]. Thereby, the theoretical overall measurement uncertainty of every strategy is defined by all input quantities and their corresponding uncertainties. A detailed review of all calibration strategy uncertainties is derived in [4]. The resulting standard uncertainty for the radar cross section of the transponder are summarized in TABLE I. .

TABLE I. CALCULATED OVERALL MEASUREMENT UNCERTAINTIES.

Calibration Strategy	Uncertainty (1σ)
Trsp. as target – radar equation	0.67 dBm^2
Trsp. as target – comparison m.	0.25 dBm^2
Trsp. as radar	0.23 dBm^2
Complex gain measurement	0.66 dBm^2

The uncertainty analysis reveals that the methods "transponder as radar" and "transponder as target – comparison measurement" are best suited for deriving the backscatter of the transponder. With regard to feasibility, the "transponder as radar" strategy has some crucial disadvantages compared with the "transponder as target – comparison measurement" method. For instance for narrow-band transponders ("Kalibri" transponder: 100 MHz at 5.4 GHz center frequency) time gating techniques are not well suited for multipath suppression because of the related insufficient spatial resolution [4]. This circumstance yields additional uncertainties. Therefore the "transponder as target – comparison measurement" strategy has been finally recommended as the most suitable one for an accurate determination of the transponder RCS.

III. TRANSPONDER CALIBRATION WITH RADARSAT-2 ACQUISITIONS

A potential realization of the strategy "Transponder as Target – Comparison Measurement (C)" is a measurement setup by means of a spaceborne SAR system. For this purpose RADARSAT-2 was chosen with similar system parameters as the DLR transponder being to be calibrated. This approach was already successfully demonstrated during an executed campaign in April 2013 with a transponder prototype [9].

A. Measurement Setup

In order to achieve a precise absolute radiometric calibration of the transponders an amount of 7 overpasses was necessary to reduce the uncertainty by averaging. As reference targets two different corner reflectors (1.5 m and 3.0 m inner edge length) were used. Figure 4 illustrates one single look image product of RADARSAT-2 (provided by the European Space Agency (ESA)) containing thirteen impulse responses of the transponders and the small corner reflectors. Six bigger corner reflectors were located in the surrounding region. At the beginning of the campaign the transponders were aligned absolutely one-time with a differential GPS for the north orientation and a tachymeter for the elevation adjustment. With this reference it was possible to carry out the overpass alignment in azimuth and elevation automatically with a high precision positioner. On the other hand the corner reflectors were aligned manually with an inclinometer and a compass.
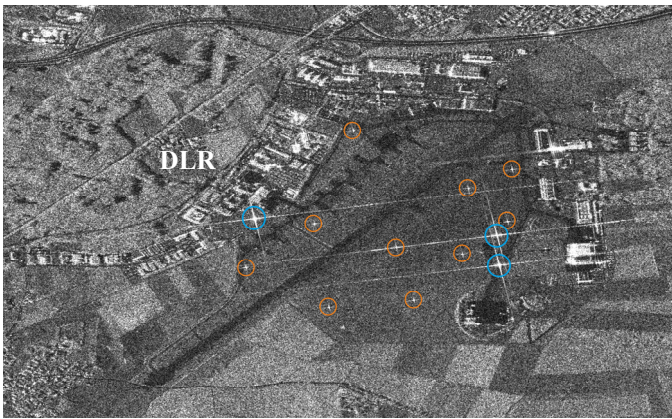

Fig. 4. One of seven RADARSAT-2 images of three transponders with strong backscattering and ten 1.5 m corner reflectors at Oberpfaffenhofen, Germany, acquired in February 2014.

B. Evaluation of the RCS

The evaluation of the transponders' RCS was conducted in following three main steps:

- Extraction of the image target power derived by integrating over side-lobes and subtraction of the background clutter.
- Satellite drift compensation by Bayesian statistics and hierarchical modelling.
- Determination of the transponder RCS by means of the 1.5 m corner serving as reference.

Within this campaign, the RADARSAT-2 system was considered radiometrically uncalibrated because the daily, systematic drifts, albeit small for operational conditions, exceeded the requested accuracies. Therefore after extracting the image power for each target and overpass, it was necessary to remove this drift by a method described in detail in [9]. Figure 5 shows the resulting image power of all targets and overpasses.
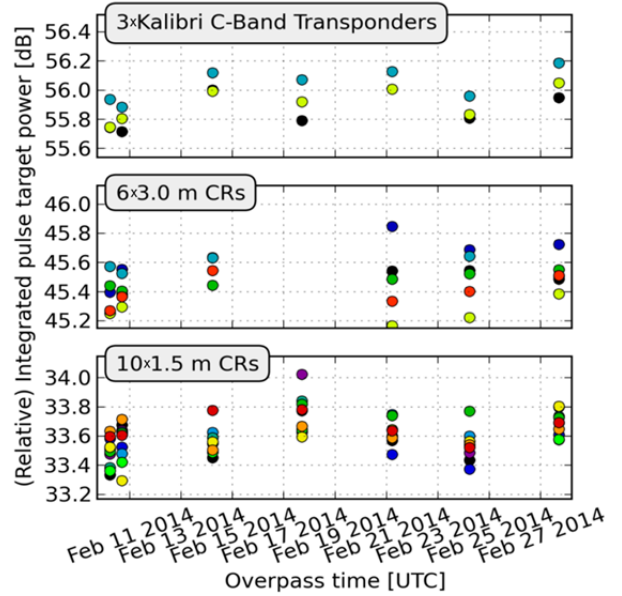

Fig. 5. Derived integrated image power of each target per campaign day. This data set is the starting point for the subsequent hierarchical Bayesian data analysis, which estimates the transponders' RCS and their measurement uncertainties.

The final transponder RCS was then calculated according to the relationship in (2). The results and the corresponding probability density intervals are summarized in TABLE II. The comparatively small standard uncertainty of 0.21 dBm^2 (1 σ) is dominated by the RCS knowledge uncertainty of the 1.5 m corner reflectors.

TABLE II. RCS MEASUREMENT RESULTS INCLUDING 95 % HIGHEST PROBABILITY DENSITY INTERVAL (HPDI, DERIVED FROM BAYESIAN ANALYSIS).

Target	RCS [dBm²]	95% HPDI [dBm²]
Kalibri 1	60.61	[60.20; 60.98]
Kalibri 2	60.81	[60.43; 61.19]
Kalibri 3	60.70	[60.31; 61.08]

C. Cross Validation

As a single measurement setup always carries the risk of an overseen systematic error further measurement setups for the estimation of the transponders' RCS were prepared and analyzed. One additional campaign, also based on method C, was executed in DLR's Compact Test Range (CTR). In this case two different sized circular metal plates were used as measurement standard. A further description and a detailed summary of the results can be found in [10].

Due to the fact, that the uncertainty budget of both campaigns is dominated by the knowledge of the required reference target, the DLR recently developed a novel calibration strategy. The principle of the so called "Three Transponder Method" is derived from the well-known three antenna method described in [11], and based on the radar equation. Analogue to the known method it is necessary to perform three measurements with different transponder combinations where one transponder is operated in the standard

mode and the second one is used as radar (create, emit and record radar pulses). This radar mode is a special feature of the 'Kalibri' transponders and the prerequisite for the feasibility of the novel method (see also section 2.D.). Up to now this strategy was not considered for the calibration of active reference targets. A detailed description, also containing first measurement results, is given in [12].

The results of all three campaigns were used to perform a cross validation and are shown in Fig. 6. The confidence intervals of all evaluated RCS estimates overlap in a significant region for all transponders. This indicates the plausibility of all methods and is also confirmed by the reasonably small difference of the RCS between all transponders. The performed validation proves the plausibility of the absolute radiometric calibration of the novel DLR transponder "Kalibri", described in the section before.
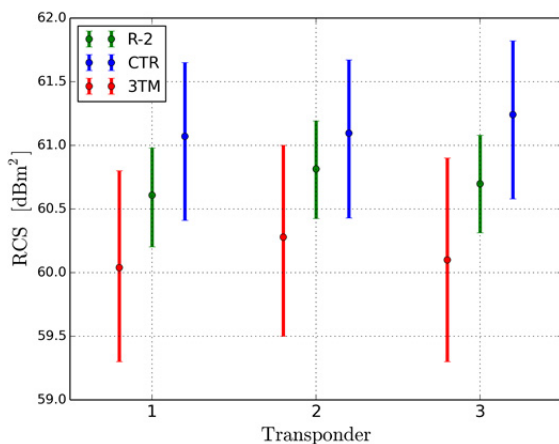

Fig. 6. Overview of the RCS of the three "Kalibri" transponders derived from all executed calibration campaigns (R-2: RADARSAT-2, CTR: Compact Test Range, 3TM: Three Transponder Method) with the corresponding 95% confidence intervals.

IV. CONCLUSIONS

In order to determine accurately the RCS of a transponder the paper describes four different measurement strategies and their uncertainty analysis. With respect to accuracy and feasibility the strategy "Transponder as Target – Comparison Measurement (B)" has been established as most suitable. This strategy was realized by using a SAR system in orbit. By means of RADARSAT-2 the DLR transponder could be absolutely calibrated down to an accuracy of only 0.21 dBm^2 (1 σ).

Two additional campaigns have been executed and analyzed in order to achieve a cross validation of this result:

- one setup based on the same strategy using a compact test range and

- one novel strategy recently developed by the Institute.

A summary of all three executed campaigns reveals that the campaign with RADARSAT-2 as 'measurement device' led to the lowest standard uncertainty but was realized with relative high efforts. Whereas the resulting RCS of each transponder

was one estimate averaged over the bandwidth of 100 MHz both of the other campaigns delivered an RCS estimate over frequency and angle.

Future developments and efforts are currently focused on the novel strategy, which has the potential to achieve a transponder calibration with even lower uncertainty due to absence of a radiometric reference target.

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