Comparison of Absolute Radiometric Transponder Calibration Strategies

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Abstract

Spaceborne synthetic aperture radars are systems capable of acquiring high-resolution earth-observation data independent on time of day and weather. These radar systems have to be calibrated before first use and at regular intervals. For these radiometric calibrations active targets with known backscatter, so called transponders, serve as an external reference. For determining the frequency-dependent radar cross section of these transponders, different measurement methods are available. This paper gives an overview of four different strategies with a following uncertainty analysis according to the *Guide to the Expression of Uncertainty in Measurement* (GUM). After comparison with respect to accuracy and feasibility, a recommendation for the best absolute radiometric transponder calibration method is given.

1 Introduction

Over the last decades, the geometric and radiometric requirements for a spaceborne synthetic aperture radar system (SAR) towards better product quality have constantly risen. This stresses the importance of a highly precise and accurate geometric and radiometric calibration. For this external calibration process, passive (corner reflectors) and active (transponders) reference targets are used [1]. By recording their known backscatter with the SAR instrument, the calibration parameters can be derived. The quality of the computed calibration parameters depends on the quality of the deployed transponders because they act as an external, absolute reference. An accurate knowledge of the reference targets' backscattering properties is the prerequisite for a high product quality of delivered SAR images.

The Microwaves and Radar Institute has been developed and manufactured a new C-band transponder [2] for the upcoming Sentinel-1 calibration campaign [3]. These targets need to be absolutely calibrated prior to their first use for SAR system calibration. This radiometric transponder calibration requires an accurate measurement of their radar cross section (RCS). For this purpose several different measurement methods are available, of which four will be described in this paper. An analysis of the respective measurement principles leads to the recommended method with respect to accuracy, feasibility and costs. Therefore tradeoffs between the mentioned issues are necessary to obtain a reliable radiometric calibration of the reference target.

2 Principles of the Calibration Strategies

Overall four different strategies for transponder calibration are analyzed. An introduction to the basic principles of all methods is given in this section.

2.1 Transponder as Target – Radar Equation (Method A)

The transponder is considered as a point target and is illuminated by the beam of a radar system. The model of the measurement setup ist shown in **Figure 1**. The RCS of the transponder σ_{Trsp} can be derived with the fundametal principle of the radar equation [4]

$$\sigma_{Trsp} = \frac{P_r \cdot (4\pi)^3 \cdot R^4}{P_t \cdot G_{t,rad} G_{r,rad} \cdot \lambda^2} \quad . \tag{1}$$

P_r and P_t are the power received and transmitted by the radar system and R represents the one-way distance between radar and transponder. $G_{t,rad}$ and $G_{r,rad}$ are the gain of the transmit and receive antenna of the radar instrument and λ signifies the wavelength of the radar signal.

The transponder RCS is derived by measuring all unknowns on the right-hand side of **Equation 1**.

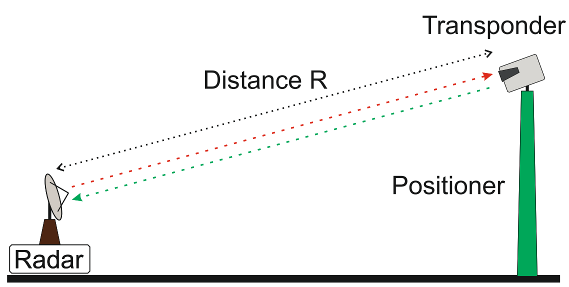

Figure 1: Model of measurement setup for "transponder as target - radar equation" strategy.

2.2 Transponder as Target - Comparison Measurement (Method B)

The second 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 in two different campaigns with an external radar system. **Figure 2** shows the measurement setup.

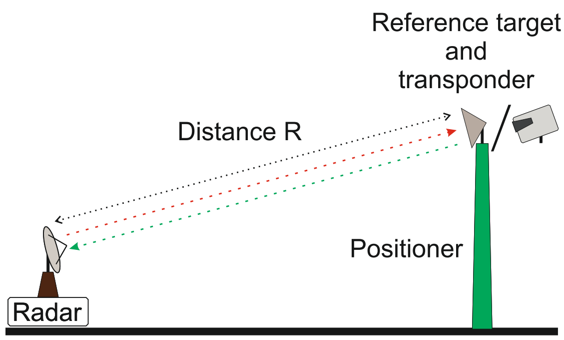

Figure 2: Model of measurement setup for "transponder as target - comparison measurement" strategy. A separated measurement for each target has to be executed.

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

$$\sigma_{trsp} = \frac{P_{r,trsp}}{P_{r,ref}} \cdot \sigma_{ref} \tag{2}$$

where σ_{ref} is the known RCS of the reference target.

2.3 Transponder As Radar (Method C)

In addition to the regular usage as a point target, 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 derive the transponder RCS from a measurement with a reference target with known radar cross section. **Figure 3** shows the measurement setup.

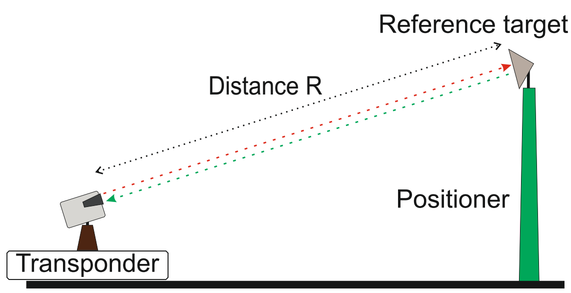

Figure 3: Model of measurement setup for "transponder as radar" strategy.

The underlying causality for the transponder RCS σ_{trsp} is given by [5]

$$\sigma_{trsp} = \frac{P_{r,trsp}}{P_{t,trsp}} \cdot \frac{(4\pi)^2 R^4}{\sigma_{ref}} \quad . \tag{3}$$

Besides the measurement of the ratio of the receive to the transmit power $P_{r,trsp}/P_{t,trsp}$ of the transponder, the distance R between radar and target has to be determined. With the known backscatter of the reference target σ_{ref} the radar cross section of the transponder can be computed.

2.4 Complex Gain Measurements (Method D)

The transponder radar cross section can be derived by determining the total loop gain of the transponder with three individual measurements for

- the receive antenna gain G_r,
- the transmit antenna gain G_t, and
- the gain of the radiofrequency system G_{sys}.

The essential equation for this strategy is given by [6]

$$\sigma_{trsp} = \frac{G_t G_r G_{sys} \cdot \lambda^2}{4\pi} \quad . \tag{4}$$

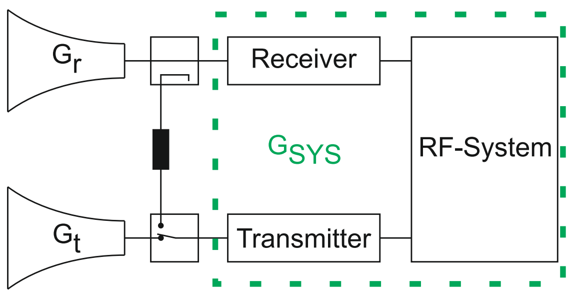

Figure 4: Model of transponder setup with internal calibration loop.

3 Review of Calibration Strategies

3.1 Uncertainty Analysis based on GUM

A statement on measurement uncertainty is a prerequisite for any determination of a measurand. The *Guide to the Expression of Uncertainty in Measurement* (GUM) [7] provides general rules for deriving the uncertainty of measurement quantities (here the transponder RCS). The overall uncertainty of the measurand is defined by the process equation of the measurement model and the corresponding uncertainties of all input quantities. In the GUM the input quantities are expressed as type A or type B uncertainties. The evaluation of type A uncertainties is derived from series of repeated observations, whereas type B uncertainties are derived from any other sources (for instance expert knowledge or data sheet).

For all calibration strategies described above, the theoretical overall measurement uncertainties are derived according to GUM. Therefore the uncertainties of all input quantities are estimated at first and assigned to the corresponding method:

Drift Network Analyzer (Type B)

The drift of the measurement device can be taken from a data sheet and is declared here with 0.05 dB [8].
Influence on methods: A, B, D

Antenna Measurement (Type B)

The gain of transmit and receive antenna of the transponder G_t and G_r can be determined with a standard gain horn comparison measurement. The uncertainty of the measurement is assessed to be 0.3 dB [9]. For the gain calculation of the reference horn, an uncertainty of 0.1 dB is estimated. Assuming that both error contributions are stochastically independent, the overall uncertainty is given by the root mean square yielding an accuracy of 0.32 dB for one antenna.
Influence on methods: A, D

Distance Measurement (Type B)

The main uncertainty arises not from the measurement execution with a tachymeter, but from an inadequate knowledge of the location of the antenna phase center. An estimation of this uncertainty with 0.15 m on a measurement range of 150 m leads to a relative uncertainty of 0,004 dB.
Influence on methods: A, C

Transponder Alignment (Type A)

Due to mechanical errors during the alignment process, a maximum misalignment of 0.5° is feasible, resulting in a radiometric uncertainty of 0.02 dB (based on shape of the antenna pattern) [10].
Influence on methods: A, B, C

Transponder Drift (Type A)

During measurement execution, the transponder gain varies due to thermal drift of the mounted RF-components. Based on an included temperature control and an internal calibration loop (see **Figure 4**), a transponder drift uncertainty of 0.05 dB is determined [11].
Influence on methods: A, B, C

RCS Reference Target (Type B)

The RCS of a trihedral corner reflector can be determined with physical optics approach and field simulations, with a remaining uncertainty of 0.2 dB. Furthermore mechanical deformations and misalignment of the reference target contributes to an inaccuracy of 0.1 dB in practice. Thus the overall reference target uncertainty of 0.22 dB is given by the root mean square, supposing that both error contributions are stochastically independent [11].
Influence on methods: B, C

Based on the uncertainty of all input parameters described above, the uncertainty for every calibration strategy can be determined. Due to the corresponding process equation, the influence of the input quantities distinguishes for every method. The resulting uncertainties (represented with standard deviation σ) for the estimation of the radar cross section of the transponder are shown in **Table 1**.

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

Table 1: Calculated overall measurement uncertainties for different calibration strategies according to [7].

3.2 Consideration of the Uncertainty Analysis

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.
For achieving the theoretical uncertainties derived in **Table 1**, measurements with great efforts and best measurement conditions are necessary. In practice some influences not considered or underestimated could lead to further uncertainties. An increasing variance of the measurement results is an indication for this, i. e., the measurement environment has an decisively influence to the overall measurement uncertainty. This effect can be specified by analyzing the results of repeated measurements of the same method.
With regard to feasibility, the "transponder as radar" strategy has some crucial disadvantages compared with the "transponder as target – comparison measurement" method. Specifically, comparatively narrow-band (100 MHz) transponders, time gating technique's are not well suited for multipath suppression because of the related insufficient spatial resolution.
Furthermore, in case of a transponder design, based on one antenna (for receive and transmit), the duration of the radar pulse has to be adapted to the measurement range for time separation of the transmit and the receive pulses. Thus, either a large measurement range is required or the measurement have to be executed with extreme small pulse length yielding additional uncertainties (transient response).
It can be concluded that the "transponder as target - comparison measurement" is advantageous with regard to practicability and can be considered as the best method among the four analyzed for the external calibration of

the transponder.
At DLR several indoor and outdoor measurement campaigns were executed according to "transponder as target - comparison measurement" strategy. By an outdoor antenna measurement facility the transponder RCS was determined using two corner reflectors of different size and serving as reference targets. The measurement uncertainty computed for this campaign with 0.36 dB (1σ) is slightly higher than the theoretical one derived in **Table 1**, as additional error contributions arising from the measurement setup were considered.
An approach for two further measurement campaigns with corresponding uncertainty analysis is given by [12].

4 Conclusions

This paper compares four different strategies for the calibration of an active reference target, which may then be used for the calibration of spaceborne SAR systems. The theoretical principles of all methods including the corresponding process equations are introduced. For the subsequent comparison a measurement uncertainty analysis was executed by two steps. First the uncertainties of all input parameters are quantified, followed then by deriving the resulting measurement uncertainty for all strategies. Due to practical considerations the "transponder as target – comparison measurement" strategy is finally recommended as the most suitable method for the transponder RCS measurements.

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