# TerraSAR-X Calibration Ground Equipment

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***Abstract*— The German SAR satellite TerraSAR-X was successfully launched in June 2007. Before it is ready for scientific and commercial use, the instrument has to be calibrated to ensure highly accurate data products. The calibration procedure includes a 6 month lasting field campaign during which reference point targets are being distributed in the South of Germany. This paper describes these reference targets (i. e. ground receivers, passive corner reflectors, and active transponders) and their characterization.**

## I. Introduction

TerraSAR-X is the first German SAR mission, which is realized by a public-private partnership between DLR and EADS Astrium GmbH. The instrument is designed to serve both scientific and commercial applications, and is required to be highly precise (absolute radiometric accuracy better than 1 $dBm^2$). It operates at X-band frequencies. In order to achieve high relative and absolute radiometric accuracies as well as a precise geometric calibration, the SAR instrument is being fully validated and characterized by internal and external calibration procedures since the launch in June 2007 [1]–[3]. The on-ground calibration campaign is carried out during the first six months after the launch during the commissioning phase of the satellite. Active and passive point reference targets and ground receivers are being deployed in a calibration field in the South of Germany. The goals of this calibration campaign are to acquire

- Geometric calibration
- Relative radiometric calibration
- Absolute radiometric calibration

The instrument features an electronically steerable antenna array. Since TerraSAR-X allows operation in different modes, many (more than 10 000) antenna beams exist. Since it is not possible to calibrate each beam in a reasonable amount of time, a new approach had to be taken. In this antenna model approach [4], a precise antenna model has been created prior to launch based on on-ground measurements. The subsequent goal is to verify the antenna model in space for several antenna beams to ensure that the model is accurate. This approach therefore adds another requirement for the calibration campaign: The antenna patterns in azimuth and elevation need to be measured.

The calibration ground equipment which is used during the calibration campaign is shown in Fig. 1. Passive targets (i. e. trihedral corner reflectors), active targets (i. e. transponders), and ground receivers constitute the utilized targets. For transponder/receiver initialization and data evaluation, software tools are necessary. In order to accurately position and align the targets with the main beam of the SAR instrument, D-GPS receivers and precise compasses and clinometers are used.

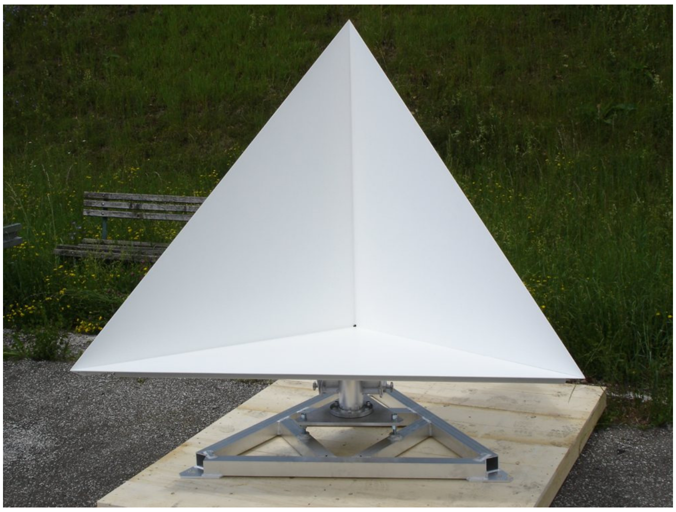

Fig. 2. Passive calibration target: Trihedral corner reflector with an inner leg length of 1.5 m.

The quality of the TerraSAR-X instrument products depends highly on the calibration of the instrument. The uncertainty for the resulting data products with respect to relative and absolute radiometric accuracy is directly influenced by the radiometric uncertainties of the utilized reference targets. Therefore it is important to precisely characterize the ground equipment prior to the in-orbit calibration of the satellite.

In the following, the ground equipment used during the in-orbit calibration campaign and the tests performed to characterize the equipment are described.

## II. Passive Targets

Passive calibration point targets offer several advantages over active transponders. They can be build with high radiometric accuracies, do not delay the reflected signal (a desired property for geometric calibration), and are relatively robust for field-use during the calibration campaign. On the other hand, they are bulky and cannot easily be moved to a new location, and they obviously do not allow for data recording.

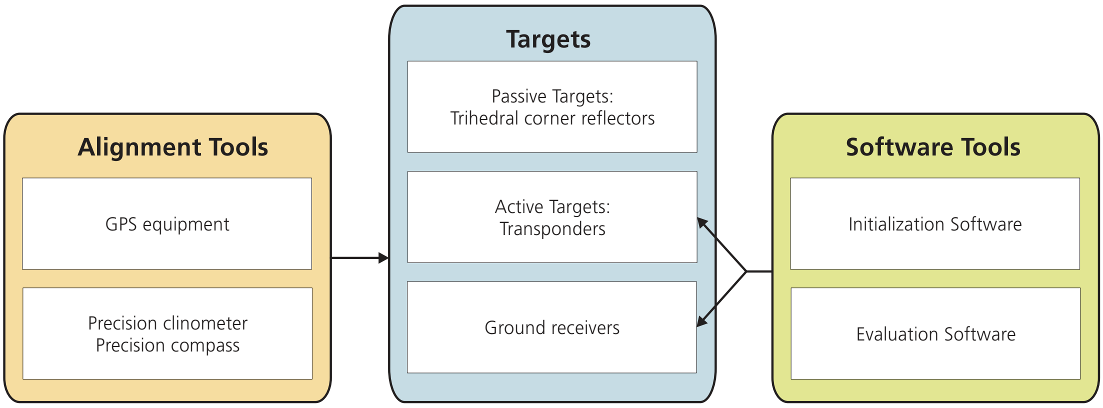


Fig. 1. Overview of the calibration ground equipment.

During the calibration campaign, triangular-faced trihedral corner reflectors in two sizes are used, which feature different radar cross sections (RCS, symbol $\sigma$) at the center frequency of 9.65 GHz:

- Inner leg length of 1.5 m, $\sigma = 43.4\,\mathrm{dBm}^2$
- Inner leg length of 3.0 m, $\sigma = 55.5\,\mathrm{dBm}^2$

An image of one of the smaller corner reflector is shown in Fig. 2.

The uncertainty of the radar cross section is mainly governed by the following factors:

- Misalignment from cardinal direction
- Interplate orthogonality error
- Plate curvature deviation
- Surface irregularities

Trihedral corner reflectors are relatively insensitive to misalignments which is a main reason for their use. Utilizing precise levels and compasses (taking the local declination into account), an alignment accuracy of 0.5° for both azimuth and elevation can be achieved. This results in a misalignment uncertainty of below 0.1 dB.

The radar cross section of corner reflectors can be easily computed for the ideal case. However, mechanical imperfections will lead to a reduction of the theoretical value. Empirical formulas exist which describe this reduction, and they are summarized in [5]. The manufactured corner reflectors with an inner leg length of 1.5 m meet the following tolerances:

- Interplate orthogonality $\leq 0.2°$
- Plate curvature $\leq 0.75$ mm
- Plate surface irregularities $\leq 0.5$ mm

All three values are known with an uncertainty for angular measurements of (1/60)° and for distances of 10 $\mu$m. These tight tolerances show that special care has to be taken during the field campaign to avoid unnecessary mechanical stress, which might lead to a deviation from the originally measured values. From these values, the RCS reductions have been computed to achieve the actual radar cross section of each reflector. An absolute radiometric accuracy of better than 0.3 dBm$^2$ results.

Fig. 3. Ground receiver. The housing can be rotated in steps of 45° to allow polarimetric characterization of the satellite.

## III. Ground Receivers

16 field-deployable ground receivers were built by the Universität Karlsruhe, Germany. They allow to record the pulsed radar signal at a sampling rate of 10 MHz for up to 20 s. The dynamic range is 40 dB, and the frequency band ranges from 9.5 GHz to 9.8 GHz. The weather-proof housing allows outdoor use.

### A. Alignment

The horn antennas have a half-power beam width of about 13°, which means that the ground receiver is more sensitive to misalignment with respect to the instrument's main beam direction than a trihedral corner reflector. During field campaigns, the receivers are aligned in azimuth and elevation by $\pm 0.25°$.

The receivers are mounted on a round baseplate which allows the rotation of the receive antenna around the receiver

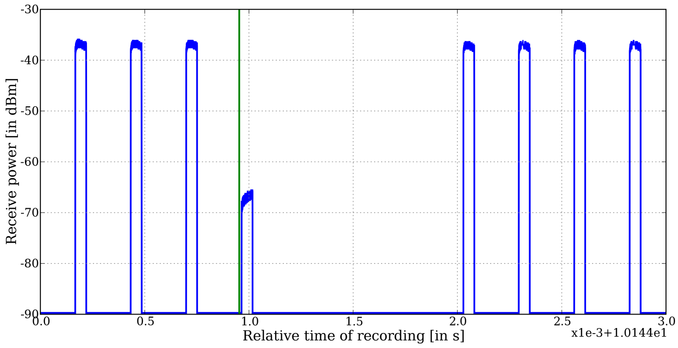


Fig. 4. Ground receiver: Verification of receiver/instrument synchronisation. The timestamp (vertical line) matches, as expected, the rising edge of the first calibration pulse.

main-lobe axis. This is how the receive polarization can be set for H, V, and H-V polarization.

*B. Precise Timing*

The ground receivers are used to assess the antenna pointing of the satellite. For this purpose precise absolute timing information bound to the recorded pulses must be known. This has been realized by an internal GPS receiver which serves as a reference clock. The GPS receiver's pulse-per-second signal is recorded along with the datatake. From this information, the actual sampling rate of the ground receiver can be determined and the absolute time of the first sample computed. Measurements with a reference source confirmed that the sampling rate does not vary significantly during one recording, and that precise timing information can be deducted from the recorded GPS timing information. The absolute timing information is better than 1 $\mu$s, fulfilling the requirement.

As an in-orbit receiver verification, a datatake including internal calibration pulses was recorded. Internal calibration pulses intercept nominal transmission and are easily distinguished from nominal pulses in the recorded datatake since the receive power appears reduced or no external pulses are being transmitted. By synchronizing the instrument and receiver times, each pulse in the receiver recording can be mapped to a transmitted instrument pulse. This mapping is exemplary shown in Fig. 4, where the timestamp (vertical line) matches, as expected, the rising edge of the first calibration pulse. This shows that each transmitted pulse can later on be extracted separately by the timing only.

*C. Software*

The recorded digital values have to be post-processed to convert digital values into meaningful power levels. In this step a compensation is included to take the antennas' and electronics' frequency response for all power levels and temperatures into account. This compensation is based on the device characterization performed by the Universität Karlsruhe.

An exemplary receiver datatake, which lasted 20 s, is shown in Fig. 5. As expected, the main lobe is off-center by less than a second (the remaining offset has mainly to do with the

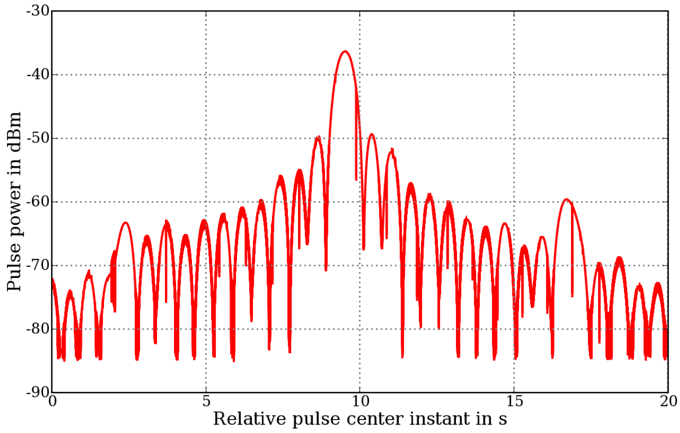


Fig. 5. Recorded datatake from a ground receiver showing the azimuth pattern.


Fig. 6. Active target (transponder). The transponder housing including the antennas can be rotated which results in different scattering matrices.

granularity by which the overflight time can be configured). The occasional notches (showing as vertical lines in the pattern, for instance at about 17 s in Fig. 5) do not state an error in the recording, they merely represent calibration pulses (compare with Fig. 4).

## IV. Active Targets

Transponders emulate the behavior of a passive corner reflector. The main building blocks are a receive antenna, a high-precision amplifier, and a transmit antenna. The main advantages of a transponder over a corner reflector are its small size and therefore portability, and the possibility to easily change the receive and transmit polarization. The main disadvantage lies in the fact that a precise electronic amplification for a relative large temperature range (outdoor use) is difficult to implement.

18 transponders (see Fig. 6) were build by the Universität Karlsruhe. The transponders can both record a received signal (analog to a ground receiver) and retransmit it with a known amplification $G_e$. The transponders have a maximal radar cross section of 50 dBm$^2$ for an unipolar operating SAR instrument

(HH, VV), and 56 $\mathrm{dBm}^2$for a cross-polar operating instrument (HV, VH). This is because the transponder receive and transmit antennas are rotated by 90° to achieve a high transmit/receive decoupling.

Assuming known receive and transmit antenna gains, $G_r$ and $G_t$, as well as the electronic amplification $G_e$, the transponder RCS $\sigma$ can be computed according to

$$\sigma = \frac{\lambda^2}{4\pi} G_r G_e G_t \,, \tag{1}$$

where $\lambda$ is the wavelength [6]. An adjustable attenuator in the transmit path results in a 20 dB RCS range from about 30 $\mathrm{dBm}^2$ to 50 $\mathrm{dBm}^2$ for the nominal antenna orientation.

The basic functionality and design is identical to that of the ground receivers. The signal delay between receive and transmit is 5.5 ns, which translates to 1.65 m in slant range. The known delay can be taken into account for geometric calibration.

The uncertainty with respect to the transponder RCS for the absolute radiometric calibration of the instrument is required to be better than 0.5 $\mathrm{dBm}^2$. Therefore, the electronic amplification has to be precisely known for all relevant frequencies, receive power levels, and temperatures. This will be discussed in the following sections.

### A. Temperature Stability

The transponders are equipped with an internal temperature compensation to allow an operation in winter (say $-15$ °C) and summer (35 °C) scenarios. Climatic chamber measurements showed that the initial approach of the internal temperature compensation works well only for the summer scenario. For the summer scenario the gain oscillates by about 0.1 dB over temperature, which is well inside the requirement. For the winter scenario, the resulting gain variations exceeded the required accuracy.

As a solution, a controlled transponder heating and thermal insulation was added. Basically, the operation was shifted to the summer scenario even for lower ambient temperatures. Repeated climatic chamber tests showed that now the transponder gain does not vary by more than 0.1 dB over temperature once the warm-up phase is completed, and that now the requirement can be met.

### B. Antennas

The antennas are identical in construction as the ones used for the ground receivers. The transponder support allows for the rotation of the transponder in 45° steps (round base plate in Fig. 6). Therefore, the transponder can receive and send in three different polarizations, allowing polarimetric calibration of the satellite.

The feeds of the receiving and transmitting antennas are separated by about 80 cm. This along with an orthogonal orientation of the antennas results in a high decoupling. Measurements confirmed that antenna coupling can be neglected.

To measure the antenna gains, the antennas were disassembled and measured separately in a test range. To ensure that no mutual coupling between the antennas or the transponder housing influences the values, the gain has also been determined by mounting the complete transponder on the positioner while the antennas were mounted as for the nominal configuration. A comparison of the results showed that mutual coupling and the transponder housing do not influence the antenna gain.

The measurements also showed that, as expected, the antenna rotation is critical for the 45° orientation. Slight rotational misalignments (in the order of 2°) of the antennas on the transponder housing or a slightly tilted antenna feed result in measurable antenna gain differences, which are also being taken into account.

TABLE I

ERROR TERMS OF TRANSPONDER RADAR CROSS SECTION.

| Error term | Error ($1\sigma$) in dB |
|---|---|
| Temperature stability (internal compensation) | 0.1 |
| Rx antenna gain | 0.2 |
| Tx antenna gain | 0.2 |
| Rx antenna port mismatch | 0.05 |
| Tx antenna port mismatch | 0.05 |
| Transponder gain | 0.1 |
| RSS | 0.33 |

### C. Absolute Radiometric Accuracy

The combined radiometric uncertainty results from the individual uncertainties. The individual uncertainties, which are statistically described by Gaussian distributions, are listed in Tab. I. They can be combined by the method of root-sum-squares (RSS) and result in a $1\sigma$ uncertainty of 0.33 $\mathrm{dBm}^2$.

Additionally, a deviation of $\pm 0.1$ dB was observed for the climatic chamber measurements which cannot be described by statistical means. This was added linearly to the previously determined combined uncertainty. The resulting absolute $1\sigma$ uncertainty of the transponder RCS is 0.44 $\mathrm{dBm}^2$, which fulfills the requirement.

## V. CONCLUSION

This paper discussed reference targets (i. e. corner reflectors, ground receivers, and active transponders) which are being used during the TerraSAR-X calibration campaign. Special attention has been given to the radiometric accuracy of the reference targets. It was shown that the corner reflectors' uncertainty with respect to the radar cross section is better than 0.3 $\mathrm{dBm}^2$ and that of the active transponders' is better than 0.5 $\mathrm{dBm}^2$. Therefore, precise calibration of the TerraSAR-X mission based on these reference targets is possible.

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