Absolute Radiometric Calibration of TerraSAR-X – Approach and Ground Targets

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***Abstract*— The German SAR satellite TerraSAR-X was successfully launched in June 2007. During the commissioning phase, the first months after launch, a calibration field campaign was carried out to conduct geometric as well as relative and absolute radiometric calibration. This was necessary to prepare the satellite for scientific and commercial use. This paper addresses results concerning the absolute radiometric accuracy and the reference ground targets involved. The two types of utilized ground targets were trihedral corner reflectors and active transponders. It will be shown that an absolute radiometric accuracy of much better than 1 dB can be achieved using both types of targets.**

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, i. e. the absolute radiometric accuracy is specified to be better than 1 dB. In order to achieve high relative and absolute radiometric accuracies as well as a precise geometric calibration, the SAR instrument was characterized and verified by internal and external calibration procedures [1]–[4] during the 5 months lasting calibration campaign, which began shortly after the launch in June 2007.

The main objective of the imaging system is to acquire a georeferenced backscatter coefficient for each image element. Absolutely calibrated data can only be achieved after considering and incorporating many different influences. The instrument's state needs to be closely monitored and adjusted, and the respective impacts on the recorded data need to be compensated during data processing. This is referred to as internal calibration. Second, the antenna beams need to be known. The SAR instrument features an electronically steerable antenna array. Since TerraSAR-X allows operation in a multitude of modes, a large number (about 12 000) antenna beams exist. Since it is not possible to measure each beam in a reasonable amount of time, a new approach had to be taken. In this antenna model approach [5], a precise antenna model was created and validated prior to launch based on on-ground measurements. The final verification of the antenna model was performed in space by measuring a few selected beams only, and therefore fulfilling the tight commissioning phase schedule.

The internal calibration, the antenna model, and subsequent data processing lead to a relatively calibrated image. In the last step, each image intensity (i. e. gray value) is bound to a backscatter coefficient by means of absolute radiometric calibration. Not until then can a physical meaning be attached to the measured amplitudes.

In practice, absolute radiometric calibration is being achieved as for all measurement instruments: The instrument's output is related to a known measurement standard. For absolute radiometric calibration, point targets, i. e. trihedral corner reflectors and active transponders, were used [6]. They have been distributed in the South of Germany during a more than five months lasting calibration field campaign.

One problem in determining the absolute calibration factor is that highly precise measurement standards are needed. They are the only link between measured amplitudes and absolute radiometric backscatter coefficients. It will be shown that the RCS for both groups of calibration standards (corner reflectors and transponders) was determined independently while at the end yielding a close match for the absolute calibration factor. This is a very good indication for the quality of the absolute calibration.

II. Point Targets

Both distributed and point targets could be employed for the absolute radiometric calibration. Due to the lack of distributed targets (rain forest, flat surfaces, etc.) for which the backscatter coefficient is precisely known, only point targets are being used. They themselves can more readily be calibrated based on geometric considerations or laboratory measurements.

A. *Trihedral Corner Reflectors*

A trihedral corner reflector is a metallic structure featuring three orthogonal, triangular plates, See Fig. 1(a) for an example. Its ideal radar cross section (RCS) can easily be computed based on its mechanical dimensions according to

$$\sigma_{RCS} = \frac{4}{3}\pi \cdot \frac{l^4}{\lambda^2} \tag{1}$$

where l is the inner leg length and λ the wavelength [7]. Possible losses due to mechanical imperfections can be assessed and are explained below.

Corner reflectors offer several advantages over active transponders. They can be build with high radiometric accuracies, do not delay the reflected signal (a desired property

(a) Trihedral corner reflector with an inner leg length of 1.5 m. (b) Active transponder.

Fig. 1. Calibration ground targets.

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, they obviously do not allow for data recording, and it is rather difficult to repeatedly assess geometrical imperfections over time. During the calibration campaign, triangular-faced trihedral reflectors featuring an inner leg length of 1.5 m were used. At the TerraSAR-X center frequency, this results in an RCS of 43.3 dBm^2.

The uncertainty of the radar cross section is mainly governed by the following factors: (a) misalignment from cardinal direction, (b) interplate orthogonality error, (c) plate curvature deviation, and (d) surface irregularities [8], all of which result in a decreased RCS. The remaining 1σ RCS uncertainty was determined to be 0.3 dBm^2 or below.

B. Transponders

Transponders (see Fig. 1(b)) are battery-operated, field-deployable calibration targets, which first of all emulate the functionality of a passive target. They basically consist of a receive antenna, a precise RF amplifier, and a transmit antenna. By accurately knowing the receive and transmit antenna gains G_r and G_t, and the electronic amplification G_e, the transponders' RCS can be determined according to

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

where λ is the wavelength [9]. By rotating the antennas with respect to the incident wave, the receive/transmit polarization can be modified. Additionally, the transponder allows to digitally sample the received signal and to store it internally for later analysis. Besides the receive power, precise timing information is recorded which allows analysis of the satellite antenna's pointing and orbit position.

In the following, the key technical parameters for the transponders, which were built by the Universität Karlsruhe, are being summarized:

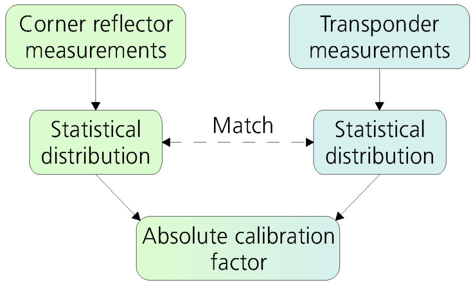

Fig. 2. Two independent lines of measurements for determining the absolute calibration factor.

- Frequency band: 9.5 GHz to 9.8 GHz
- RCS: nominal 50 dBm^2, range from 30 dBm^2 to 56 dBm^2
- Possible polarisations (receive/transmit): H/V, V/H, HV/HV
- Dynamic range: 40 dB
- Weather-proof housing
- Battery operation: 12 V

Transponders offer some main advantages over corner reflectors: They are smaller (considering the same or even larger radar cross section) and are therefore more portable, their receive and transmit polarization can easily be changed (yielding different scattering matrices, which are important for polarimetric calibration), and they can record the received SAR pulses. The main disadvantage lies in the fact that a precise electronic amplification for a relative large temperature range (outdoor use) is difficult to implement. The utilized transponders feature a remaining 1σ uncertainty of less than 0.5 dB and are therefore slightly less precise than the corner reflectors. On the other hand, they feature a higher RCS so that the signal-to-background ratio is improved.

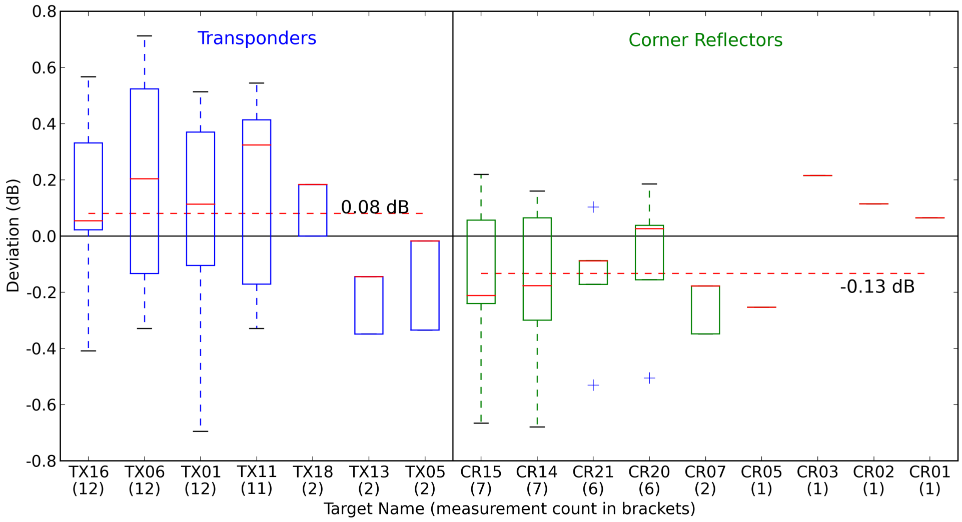

Fig. 3. Statistical visualization for the two groups of Stripmap point target measurements (TX for transponder, CR for corner reflector). Respective mean values indicated as dashed (red) line.

III. Absolute Calibration Factor

The point targets' RCS has a direct impact on the resulting absolute calibration factor, which itself is the link between measured amplitudes and absolute radiometric backscatter coefficients. Therefore, utmost care must be taken to ensure highly precise results. Since two groups of point targets have been utilized, two independent sets of measurements can be performed to determine the absolute calibration factor. If a close match can be found, this ensures improved confidence in the overall result. The approach is illustrated in Fig. 2. Then these measurements need to be combined to yield a highly precise absolute calibration factor.

The absolute calibration factor derived from each target of known RCS and each measurement is determined at the last step after internal calibration and antenna pattern have already been taken into account for relative radiometric correction. This implies that the remaining uncertainty of the absolute calibration factor does not only depend on the point targets' accuracy and stability, but also on:

- SAR instrument stability (internal calibration)
- Residual atmospheric effects
- Post-processing errors

The analysis software Calix [10] was used to determined the absolute calibration factor. The software integrates the signal energy of the point target impulse response and subtracts the background contribution to increase the accuracy.

Fig. 3 shows a boxplot of 85 Stripmap mode measurements performed to assess the absolute calibration factor. Note that rain-effected measurements were filtered out based on weather observations during the overflights. The ordinate is normalized with respect to the final absolute calibration factor and therefore the individual deviations from the final (mean) absolute calibration factor for each target is directly visible. The point targets are sorted according to type (transponders and corner reflectors) and number of measurements performed with each target. The median value for each target is indicated as a horizontal red line, and the box itself contains 50 % of the measurement values.

Looking at the spread it becomes obvious that the standard distribution for corner reflectors is smaller than for transponders. This was expected since the transponders were specified to be less accurate from the outset, a result of the more complex design of active targets. Maybe the most important detail given in the plot is the mean value for both groups of point targets (indicated as a dashed, red line). The difference characterizes the match between both sets of measurements, and can be stated as 0.21 dB. This already indicates a precise knowledge for the absolute reference, the link between measured amplitudes and backscatter coefficients. The precise knowledge is required in order to adjust the whole SAR system to an absolute radiometric accuracy of better 1 dB .The offset of 0.21 dB between the corner reflector and transponder measurements can partially be attributed to the transponder housing and mount, which slightly increases the radar cross section. This has not been taken into account in Eq. (2).

Further statistical parameters are summarized as follows:

μ_{CR}	-56.71 dB
μ_{TX}	-56.50 dB
σ_{CR}	0.24 dB
σ_{TX}	0.32 dB
μ	-56.58 dB
σ	0.31 dB

The last two values represent the mean and standard deviation, respectively, for all (combined) measurements.

The determined parameters are only estimates of the true mean and the true standard deviation, since only a limited number of measurements could be performed. The question arose how precise the estimated absolute calibration factor, i. e. $\mu = -56.65$ dB is. First, it was analyzed if the combined measurements are normally distributed since only then are

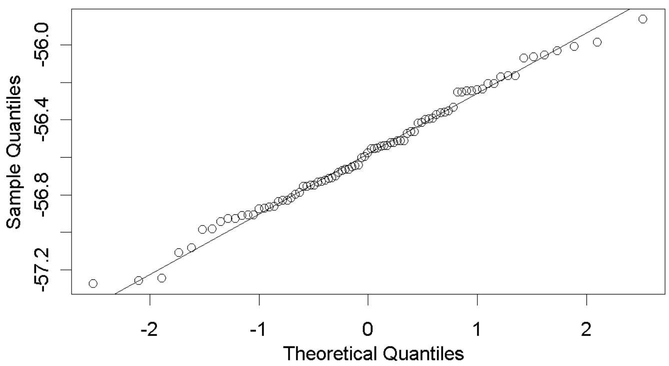

Fig. 4. Normal quantile-quantile plot for all measured absolute calibration factors.

μ (mean) and σ (standard deviation) meaningful parameters. Quantitatively this was verified using the Kolmogorov-Smirnov test, visually it is shown in Fig. 4, where a good match between the data points and the line (indicating normal distribution) indicates normal distribution.

In the next step, a confidence interval for μ was determined. Following the procedure as given in [11], it can be concluded that the 95 % confidence interval for the absolute calibration factor is [-56.64; -56.51] dB, or $\mu_{0.95} = (\text{-}56.58 \pm 0.07)$ dB. After completing the calibration campaign, the absolute calibration factor is known to an accuracy better than 0.1 dB, a very precise result.

A similar confidence interval can be determined for the standard deviation. Following again [11], the 95 % confidence interval for the standard deviation is [0.27; 0.37]. It has to be noted that this value also represents the 1σ value of the absolute radiometric accuracy of the TerraSAR-X system, although with several constraints: First, effects due to rain are not included (due to the aforementioned filtering); second the error cannot yet reflect the influence of the long-term instrument stability; third a possible error due to non-linearities have not been fully characterized (since the targets only support two distinct radar cross sections); finally has to be noted that the calibration was performed for Stripmap only (in accordance with the calibration plan). Nevertheless, the 1σ error is surprisingly low in comparison to the requirement of an absolute radiometric accuracy of better than 1 dB.

IV. Conclusion

The approach and utilized ground targets for the absolute radiometric calibration of TerraSAR-X have been presented. The calibration is based on two sets of independent measurements, and it was shown that both transponder and corner reflector measurements fulfill the required accuracy. By proving that all values are normally distributed, it was shown that all measurements can be combined to yield the absolute calibration factor. Since the absolute calibration factor could only be estimated out of the limited number of measurements, a confidence interval was stated. After the calibration campaign, the absolute calibration factor is now known with a precision of better 0.1 dB.

Also, the standard deviation for absolute radiometric measurements during the commissioning phase was determined. Since the standard deviation for the absolute calibration factor equals the standard deviation of the absolute radiometric accuracy, these measurements are the first proof that TerraSAR-X is capable of delivering backscatter coefficients with a 1σ error below 0.4 dB. For nominal mode, rain effects and long-time drifts also have to be considered.

It can be concluded that, after incorporating the antenna model and the internal calibration, the TerraSAR-X instrument is capable of delivering highly precise products to the scientific community and the commercial market. For the first time, a complex SAR system like TerraSAR-X could be absolutely calibrated to an accuracy usually only found for laboratory equipment.

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