Application Article

First TerraSAR-X TOPS Mode Antenna Pattern Measurements Using Ground Receivers

Gabriel Castellanos Alfonzo,¹ Marco Schwerdt,¹ Steffen Wollstadt,¹ Markus Bachmann,¹ Björn Döring,¹ and Dirk Geudtner²

¹ German Aerospace Center (DLR), Oberpfaffenhofen, 82234 Wessling, Germany

² European Space Agency (ESA-ESTEC), Keplerlaan 1, 2200 AG Noordwijk, The Netherlands

Correspondence should be addressed to Gabriel Castellanos Alfonzo; gabriel.castellanosalfonzo@dlr.de

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The antenna model used for correcting the influence of the antenna pattern on synthetic aperture radar (SAR) images requires on-ground validation and in-flight verification. A methodology for the in-flight verification that is based upon the measurement of azimuth antenna patterns using ground receivers has been successfully demonstrated for the operational SAR modes of the TerraSAR-X (TSX) and TanDEM-X (TDX) missions. Recently, the novel (terrain observation by progressive scans) TOPS mode was for the first time implemented as an experimental mode on TerraSAR-X to demonstrate its feasibility in support of its implementation on ESA's Sentinel-1 mission. In this mode, besides scanning in elevation, the antenna beam is steered in flight direction from aft to the front at a constant rate to achieve an enhanced radiometric image performance. This paper discusses the methodology and presents results of the first in-flight antenna characterization of a SAR instrument operating in TOPS mode, in this case TerraSAR-X, using ground receivers. The results demonstrate that the TOPS one-way azimuth antenna pattern can be accurately modeled by the TSX antenna model indicating the general suitability of this approach for the in-flight antenna model verification during TOPS mode operations.

1. Introduction

The correct modeling of the phased-array antenna in a synthetic aperture radar (SAR) system is of main importance for precise SAR image processing. Accurate knowledge of the antenna characteristics is required in order to remove the influence of the antenna pattern from the image during SAR processing. The large number of SAR beams used by modern SAR satellite missions along with the requirement for having a short duration of the commissioning campaigns requires a SAR calibration concept that is mainly based on the use of a precise antenna model [1]. Other elements of such a calibration concept include the internal calibration and in-orbit health check of the SAR antenna system based on the pseudonoise gating method [2]. Thus, only a limited number of SAR imaging beams would need to be actually measured during the commissioning phase. Following a previous on-ground validation, the antenna model needs

to be verified in orbit: in elevation by analyzing the two-way elevation pattern using acquisitions across homogeneous distributed scatterers, that is, Amazon rainforest, and in azimuth by measuring the one-way azimuth pattern using ground receivers (GRs).

In the case of TerraSAR-X (TSX) as well as TanDEM-X (TDX), the accuracy of the antenna model was verified to be ± 0.2 dB for the two-way elevation pattern and ± 0.1 dB for the one-way azimuth pattern [3]. Furthermore, the peak to peak gain offset between different beams in elevation was verified by evaluating ScanSAR data and proved to be less than ± 0.2 dB (peak to peak) [4]. These results demonstrated that the patterns of thousands of possible beam combinations could be accurately calculated from the available antenna model. Even as the TSX mission reaches its nominal end of life, the long-term monitoring of the SAR system has shown that the antenna gain and consequently the antenna model still achieve these accuracies [5].

Novel SAR modes such as the (terrain observation by progressive scans) TOPS mode impose new challenges on the SAR system calibration. In this mode, just like in ScanSAR, several subswaths are acquired by subswath switching in elevation from burst to burst. In addition to the elevation beam steering, the antenna azimuth beam is steered from aft to the fore within each burst at a constant rate [6]. As a result and in contrary to ScanSAR, all targets on ground are observed by the complete azimuth antenna pattern eliminating almost entirely the scalloping effect and achieving constant azimuth ambiguities and signal-to-noise ratio (SNR) along azimuth. However, the fast azimuth beam steering reduces the target dwell time and as such causes the virtual shrinking of the antenna footprint and thus a reduction of the spatial resolution in azimuth. Besides, TOPS acquisitions may still be affected by a residual scalloping caused by the shape of the subarray antenna element pattern [7, 8], albeit inferior to the scalloping observed in normal ScanSAR.

The novel TOPS mode was first implemented as an experimental mode on TSX to demonstrate its feasibility in support of its implementation on ESA's Sentinel-1 mission where it will be used as an operational imaging mode, that is, the interferometric-wide swath (IW) and the extrawide swath (EW) modes [9].

The motivation of this paper is to demonstrate that ground receiver measurements can be used for the in-flight characterization of TOPS one-way azimuth antenna pattern and as such for the verification of the antenna model. In particular, the methodology for preprocessing and analyzing TSX TOPS one-way azimuth antenna pattern acquired by GRs is discussed. This considers the beam switching not only between subswaths in elevation but especially in azimuth and consequently the beam-to-beam gain variation in elevation and in azimuth.

First, the characteristics of the implementation of the TOPS mode on TerraSAR-X and the impact on the TOPS antenna footprint are discussed. Second, the approach based on GR measurements and the reconstruction of the azimuth antenna pattern using the antenna model is explained along with the experimental setup. Finally, the TSX GR measurement results are presented and discussed.

2. TOPS Mode Characteristics

2.1. TSX TOPS Mode Implementation. The operation flexibility of the TSX mission [10] enabled the experimental implementation of the TOPS mode and the acquisition of TOPS data, which was demonstrated for the first time in 2007 [11]. However, the commanding of a TSX TOPS data take is challenging because the TSX SAR instrument was not designed for operating the TOPS imaging mode. Thus, acquisition parameters must be optimized taking into account the instrument constraints. Such constraints were explained by Meta et al. in [12]: first, only a limited number of azimuth beams can be stored on board; therefore the instrument cannot be continuously steered from pulse to pulse, causing a coarse steering angle step size; second, there is a limited number of azimuth beams that can be commanded on a single

acquisition; third, because of the limited number of azimuth beams that can be steered, the azimuth steering step size has a direct impact on the steering rate which determines the achievable azimuth resolution. As a consequence of the coarse azimuth steering step size (the minimum step for TSX is 0.013 deg), an amplitude modulation in the azimuth antenna pattern is introduced [7, 12].

2.2. TOPS Antenna Pattern. The TOPS antenna pattern, as seen by a point target and defined in a flat-earth coordinate frame, was approximated by [6] using

$$G_T(\vartheta(\tau)) \approx G_0 \text{sinc}^2 \left(\frac{L v_s \tau}{\lambda R_0} \left(1 + \frac{R_0 |k_\psi|}{v_s} \right) \right), \quad (1)$$

where G_0 is the antenna power gain, $\vartheta(\tau)$ is the azimuth angle as a function of time τ , v_s is the velocity of the satellite, λ is the radar wavelength, R_0 is the slant range to the closest approach point, L is the azimuth antenna length, and k_ψ is the antenna steering rate. The expression in (1) is equal to the ground footprint of a fixed antenna, that is, strip map, but shrunk by a factor [6]

$$\alpha = 1 + \frac{R_0 |k_\psi|}{v_s}. \quad (2)$$

The antenna pattern, as seen by a point target on the ground, can be simulated for the TSX case using the parameters shown in Table 1 and inserting them in (1). The resulting one-way azimuth pattern is shown as a full line in Figure 1. The plot shows that the TOPS azimuth pattern is compressed as compared to the pattern of a fixed antenna. It should be noted that the steering in elevation, that is, different subswaths, is not simulated.

The effects of the steering angle quantization described in the previous subsection are observed in the staircase shape of the pattern in Figure 1. However it should be noted that (1) is only an approximation, since it assumes a sinc²-like shape (bell) of the pattern. A more accurate representation of the TOPS antenna pattern is achieved by using a precise antenna model, which provides the exact steered azimuth beam patterns by means of changing the excitation coefficients of the active antenna array at a given rate.

3. Methods and Measurement Setup

3.1. Methodology. For measuring the TOPS antenna pattern during a satellite overpass, the deployed ground receivers (GRs) need to be aligned in direction to the line of sight of the SAR antenna in zero-Doppler position [13]. The used DLR ground receivers detect the received power with a logarithmic detector. The detector amplitude is digitized with an analog-to-digital converter. The digital values are stored within the GR and are read out in the laboratory after each overpass. The first step for data analysis is to transform the recorded digital samples to power expressed in dBm over a time axis. The time axis is derived from a GPS pulse-per-second signal, which was recorded by the ground receiver in parallel to the received power.

FIGURE 1: One-way azimuth antenna pattern gain in TSX TOPS mode as seen by a point target.

Due to the movement of the platform, the signal recorded by the GR represents a cut through the spherical antenna pattern. Naturally, the GRs can only measure the transmit pattern of the SAR antenna. This one-way azimuth antenna pattern is then obtained by considering the position of the target and the platform and transforming time units into equivalent azimuth angles. A correct time synchronization between the SAR instrument in orbit and the GR is required, because each received radar pulse must be mapped to the nominal excitation coefficients in elevation and azimuth.

Once this measurement is correctly time-labeled, the main focus is to obtain a reference pattern to which the measured azimuth antenna pattern can be compared. Therefore, a novel method was developed which enables the reconstruction of the actual TOPS azimuth antenna pattern using the following information:

- (i) the timed sequence of antenna excitation coefficients (in azimuth and in elevation) that are used to steer the antenna during the acquisition,
- (ii) the antenna model providing the reference patterns for each switched beam (pair of azimuth/elevation pattern),
- (iii) the exact knowledge of the imaging geometry, that is, the line of sight vector between the platform and the GR.

3.2. Measurement Setup and Configuration. For this experiment, four TSX descending passes in TOPS mode were commanded and acquired during the spring of 2012. The equipment used for measuring the azimuth pattern is a set of GRs in X-band. In particular, three GRs were deployed at each of the two test sites (D28 and D30) within the DLR calibration field located in Southern Germany, as shown in Figure 2.

TABLE 1: Parameters of TSX TOPS data take over DLR calibration field.

Parameter	Value, [subswath 1/2/3/4]
Ground swath width	$\approx [30/27/27/27]$ Km
Pulse repetition frequency	$[3233/3728/3465/3752]$ Hz
Azimuth resolution	≈ 19 m
Incidence angle/midslant range	$\approx 52^\circ/790$ km
Burst width	≈ 10.4 km
Number of bursts per subswath	$[13/13/13/13]$
Maximum azimuth steering angle	$[0.47/0.47/0.46/0.46]^\circ$
Minimum azimuth steering angle	$[-0.47/-0.47/-0.46/-0.46]^\circ$
Number of azimuth beams per burst	$[25/25/36/36]$
Angle steering quantization step	$[0.039/0.039/0.026/0.026]$ deg
Pulses per azimuth beam	$[45/52/34/37]$

The test sites were located in an overlap region between two subswaths (here strip_018 and strip_019) and two bursts. The different bursts of interest (regions filled by green color) are labeled with a number (from 0 to 5) which will be used from now on in the following analysis. Due to the relatively small size of the burst overlap area on ground, not only the GRs had to be accurately deployed and configured but also at instrument level the TOPS acquisition had to be precisely and reliably commanded.

The acquisition parameters used for these four TSX passes are presented on Table 1. These parameters have been optimized taking into account the instrument-related constraints explained in Section 2.1.

4. Measurement Results

The conformity of azimuth antenna pattern derived from the antenna model with the actual GR measurements is shown in Figure 3. As previously outlined, the azimuth angles of the horizontal axis correspond to time, which was converted to azimuth angle using the exact knowledge of the imaging geometry between the satellite and the GR. It can be seen that the measurements match the reconstructed theoretical pattern match very closely including in the lower sidelobes. This demonstrates that the TSX antenna model can accurately predict the beam-to-beam gain offsets not only between elevation beams but also for the steered azimuth beams.

In Figure 3, four peaks can be observed, which correspond to the four neighboring bursts in the vicinity of the test site D28, when the SAR antenna was steered while imaging the GR. The peaks correspond from right to left to bursts 0-1-2-3. In each burst, the antenna is steered in the azimuth direction following a sequence of beams. As this sequence is not continuous, the antenna beam configuration remains in a determinate beam (as expected from the values in Table 1) during 45 PRIs for the first subswath and 52 PRIs for the second subswath, originating the staircase shape of the pattern (see Figure 1). Sharp changes in the staircase sequence correspond to not only burst but also subswath changes

FIGURE 2: TSX TOPS acquisition coverage with subswaths and bursts indicated. The target position and burst labeling are also shown. The arrow indicates the flight direction (Google Earth).

FIGURE 3: Comparison of the normalized TOPS azimuth pattern measured by GRs during one overpass and the reconstructed pattern derived from the antenna model. Only the relevant azimuth angles corresponding to bursts 0-1-2-3 are shown.

(e.g., transition from burst 0 to 1 at approximately $+0.45^\circ$). Other peaks with lower amplitude correspond to other subswaths (strip_020 and strip_021). Furthermore, it should be mentioned that, just as expected, the 3 dB beamwidth is narrower than in the fixed-antenna case, because the TOPS azimuth antenna pattern is compressed due to the steering, as predicted by (1).

Looking closer at a single burst, the staircase shape of the pattern becomes obvious, as shown in Figure 4. Here only burst 2 is shown, since it is one of the bursts covering the overlap region for test sites D28 and D30. Due to the different imaging geometries, a different segment of the pattern is seen by the GRs at each test site. At a given time, the backward looking beams are observable by the GRs at D28, while the forward looking beams are observable by the GRs at D30; that is, while D28 is illuminated directly with the main lobe of these backward beams (main lobe in Figure 4(a)), D30 is irradiated with the sidelobe of the backward beams (sidelobes

in Figure 4(b)), and when D30 is illuminated with the main lobe of the forward beams (main lobe in Figure 4(a)), then D28 is irradiated by the sidelobe of these forward beams (sidelobes in Figure 4(b)).

The interesting area for the analysis is the 3 dB region of the pattern, which represents the main lobe of the SAR antenna that illuminates the target. As previously discussed, the main lobe is composed of many azimuth beams. For this region, the difference between the measurement and the theoretical pattern derived from the antenna model has been calculated and is likewise shown in Figures 4(a) and 4(b). Since each GR has slightly different characteristics, the measurements of 3 GRs deployed at a single test site are combined to obtain an averaged measurement pattern. The graphs show that the deviation is kept between ± 0.1 dB along the 3 dB region of the azimuth patterns for different beams as well as for different azimuth look angles (corresponding to the different bursts and sites).

These results are remarkable since they demonstrate that the antenna model can accurately predict the antenna pattern gain with extreme precision also in the case of TOPS. Hence, the accuracy of the TSX antenna model of ± 0.1 dB for one-way azimuth antenna patterns is also achieved for measurements in the experimental TOPS mode, after 5 years of mission time.

In Figure 5(a) the difference between the measurement and the theoretical antenna pattern is shown for the 3 dB region of the pattern (for each of the analyzed six bursts). The measurements are again averaged over the three deployed GRs per test site and pass. The statistics are presented by the vertical bars on the left of the graphs. The upper and lower ends of each bar represent the minimum and the maximum, the star is the mean deviation, and the triangles are the standard deviation. For this specific pass, the deviation exceeds ± 0.1 dB. However, the deviation decreases when the pattern derived from the antenna model is shifted slightly by about 0.005 degrees, as shown in Figure 5(b). As this shift can be observed for both test sites (each test site has a different color: D28 is blue, D30 is yellow), which means that for different lines of sight between the satellite and the test site, the same residual “mispointing” has been measured. This residual mispointing is in the order of a few millidegrees which represents the order of accuracy of the TSX attitude

FIGURE 4: TOPS measurements of burst 2 acquired on May 18, 2012, (a) at test site D28 and (b) at test site D30.

FIGURE 5: Difference between measurement on March 24, 2012, and model for the 3 db region of the TOPS azimuth patterns, statistical values: grey/black. (a) Without pointing correction, (b) with pointing correction.

FIGURE 6: Difference between measurement on May 18, 2012, and model for the 3 db region of the TOPS azimuth patterns, statistical values: grey/black. No pointing correction was needed for this data set.

knowledge. This was verified at the beginning of the TSX mission [3, 14] (i.e., having a pointing accuracy of 0.002 degrees). The antenna mispointing changes from pass to pass due to the total zero-Doppler attitude steering of the satellite, but it stays rather constant during one pass. For example, the measurement on 2012/05/18 presents a very low deviation value even for the uncorrected case, as it is shown in Figure 6.

Finally, when applying the pointing correction, the difference between measurement and model, including the minima and the maxima, is less than ± 0.2 dB. Thus, the characterization of the TOPS mode azimuth antenna pattern using GRs is also well suited for deriving the actual SAR antenna pointing in the azimuth direction.

5. Conclusions

The method for azimuth antenna pattern verification based on ground receiver measurements was applied to the TerraSAR-X instrument operating in TOPS mode during four passes/four acquisitions at two different test sites with 3 GRs per test site. The results show that for reconstructing the azimuth pattern by means of the antenna model, taking into account the accurate knowledge of the imaging geometry (i.e., between the satellite and the GR position on the Earth's surface) as well as the antenna excitation coefficients, the deviation between the measured azimuth patterns and the theoretical patterns is in the order of two tenths of a dB.

Compensating for a slight antenna mispointing caused by a finite knowledge of the attitude of the satellite, an accuracy of the antenna model of better than ± 0.15 dB has been achieved for the experimental TSX TOPS mode. The accuracy includes both the shape within the main lobe and the gain offset between subswaths in elevation, as well as between backward and forward steered azimuth beams. This accuracy is similar to that demonstrated for all operational

TSX modes, considering that the satellite is now reaching its nominal end-of-life phase.

The current analysis was performed for each transmitted radar pulse. In other words, for the method described in Section 3.1, the number of azimuth beams that were steered during the acquisition is of no relevance. Instead, precise knowledge of the right sequence of steered azimuth beams and scanned elevation beams, together with the correct synchronization of the data, is required. Therefore this calibration method is suitable for other satellite missions such as Sentinel-1 that will use TOPS as an operational mode. However, the complexity of analyzing ground receiver measurements may increase with a higher amount of steered azimuth beams.

Finally, the method based on GRs and proposed for measuring the azimuth pattern of a SAR system in the complex TOPS mode is well suitable for the verification of the antenna model using TOPS acquisitions and deriving a residual mispointing.

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