TerraSAR-X: Design of the new operational WideScanSAR mode

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Abstract

The TerraSAR-X mission launched in June 2007 provides brilliant SAR products in several different modes ranging from high resolution spotlight, with 5 km x 10 km scene coverage, up to ScanSAR acquisitions, with 100 km swath width. For ice and oceanographic applications there is a demand for even larger coverage. This paper describes the development of the new recently implemented and released WideScanSAR mode with swath widths between 190 km and 260 km, depending on the varying incidence angles. Furthermore, the optimization of the swaths and beams for all orbit heights is shown and first SAR image evaluations are presented.

1 Introduction

The TerraSAR-X mission is an X-Band SAR mission utilizing two radar satellites named TSX-1 launched in June 2007 and TDX-1 launched in 2010. The mission initially provides 4 different SAR modes which are two spotlight modes (HS, SL), one stripmap mode (SM) and one 4 beam ScanSAR (SC) mode. The resolution range of these modes is between 1.1 m and 13 m, with cross track coverage from 10 km to 100 km, respectively. Although there was no plan to extent the mode portfolio, the user demand for more resolution or more coverage was evident. This paper describes the design of a new, wider coverage product, namely a six-beam ScanSAR. The paper is divided into design approach, parameters to be optimized and measurements on the first acquired data.

The design of the TerraSAR-X beams, i.e. swaths in all SAR modes is a trade-off between swath width and ambiguities. ScanSAR is sensitive to azimuth ambiguities, which can be avoided by increasing the pulse repetition frequency (PRF). On the other hand, low PRFs are needed to allow larger swath widths. Decreasing the transmit duty cycle is relaxing the timing problem to a certain extent, but further parameter optimization was necessary for the operational WideScanSAR mode. Accurate beam design minimizes the received side lobe energy but guarantees enough antenna gain in the main lobe for a good SNR over the full swath. To achieve this, beam width margins are minimized, i.e. the subswath overlap is minimized to only covering the satellite altitude variations and the uncertainties in orbit control. With the introduction of incidence angle dependent variations of the range bandwidth a new mean to optimize the SNR has found its way into the TerraSAR-X mission.

2 Swath and Beam Design Process

2.1 Iterative approach

The design of the (sub-)swaths for the WideScanSAR mode is done in an iterative manner and depicted in **Figure 1**. Starting from timing considerations, the SAR performance is calculated. A goal of the iterations is to equalize the SAR performance of the different subswaths as far as possible. The timing considerations show that some swaths are restricted to ranges of higher PRFs with smaller swath widths and better NESZ, whereas some subswaths are restricted to ranges of lower PRFs, wider swath widths and slightly worse NESZ. This has to be compensated within the iteration process by other design parameters like the range bandwidth. The orbit height of the satellite varies within one orbit of about 30 km from 510 km to 537 km.

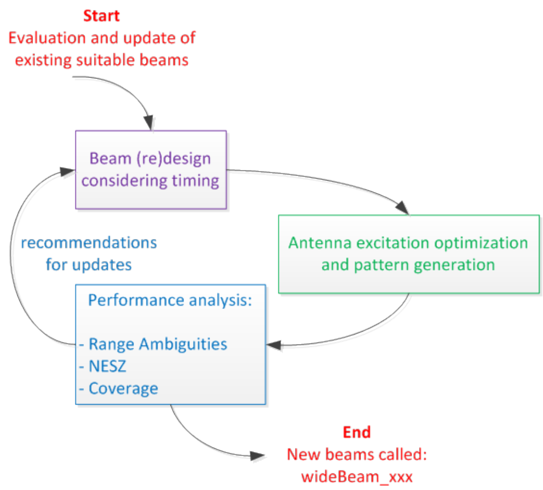

Figure 1: Iterative swath and beam design process

Since the timing is very tight in the case of wide swath design, all calculations have been performed for different orbit heights. **Figure 2** shows the different action within one pulse repetition interval (PRI). Green illustrates the transmit pulse, grey the guard times

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between transmitting and receiving, red and yellow indicates the received echo window. Yellow is equal to the transmitted pulse length used for range compression. A decreasing of the transmitting pulse length, i.e. the transmit duty cycle (TXDC), relaxes the timing constraints twice that number, since both the green and the yellow part in this figure are affected.

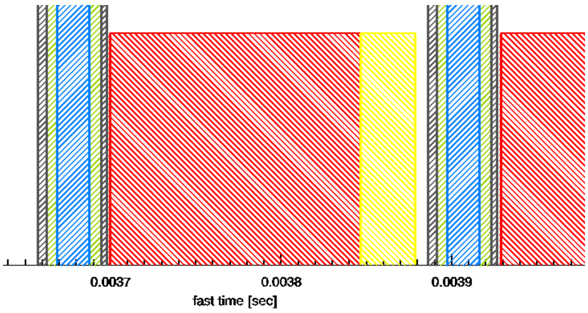

Figure 2: Timing within a Pulse Repitition Interval (PRI). Blue indicates the Nadir echo return during transmit (green).

To achieve the wide swaths, nearly the whole receive window is needed for the echo reception. Undesired echo returns from the antenna beam edges have to be fitted within the small timing windows of the pulse transmission or the pulse range compression. This implies strong requirements for the side lobes suppression during the wide beam pattern design.

Besides the strong timing constraints there are SAR performance goals, to be complied with. A resolution of better than 40 m, a homogeneous appearance of the beams, i.e. similar noise equivalent sigma zero (NESZ), azimuth ambiguity to signal ratio (AASR) and range ambiguity to signal ration (RASR) and radiometric resolution in the different subswaths are design goals.

2.2 Timing considerations

The timing diagram in **Figure 3** shows the nadir interference in brown almost vertical lines and the TX interference in green lines.

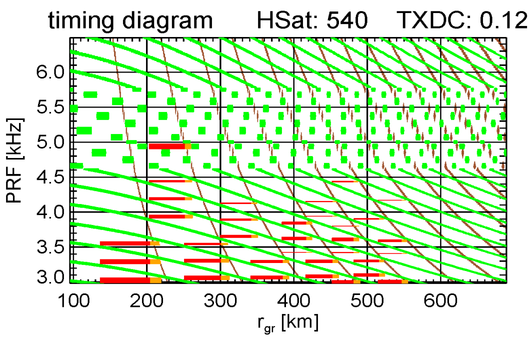

Figure 3: Timing diagram indicates strong constraints for some of the subswaths. For wideBeam_005, i.e. the 5^{th} group of horizontal red bars, only two very low PRF bands can be used, even with a very low TXDC of 12%

The echo window for the range compressed image data has not to interfere with these events. The useable PRFs can be selected from the vertical axis. The analyses were performed for different orbit heights, but the useable PRF regions should be big enough to handle terrain variations. Terrain variations are considered in detail during the last iterations [1].

2.3 Minimum PRF determination

From one side, the azimuth ambiguity to signal ratio (AASR) analysis (**Figure 4**) determines the minimum PRF for a desired AASR. From the other side, a minimum PRF of 3100 Hz, derived from timing diagrams in **Figure 3** is required to guarantee the desired swath widths for all orbit heights. The ambiguity to signal ratios in a burst mode SAR like ScanSAR is not constant, since different targets are illuminated from a part of the azimuth antenna pattern only. The worst situation, annotated as “max” in the ambiguity figures, appears when the target is illuminated from the outer parts of the azimuth processing bandwidth.

The azimuth processing bandwidth of 1950 Hz has been chosen since the mean AASR is better than -17 dB, even with a PRF as low as 3100 Hz and an azimuth resolution of better than 40 m is reached for a 6 beam ScanSAR. The minimum PRF is independent of the incidence angle.

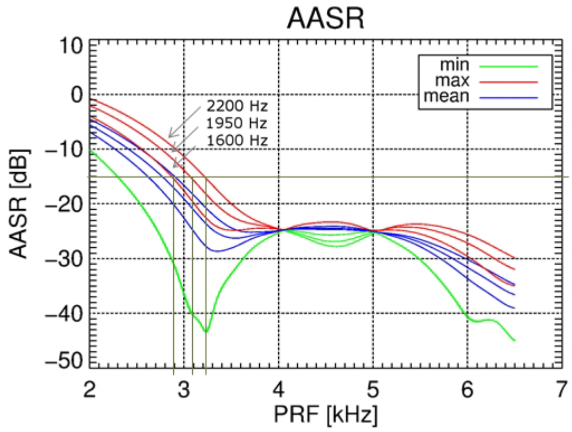

Figure 4: AASR for different azimuth processing bandwidths

2.4 Maximum PRF determination

In contrast to the minimum PRF, the maximum PRF is swath dependent and has to be updated for every iteration run. The maximum PRF for a certain beam is determined by the design goal allowed RASR, e.g. -17 dB, taken from a RASR plot. **Figure 5** shows a RASR plot for wideBeam_010, assigning a wide beam with an incidence angle range of about 47° to 49°.

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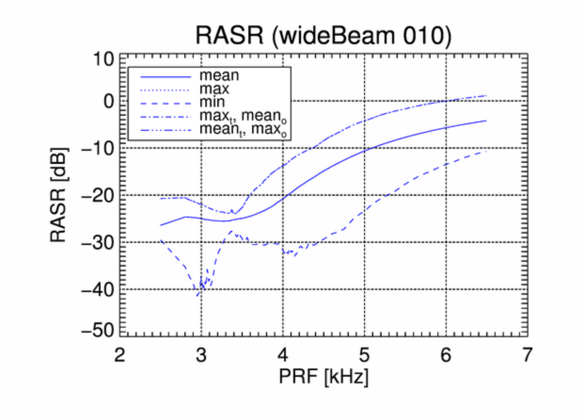

Figure 5: RASR for a low incidence angle wide beam.

2.5 Beam Overlap Optimization

All beam design is performed for a nominal swath width in distance (km swath width), not in angle. To get a combined coverage, which is free of gaps, the swath design is done under the assumption of the greatest orbit height. For this height the beam overlap is minimized. The defined subswath widths are moved to lower orbit heights and the beam angles are calculated for this lower and wider situation.

2.6 Optimized Antenna Pattern

The active phased array antenna of TSX-1/TDX-1 can be controlled in TX and RX phase and RX gain for each of the 384 Transmit Receive Modules (TRM). The most effective way is a combination of tapering all kind of parameters, however with phase tapering the sidelobe level rises.

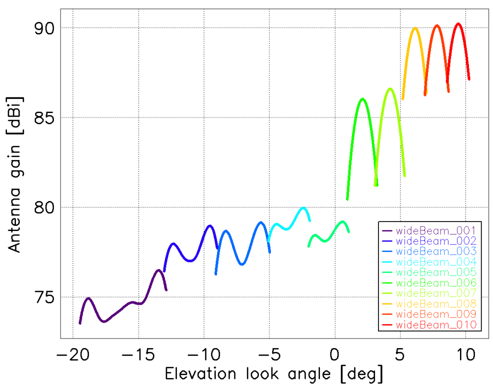

Figure 6: Optimized Beam pattern of all 10 designed wideBeams.

This is acceptable for steep incidence angles, but even for moderate incidence angles an increase of sidelobes should be avoided to keep range ambiguities small. Therefore, for these beams only RX gain tapering has been selected [3]. The 3 far range beams utilized for WideScanSAR are untapered since their natural 2.3° elevation angle of aperture is sufficient for ground range coverage of about 30 km. See **Table 1** and the official TerraSAR-X product specification [3] for the different operational WideScanSAR coverages.

wideBeam	TXDC	TXBw	minLook	maxLook	swathWidth	Overlap	swathWidth6Beam
_001	19.0%	100.00	14.150	20.610	67687.70	1720	265968.03
_002	14.0%	100.00	20.450	24.820	44467.45	1380	236135.48
_003	15.0%	85.00	24.700	28.800	49317.13	1360	218530.14
_004	12.0%	67.50	28.690	31.950	40586.67	1200	204027.42
_005	12.0%	67.50	31.860	34.860	42797.93	880	193954.44
_006	12.0%	67.50	34.760	37.030	32757.40	1200	
_007	12.0%	67.50	36.880	39.130	34984.10	1180	
_008	15.0%	55.00	39.000	40.800	29540.15	1160	
_009	15.0%	55.00	40.680	42.570	32047.83	1160	
_010	15.0%	55.00	42.460	44.130	31396.46		

Table 1: wide swath and beam specification table

2.7 Simulations

The last iterations in the swath and beam optimization process have been performed on simulations. The commanding of 20000 WideScanSAR DataTakes distributed over the world has been generated. Using the PRFs, backscatter map and terrain, as selected for the operational command generation, the SAR performance parameters are evaluated. Look into [1] for a detailed description of the method. **Figure 7** shows a 2D histogram plot for AASR. All subswaths remain below the -17 dB design goal for this performance parameter.

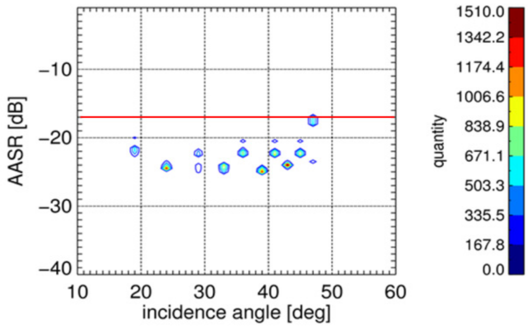

Figure 7: 2D histogram plot of the AASR parameter retreived from 20000 simulated WideScanSAR DataTakes.

The evaluation of the RASR parameter derived from the same set of 20000 DataTakes indicates also the match of the RASR design goal of better than -17 dB.

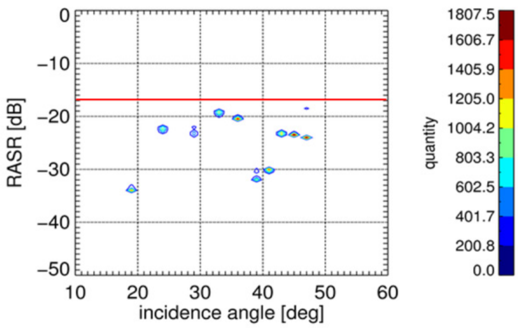

Figure 8: 2D histogram plot of the RASR parameter retreived from 20000 simulated wide ScanSAR DataTakes.

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Since the commanding of a 6 beam ScanSAR DataTake requires more on-board control sequence resources compared to the standard 4 beam ScanSAR DataTake the length of the WideScanSAR simulations are limited to 400 km. This is also described in [1] with 20000 statistical distributed DataTakes and led to an optimization (narrowing) of the beams operated with the higher PRF ranges. For flat terrain like ocean surface or sea ice coverage a DataTake length up to 2500 km is possible.

3 First SAR Image Results

3.1 NESZ

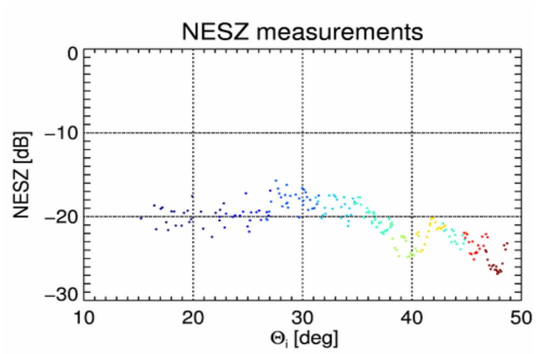

Figure 9: NESZ measurements on dark parts of an image (calm rivers) over all wideBeams.

NESZ measurements have been performed on scenes with dark water bodies found in tropical large rivers. The measurements are fitting well in the theoretical calculations. The better NESZ of the beams less widened (higher PRF) can be seen

3.2 Geometric Resolution

With a measured point target azimuth resolution of 38.73 m the desired resolution of better than 40 m is exceeded for the 6 beam ScanSAR mode. Even with reduced range bandwidths down to 55 MHz, the ground resolution can be kept to 38 m using a nearly constant number of range looks at around 7 for all subswaths. This supports the homogenous appearance and the good radiometric resolution of the operational WideScanSAR product.

4 Conclusions

The new operational TerraSAR-X 6 beam WideScanSAR mode with cross track coverage of up to 260 km shows excellent results in NESZ, ambiguity ratios and resolution. Taking into account that during the design of the satellite only swath widths of 100 km were required, the challenging task was achieved with an iterative optimization approach. The outcome is a very impressing achievement for the mission.

References

[1] Thomas Kraus et al.: *A Global Performance Assessment Approach for the TerraSAR-X Staring Spotlight and Wide ScanSAR Modes*, Proceedings of European Conference of Synthetic Aperture Radar (EUSAR), 2014.

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[3] Thomas Fritz et al.: *TerraSAR-X Basic Product Specification Document*, DLR, public version 1.9, October 2013

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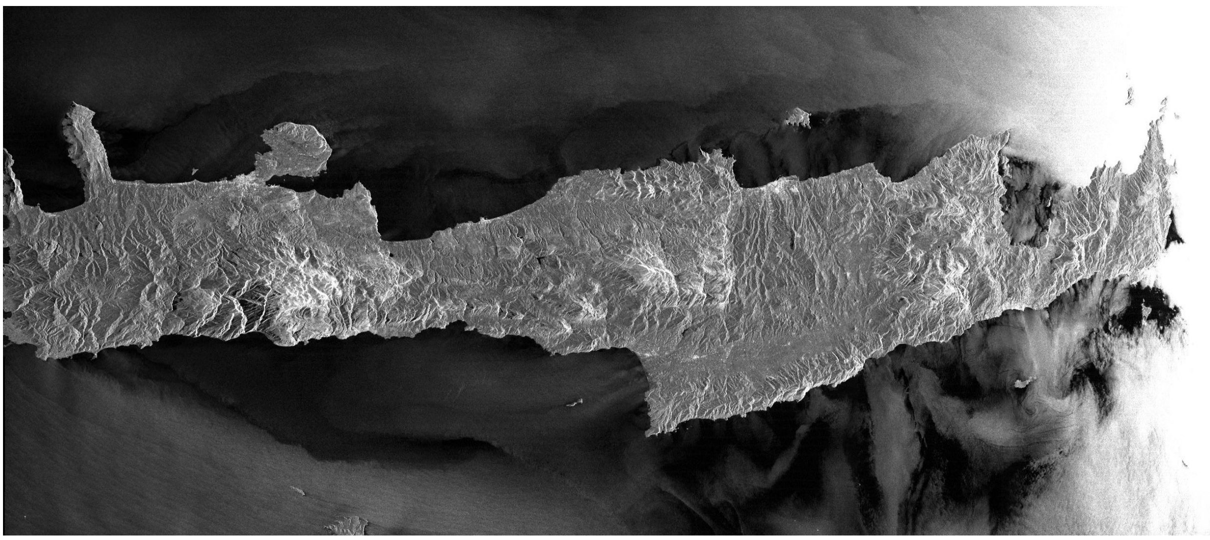

Figure 10: WideScanSAR of Crete with 260 km range extent, acquired on 28-Sep-2013

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