TerraSAR-X with Experimental Wide Stripmap Mode

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Abstract

TerraSAR-X is a German synthetic aperture radar (SAR) satellite mission which is realized by the two satellites TerraSAR-X (TSX-1), launched in 2007 and its companion TanDEM-X (TDX-1), launched in 2010. Although the mission has been operational for 16 years, the flexible commanding capability of the SAR instruments offers the possibility to demonstrate new acquisition techniques interspersed in the nominal timeline. The development and tests with the experimental Wide Stripmap mode are presented here. The mode, with its coverage and resolution, sits between the nominal Stripmap and ScanSAR and can serve applications such as ship detection and land subsidence monitoring.

1 Introduction

The TerraSAR-X mission is the first civil German synthetic aperture radar (SAR) mission that has been serving scientific, commercial and institutional users for more than 16 years already [1]. It commenced with the launch of the TerraSAR-X satellite back in 2007 followed by its nearly identical twin TanDEM-X in 2010. Both satellites are still in very good health provided their age and continue to deliver SAR images with outstanding quality. Their main payloads are advanced high-resolution X-band radars that have been initially acquiring data in four traditional imaging modes: Stripmap, two spotlight variants called Sliding Spotlight and High-Resolution Spotlight and a ScanSAR mode [2]. On one side, the satellites have been capable of providing images with a resolution down to 1 m in range with a moderate scene size of 10 km (High-Resolution Spotlight). On the other side, wide coverages have been also possible with a coarser azimuth resolution of about 19 m and range extension of 100 km (ScanSAR).
In 2013 the TerraSAR-X imaging portfolio was significantly extended by the addition of the Staring Spotlight [3], and the Wide-beam ScanSAR [4] mode. The design of these two acquisition modes was made possible by exploiting the full flexibility of the SAR instrument and its commanding capabilities. The fine azimuth resolution of 25 cm of the Staring Spotlight as well as the cross-track coverage of up to 260 km for the Wide-beam ScanSAR have found great reception and the two modes continue to be in high demand among the TerraSAR-X users.
In this paper we will present a new imaging variant that may be of interest for certain applications. The experimental Wide Stripmap mode combines the benefits of the traditional Stripmap with the use of wide antenna beams that have been initially designed for the Wide-beam ScanSAR. In this way, a greater range extension of up to 60 km is possible with the complete azimuth spectrum compared to ScanSAR. However, that comes at the expense of resolution loss that goes down to about 7 m in worst case. The experiments have been commanded and processed manually, i.e. not in a nominal way via the operational ground segment workflows.

2 Motivation

Two applications have been identified as the main motivators for experiments that utilize the advantages of a SAR acquisition with homogeneous data properties and a medium spatial resolution. The first one is ship monitoring. The detection of small vessels in rough sea motivates the need for a medium resolution but at the same time requires a wide coverage. ScanSAR images are limited by the disturbances of the burst mode and by the fragmented azimuth spectrum.
Another important application is the land rise and the land subsidence determination. Here interferometric methods with persistent scatters are often applied. In order to interferometrically process two images acquired in ScanSAR mode, they have to be commanded fully synchronous and that is not always possible to achieve since it is dependent on the ordering by the end user. In such a case one can use Wide Stripmap mode that still provides an extended range compared to the nominal Stripmap and can be combined with either a ScanSAR image or a Stripmap one.

3 Mode Design

3.1 Utilizing Slant to Ground Behaviour

In Figure 1 the principle of the slant to ground conversion is shown. Echo windows (EW1) of exact the same duration result in different ground coverages depending on the incidence angle. Steeper incidence angles lead to wider ground ranges. Following the same geometrical law, while the ground coverage increases the resolution is getting worse.

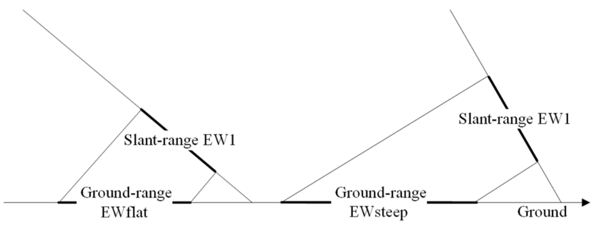

Figure 1 Slant to ground projection. The slant range EW1 results in a larger ground range coverage (EWsteep) for steep beams, compared to the EWflat for flat beams.

The use of the wide antenna beams requires as large as possible receive windows at the instrument to collect the scattered echoes from the ground. Due to a constraint of the TerraSAR-X SAR instrument, the largest echo windows can be recorded when the lowest possible range bandwidth of 100 MHz has been selected. The steepest incidence angle and the maximum range bandwidth therefore leads to a worst case ground resolution of 7 m.

3.1.1 Steep beams illumination constraint

Broadening of the transmit and receive pattern of the antenna beam by the means of tapering of phase or amplitude (in receive beam only) gives the opportunity to design a beam which is optimized for the desired task. The steepest five wide beams have been developed with higher gain in far range to compensate for the range loss [4]. Since the energy is distributed over a wider angular region the maximum gain of the pattern decreases.
For the experiments we have used the first five widened elevation beams out of the ten ones that have been developed for the Wide-beam ScanSAR mode with properties as given in Table 1.

Beam ID wideBeam_	**Swath Width**	**Incid. Angle Min**	**Incid. Angle Max**	**Look Angle Min**	**Look Angle Max**
001	67600 m	15.57 °	22.79 °	-19.47 °	-12.88 °
002	44400 m	22.63 °	27.09 °	-13.03 °	-08.98°
003	49300 m	26.96 °	31.55 °	-09.73 °	-04.96 °
004	40500 m	31.43 °	34.96 °	-05.07 °	-01.91 °
005	42750 m	34.86 °	38.31 °	-02.00 °	01.87 °

Table 1 TerraSAR-X wide beams and their main properties.

The steepest nominal (data collecting range) Stripmap beam with look angle -20.55 ° as given in Figure 2 is in near range steeper as the steepest wide beam that starts at a look angle of -19.47 ° (Figure 3), but its main beam open angle is only half of that of the wide beam. The nominal antenna pointing in elevation is 33.8° away from nadir, i.e. an antenna look angle of 0.0° is 33.8° away from the nadir and an antenna look angle of -19.47° is 14.33° away from the nadir respectively [5].

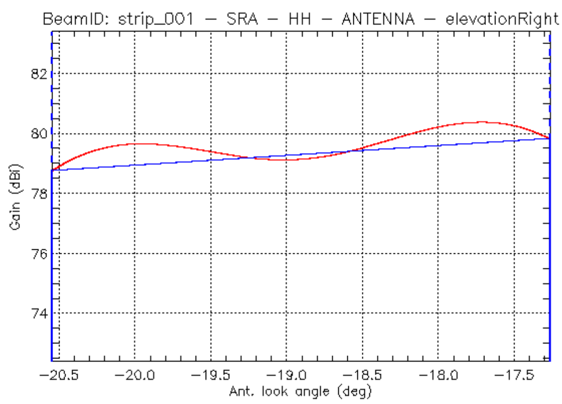

Figure 2 Antenna pattern of a nominal Stripmap beam in HH polarization with a maximum gain of 80.5 dB. The blue line represents the design goal for the antenna gain.

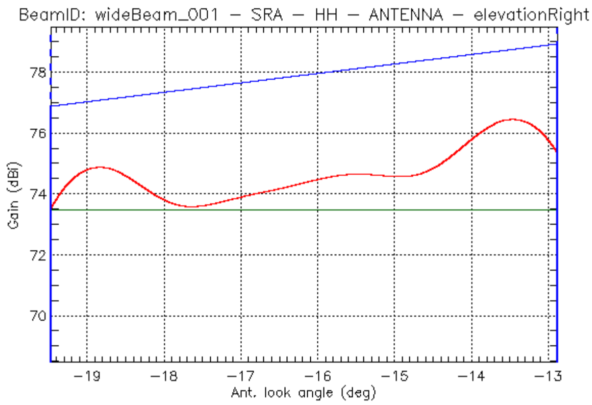

Figure 3 Antenna pattern of a wide Stripmap beam in HH polarization with a maximum gain of 76.5 dB. The blue line represents the design goal for the antenna gain and the green line represents the mask for the side lobe limitation.

The shape of the design specification (blue) has been met for the steepest wide beam (red) but its gain is 3 dB below the nominal beam. That is expected, since its opening angle is above 6 ° compared to a little more than 3 ° of the steepest nominal Stripmap beam (Figure 3).

3.1.2 Flat beams timing constraint

On the far end of the incidence angle range there is no constraint coming from a widened antenna pattern. Here the basic principle of Wide Stripmap is limited by the maximum length of the echo window. In Figure 4 the timing constraints are visible. The red echo window must not interfere with the transmit pulse (green) and the nadir echo (brown), whereas the orange part of the echo, the length of the transmit chirp used for chirp compression, can interfere with the nadir echo. In the far range region on the right of this diagram, the usable echo in ground range does not exceed the ground range of a nominal 30 km TerraSAR-X Stripmap swath.

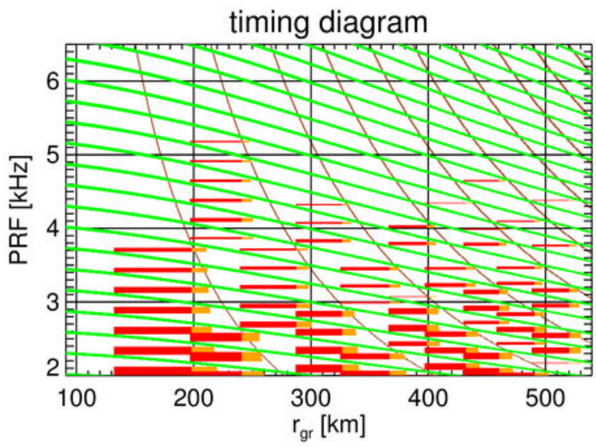

Figure 4 Diamond Diagram for all ten Wide Beams, PRF vs. Ground Range with a transmit- duty cycle of 12%.

3.2 Transmit Duty Cycle

Nominally the TerraSAR-X Stripmap mode is operated with a transmit duty cycle (TX DC) of 18%. For the experimental Wide Stripmap we have decided to tolerate a higher noise and therefore we have varied the TX DC down to 12% for the flattest wide beams 004 and 005. The PRF has to be higher than 3000 Hz to reach an azimuth ambiguity to signal ratio of -17 dB.

3.3 Coverage Comparison

Figure 5 depicts the impressive increase of coverage of the wideBeams compared to the nominal strip ones in near range. In green every second Stripmap beam is shown. In red all ten of the wide beams are plotted. For steep beams the Wide Stripmap swath covers twice the nominal Stripmap region. For flat beams the coverage of the wide beams converges to the coverage of the nominal stripmap ones. For the last five beams in far range there is no advantage for the coverage anymore and therefore they are not used for the experimental Wide Stripmap mode.

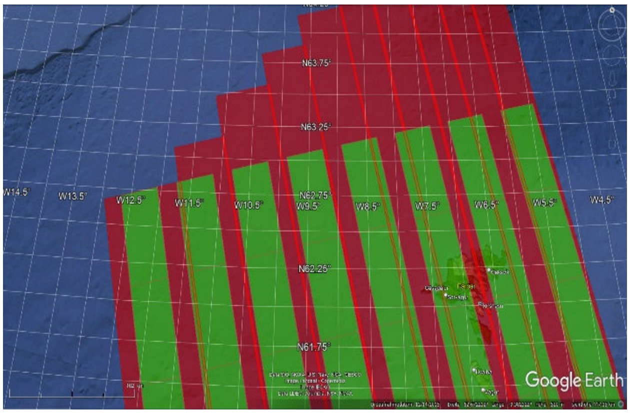

Figure 5 Coverage comparison between nominal Stripmap (green) and Wide Stripmap (red). Ten wide beams with the corresponding strip beams are depicted here with the near range being on the right of the plot.

4 Wide Stripmap Experiments

In total, we have acquired 35 manually commanded experimental Wide Stripmap DataTakes. 12 DataTakes have been performed repeatedly on 6 test sites with variation of only one parameter, either transmit range bandwidth, or co-polarization vs. cross polarization. The rest 23 DataTakes have been performed with the aim to cover a large variation of ground terrain.

4.1 Multilooking or Reduced Range Bandwidth

The worst-case resolution of Wide Stripmap is about 7 m. For the flatter beams that can possibly have better ground resolution, we had the choice to either process to the target resolution of 7 m with more range looks out of the original bandwidth of 100 MHz, or to decrease the transmitted bandwidth and thus reduce the system thermal noise. Since the number of looks is relatively low (2-4), it still has brought some advantage of having the full 100 MHz in transmit, so the speckle noise could be reduced

4.2 Cross-Polarization vs. Co-Polarization

In the context of ship detection, a moderate incidence angle is preferred, whereas the widest swathes are achieved with the steepest wide beams. A solution for improving the ship detection could be the use of cross polarization. Cross polarization keeps the clutter of the sea surface low and at the same time has a good scatter response of manmade targets with its defined edges.

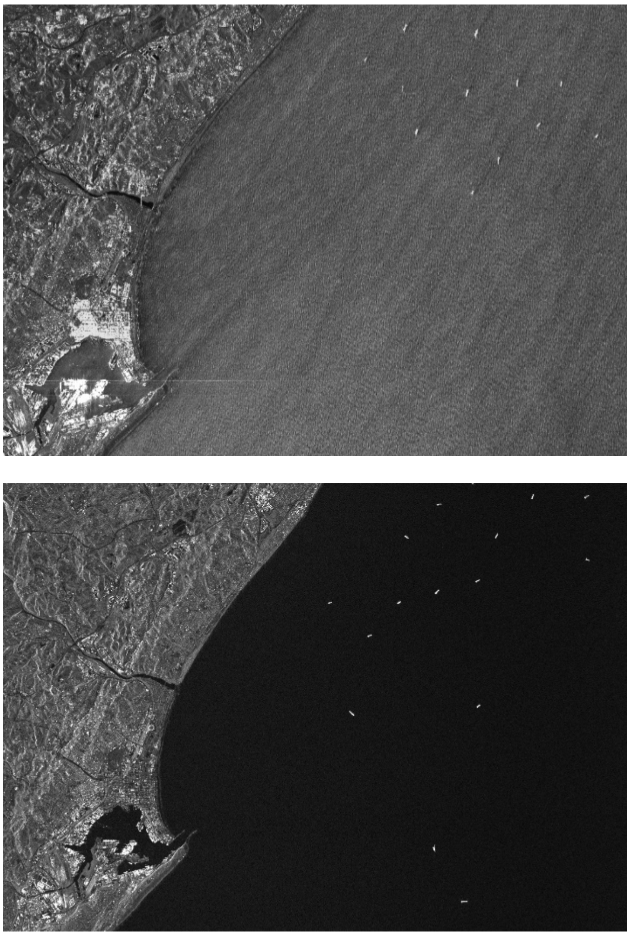

Figure 6 Durban acquired on 2022-09-19 with HH co-polarization (above) and on 2022-09-30 with HV cross-polarization (below).

The example of the Durban sea area on Figure 6 presents visually an impressive increase of the contrast with the clutter suppression of sea surface and the clear response of the ships using the cross-polarization settings. The images show different sea states and different ships due to the 11-day time lag between them. Nevertheless, it is worth looking at one exemplary ship of each scene in order to have a better impression of the improvement due to the cross polarization (Figure 7). In this example the sea clutter of the HV DataTake is 7 dB below the sea clutter of the co-polarized acquisition, as depicted in Figure 8. This may not be decisive for the detection of big ships, like these two with 240 m (HH) and 100 m (HV), but the detection of small ships could gain from this.

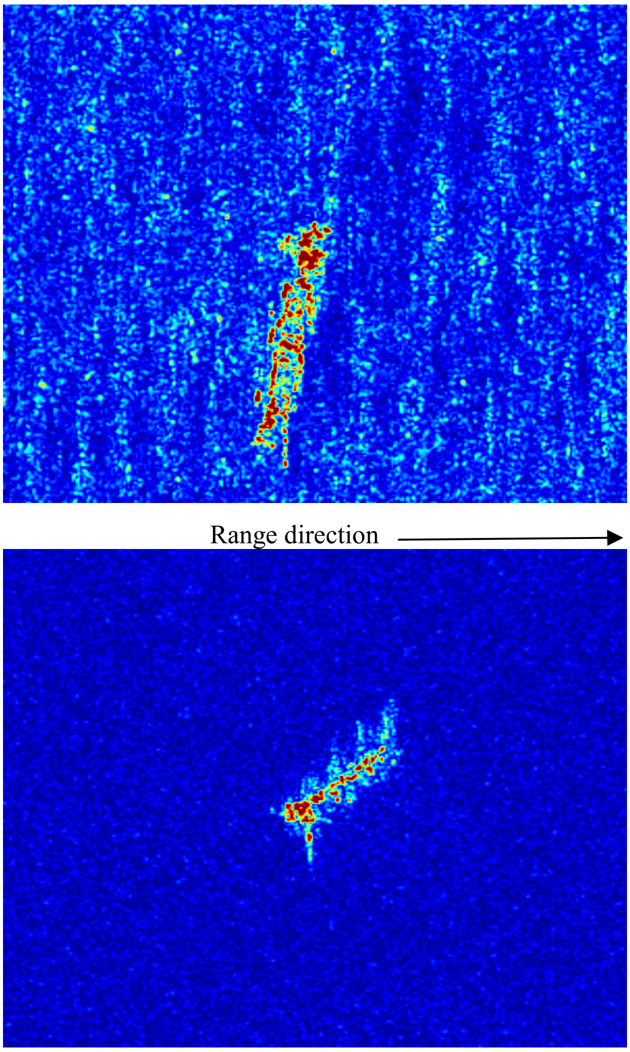

Figure 7 One ship acquired on 2022-09-19 with HH co-polarization (above) and on 2022-09-30 with HV cross-polarization (below).

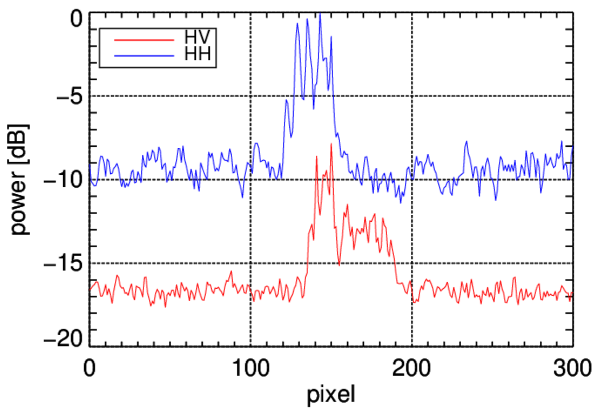

Figure 8 Azimuth cuts through ships and sea clutter.

5 Conclusions and Future Extensions

Our initial tests with the experimental Wide Stripmap mode demonstrated the potential of the experimental mode. It provides an additional possibility to acquire wide swathes with very good signal properties. This can be beneficial for some applications such as ship detection or land subsidence monitoring, for which the current TerraSAR-X mode range cannot always provide an optimal selection.

We will further analyze the current acquisitions and plan in the future to perform experiments in dual receive satellite configuration, where one satellite receives simultaneously in co- and the other satellite receives in cross-polarized antenna setting, so that we can analyze the performance with identical sea state and identical ships. Additionally, we plan to acquire data with decreased pulse repetition frequency in order to achieve larger swathes also for far range wide beams. In these cases, we expect to find azimuth ambiguities from strong scatters present in the images, but they may be removed in a post processing step by using a method similar to the one suggested in [6].

6 Literature

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