GERMAN X-BAND SPACEBORNE SAR HERITAGE AND THE FUTURE HRWS MISSION

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ABSTRACT

This paper provides an overview of the German spaceborne radar program starting with the X-band synthetic aperture radar (SAR) instrument on board the Shuttle Imaging Radar missions (SIR-C/X-SAR) in 1994, followed by the Shuttle Radar Topography Mission (SRTM) in 2000. The German national satellite radar program began in 2007 with the launch of the satellite TerraSAR-X which is providing since then high-resolution X-band images for scientific, commercial and governmental applications. TanDEM-X, an almost identical twin, joined TerraSAR-X in 2010 to form the first bistatic SAR interferometer consisting of two satellites in close formation flight, and to generate a global, high-resolution digital elevation model of the Earth surface with unprecedented accuracy. The High-Resolution Wide-Swath (HRWS) mission has been approved for realization at the end of 2020. It is a very ambitious multistatic SAR mission exploiting the formation flight of one active main satellite and three smaller passive companion satellites. HRWS implements for the first time in space the novel MirrorSAR concept. As for the current planning, the launch is expected for 2026/2027 timeframe.

Index Terms— Synthetic Aperture Radar (SAR), High Resolution Wide Swath (HRWS), digital beamforming, MirrorSAR, F-SCAN

1. INTRODUCTION

Since the 1980s, Germany has built up considerable expertise in spaceborne SAR missions. Early developments were in cooperation with NASA. The Shuttle Imaging Radar Missions SIR-C/X-SAR [1] consisted of two flights in April and September 1994 aiming to demonstrate the potential of fully polarimetric radar systems in three different frequency bands for a variety of applications. Germany developed the X-SAR radar system in cooperation with Italy, the United States developed the radar systems in C and L-band. In 2000 the SIR-C/X-SAR was expanded to SRTM, the Shuttle Radar Topography Mission [2]. Secondary antennas mounted at the end of a 60 m long boom allowed a topographic mapping of 80 percent of the Earth's land surface with a height accuracy of approximately 10 meters.

The actual highlight is the successful implementation of the TanDEM-X mission [3]. It demonstrates DLR's capabilities in the development of highly innovative mission concepts in response to demanding mission objectives, in leading the project realization facing a number of challenges, and in directing and monitoring the global generation process, from data acquisition through to the final digital elevation model (DEM). The global TanDEM-X DEM is of outstanding quality and exceeds all its specifications, in case of the absolute height accuracy even by one order of magnitude.

Given the great success of TanDEM-X, a new mission concept for an X-band SAR mission denoted as High-Resolution Wide-Swath (HRWS) mission has been proposed [4]. It consists of a main high-resolution X-band radar satellite and 3 small, receive-only satellites in formation flight. The small satellites, following the MirrorSAR concept [5], operate as radar transponders and allow an effective, low-cost implementation of a multistatic interferometric system for high-resolution DEM generation.

The following sections provide a brief overview of the current missions TerraSAR-X (TSX) and TanDEM-X (TDX). The successor mission HRWS is presented in Section 3. Conclusions summarize the achievements and the potential way forward for future spaceborne SAR missions.

2. STATUS TANDEM-X

On June 21, 2010 the still unique TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurements) mission was launched and opened a new era in spaceborne radar remote sensing [3]. The first formation flying radar system was built by extending the TerraSAR-X [6] mission by a second, TerraSAR-X-like satellite TanDEM-X. The resulting large single-pass SAR interferometer features flexible baseline selection enabling the acquisition of highly accurate cross-track interferograms not impacted by temporal decorrelation and atmospheric disturbances. The primary objective of the mission was the generation of a global Digital Elevation Model (DEM) with unprecedented accuracy (12 m horizontal resolution and 2 m relative height accuracy). While the main mission phase for DEM data acquisition has been finished in 2014, the processing of the global TanDEM-X DEM was concluded in September 2016.

The TanDEM-X mission has been and still is the first distributed SAR system in space. Late in the development, necessary features required for the TanDEM-X mission have been implemented on TerraSAR-X. Examples are additional X-band horn antennas for inter-satellite phase synchronization and a dual-frequency GPS receiver for precise orbit and baseline determination. The second satellite (TDX, launched on June 21, 2010) is mostly a rebuild of TSX with only minor modifications like an additional cold gas propulsion system for formation fine tuning.

Operational DEM acquisitions are performed using the bistatic Stripmap mode in single polarization (HH) [3], and in right-looking observation geometry in ascending/ descending orbits over the Northern and Southern hemisphere, respectively. All land masses have been acquired at least twice, mountainous regions even up to 6 or 8 times. Based on a sophisticated interferometric calibration the DEM generation relies purely on the radar and GPS measurements recorded by the two satellites. ICESat reference heights are only used in a final step to correct for residual offsets of a few meters. A systematic and data driven processing chain performs the precise synchronization, focusing, interferometric processing and mosaicking to the final global TanDEM-X DEM.

The obtained results [7] confirm the outstanding capabilities of the system, with an overall absolute height accuracy of just 3.49 m, which is well below the 10 m mission specification. Excluding highly vegetated and snow-/ice-covered regions, characterized by radar wave penetration phenomena and consequently strongly affected by volume decorrelation, it improves to 0.88 m (for generic geocells only). Finally, the Global-DEM product is also very complete with 99.89% coverage of the land mass of the earth.

Comparisons of the TanDEM-X DEM with the SRTM or among multi-temporal TanDEM-X data revealed dramatic changes and the high dynamic in the Earth's topography especially over ice and forests. It has been therefore decided to acquire data for a global change layer and the so-called change DEM will become available in 2021. Despite being well beyond their design lifetime, both satellites are still fully functional and have enough consumables for several additional years. Therefore, bistatic operations continue with a focus on changes in the cryosphere, biosphere and urban areas.

3. THE UPCOMING HRWS MISSION

Given the great success of the TanDEM-X program, the DLR space administration initiated in 2016 a feasibility study for a mission featuring both very high resolution and wide swath characteristics. Airbus Defence and Space GmbH was appointed to perform this analysis in the scope of a phase 0/A study.

An extensive user need assessment was carried out in the frame the phase 0 study, in order to gather the needs and requirements of the potential users of such a system. Originally planned as a TerraSAR-X follow-on, the HRWS mission gradually changed from a monostatic to a multistatic mission in order to fulfill the demanding scientific, commercial and institutional user requirements. The ambitious current baseline concept of the HRWS Mission, which will be discussed below, was presented in 2018, successfully concluding the Phase A of the mission.

In December 2020 the German government finally approved the implementation of the HRWS mission, continuing and enhancing with this new system the very successful German X-Band spaceborne SAR program.

The purpose of the HRWS mission is to provide the scientific community, the German national institutions and the international commercial sector with very high-resolution SAR data (down to 25 cm) and wide swaths, as well as, new monostatic and multistatic imaging modes.

The HRWS mission is to be flown in the same orbit as TerraSAR-X, at ca. 514 km altitude in a sun-synchronous dusk-dawn orbit with a repeat ground-track cycle of 11 days. The launch is currently planned in the timeframe of 2026/2027.

3.1. Mission Concept

The baseline concept of the HRWS mission consists of a powerful main satellite acting as illuminator and 3 smaller companion satellites flying in formation ca. 15 km ahead of the main satellite (Figure 1). The companions are to be used as receive-only relay satellites flying in close proximity (down to ~100 m) to one another. Based on the decade of TerraSAR-X/TanDEM-X formation flight experience collected at the DLR German Space Operations Center (GSOC), [8] and [9], this ambitious approach will exploit this challenging formation flight in order to implement for the first time in space the MirrorSAR concept. Developed by the DLR Microwaves and Radar Institute, MirrorSAR is a new multistatic approach for robust single-pass interferometry and generation of digital elevation models [5]. In this concept, the main satellite is active, i.e. sends the radar signals to the ground (and signal reference to the companions) and the companion satellites provide a kind of microwave mirror (or space transponder) which routes the radar echoes from the ground back towards the transmitter.

The forwarded radar signals are then coherently demodulated within the transmitter satellite by using the same oscillator that had been used for radar pulse generation. The MirrorSAR concept makes possible the effective low-cost implementation of a multistatic SAR system with multiple baselines for high-resolution SAR interferometry. The hardware and thermal design of the receiver satellites is therefore considerably simplified, which lowers their mass, size and power demand. MirrorSAR allows efficient multi-satellite data compression, which lowers the downlink requirements and reduces the mission operation costs.

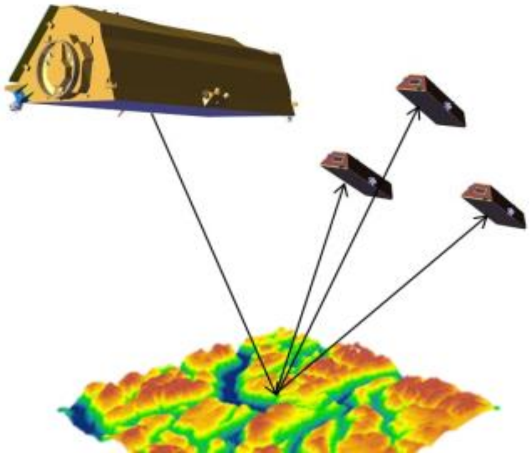

Figure 1 - Current baseline of the HRWS Mission consisting of a main SAR satellite and 3 MirrorSAR satellites.

The superior imaging characteristics will be achieved by means of digital beam forming and fractionated radar architecture. Taking advantage of the new ITU frequency allocation in X-band allowing a bandwidth of up to 1200 MHz, a frequency scanning functionality (F-SCAN) for the main satellite was proposed by Airbus during the phase A study [10].

The F-SCAN method can be implemented with much less hardware complexity than a full digital beamforming system (e.g. SCORE [11]) by using an analogue frequency scanning approach in elevation. F-SCAN offers a number of unique features, such as, inherent pulse compression achieved by aligning the chirp ramp of the transmitted pulse with the travel duration of the echoes received from the imaged swath, excellent signal-to-noise performance with reduced peak power requirements, improved impulse response sidelobe suppression and an almost overhead free data sampling of the echo window. F-SCAN uses the pencil beam in both transmit and receive. This not only leads to a higher system gain, but also has a better suppression of ambiguous targets.

Furthermore, the electronic beam steering in azimuth is complemented by a mechanical steering, using Control Moment Gyroscopes (CMG), providing a very high agility of the system. All equipped with electric propulsion, the HRWS main satellite is to be maintained within the control tube of merely 100 m (desired minimum) to maximum 250 m radius around the repeat ground-track reference orbit and the companions will fly in a Helix formation [5], [12].

3.2. Users, imaging modes and fields of applications

The main HRWS user groups are worldwide science users, institutional German civilian and military users and international commercial users. The mission goal is to fulfil their needs regarding data products and services, data ordering and information handling. Based on the user need assessment, the main fields of applications identified are surface motion monitoring, change detection, thematic mapping, maritime surveillance, image and geo-intelligence, as well as, the generation of digital elevation models. Based on the technical requirements (resolution, swath width, repetition rate, etc.) for those main fields of applications, product specifications of HRWS were developed for the Spotlight, Stripmap and ScanSAR imaging modes.

In Spotlight mode HRWS will provide a maximum spatial resolution of 25 cm with 25 x 25 km² image size in Sliding Spotlight mode and single polarization and 15 x 15 km^2 in quad-polarization mode. A new “Spotlight Theatre” imaging mode will be able to acquire up to 8 areas with 7.5 x 7.5 km^2 coverage and 25 cm resolution within an area of interest of 100 km^2 (Figure 2). The azimuth resolution of the Stripmap mode will be 1 m and 3 m covering a swath width of 50 km and 80 km, respectively. Quad-pol acquisitions in Stripmap mode will be available in 2-m spatial resolution with 30 km swath width.

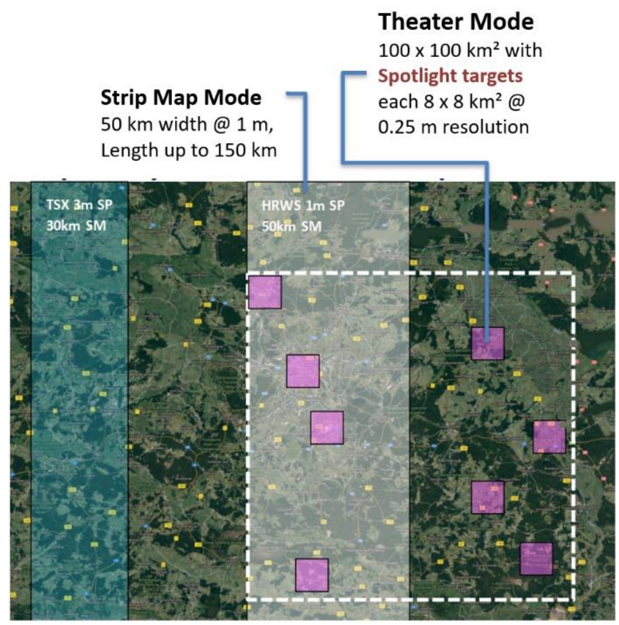

Figure 2 - Example of HRWS innovative Theater Mode and improvements in resolution and swath in Stripmap Mode between TerraSAR-X (TSX) and HRWS.

The ScanSAR mode will be able to provide imagery in various resolutions and polarization modes with a swath of up to 500+ km in single pol. The multistatic capabilities of HRWS will provide data with an 11-day interferometric repeat cycle. The multistatic mission goal will be a global digital elevation model at 4-m posting with a relative height accuracy of 2 m. The flexibility of HRWS’s multistatic mission design will allow the generation of on-demand local to regional digital elevation model products.

Based on the user demand several geo-information products and services have been identified as candidates for implementation in the HRWS service segment: i) surface movement mapping, ii) ground control point generation, iii) change detection product generation, iv) maritime surveillance and v) radargrammetry digital elevation model generation. Thanks to the multistatic capabilities of HRWS new geoinformation products and services have been identified as candidates for implementation in the HRWS service segment, as for example 3D/4D change detection, sea ice topography, SAR tomography over urban areas and ground moving target indication (GMTI), Figure 3.

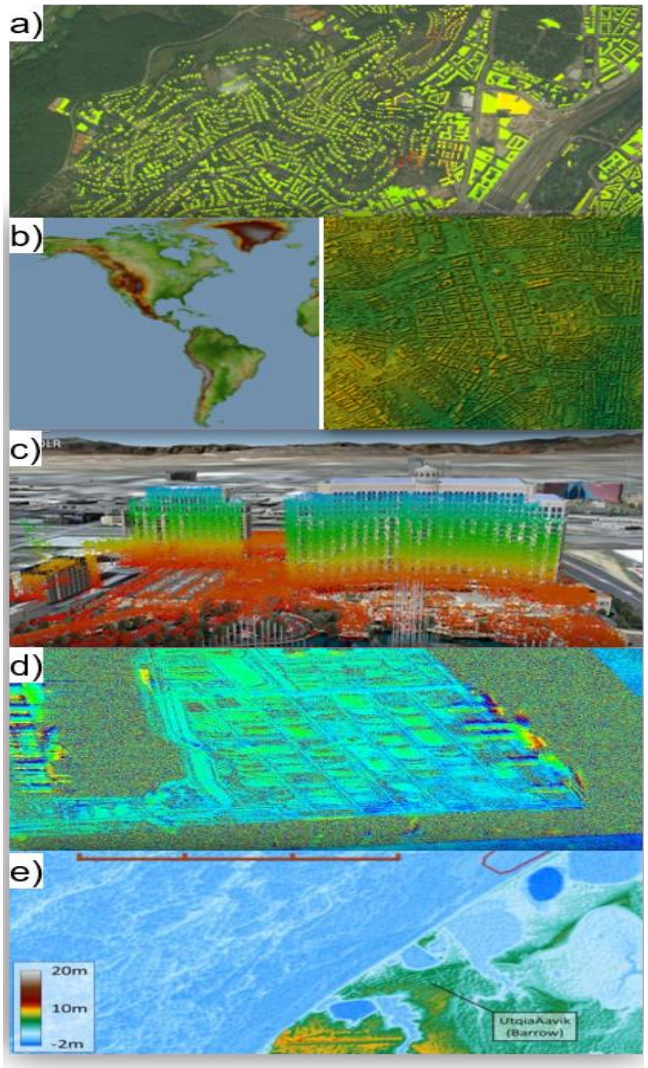

Figure 3 - HRWS interferometric and multistatic capabilities: a) Surface motion detection with millimetric precision and very high permanent scatters density; b) Global, local and regional on-demand high-resolution DEMs; c) 3D reconstruction using SAR tomography; d) 3D/4D change detection; e) Sea ice topography monitoring.

4. CONCLUSIONS AND OUTLOOK

The HRWS mission is an innovative mission concept that will provide continuity to the German spaceborne SAR program in X-band. New imaging technologies and an innovative mission concept allow the fulfillment of the demanding user requirements in scientific, commercial, institutional and security related applications. The use of digital beamforming (multiple phase centers in azimuth) in connection with F-SCAN offers a less complex SAR instrument implementation for high-resolution, wide-swath imaging. In addition, a new class of DEM will be generated by the MirrorSAR concept with a fractionated radar architecture. The phase B of the HRWS mission is expected to start later this year and the launch is scheduled for 2026/2027 timeframe.

5. REFERENCES

[1] A. Freeman, M. Zink, E, Caro, A. Moreira, L. Veilleux, M. Werner, “The legacy of the SIR-C/X-SAR radar system: 25 years on,” Remote Sensing of Environment, vol. 231, 2019.

[2] T. G. Farr, P. Rosen, E. Caro, R. Crippen, R. Duren, S. Hensley, M. Kobrick, M. Paller, E. Rodriguez, L. Roth, D. Seal, S. Shaffer, J. Shimada, J. Umland, M. Werner, M. Oskin, D. Burbank, D. Alsdorf, “The Shuttle Radar Topography Mission,” Reviews of Geophysics, Vol. 45, 2007.

[3] G. Krieger, A. Moreira, H. Fiedler, I. Hajnsek, M. Werner, M. Younis, M. Zink, “TanDEM-X: A Satellite Formation for High Resolution SAR Interferometry,” IEEE Transactions on Geoscience and Remote Sensing, vol. 45, no. 11, pp. 3317-3341, 2007.

[4] Nuncio Quiroz, A. E., Bartusch, M.: “Next Generation of the German X-Band SAR: The Multi-static High-Resolution Wide-Swath Mission”, ESA Living Planet Symposium (LPS), Milan, Italy, May 2019.

[5] G. Krieger, M. Zonno, J. Mittermayer, A. Moreira, S. Huber, and M. Rodriguez-Cassola, “MirrorSAR: A fractionated space transponder concept for the implementation of low-cost multistatic SAR missions. *Proc. of the European Conference on Synthetic Aperture Radar (EUSAR)*, 2018.

[6] R. Werninghaus and S. Buckreuss, “The TerraSAR-X Mission and System Design,” IEEE Transactions on Geoscience and Remote Sensing, vol. 48, no. 2, pp. 606–614, 2010.

[7] P. Rizzoli, et.al., “Generation and Performance Assessment of the Global TanDEM X Digital Elevation Model,” ISPRS Journal of Photogrammetry and Remote Sensing, vol. 73, pp. 119-139, 2017.

[8] O. Montenbruck et al., “Navigation and Control of the TanDEM-X Formation”, *Journal of the Astronautical Sciences*, 56 (2009):341-357.

[9] R. Kahle, S. D’Amico, “The TerraSAR-X Precise Orbit Control - Concept and Flight Results”, *International Symposium on Space Flight Dynamics*, May 2014.

[10] C. Roemer: “Introduction to a new wide area SAR mode using the FSCAN principle”. *Proc. of the IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, pp. 3844-3847, 2017.

[11] M. Suess, B. Grafmueller, and R. Zahn, "A Novel High Resolution, Wide Swath SAR System", *Proc. of the IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, Sidney, Australia, 2001.

[12] S. Spiridonova, R. Kahle, “HRWS – An Ambitious 4+ Satellite Formation Flying Mission”, *18th Australian Aerospace Congress*, Melbourne, 2019.