Spaceborne Radar Technologies for Earth Remote Sensing

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***Abstract* — Synthetic Aperture Radar (SAR) is an indispensable source of information in earth observation since SAR is the only spaceborne sensor that has high-resolution, all-weather and day-and-night imaging capability. Within the next 10 years more than 20 spaceborne SAR systems from different nations will be launched. Increased demand for larger swath width and higher geometric resolution poses contracting requirements on the system design. This paper gives an overview of the latest developments on the digital beamforming technique that allows overcoming the fundamental limitations of conventional SAR systems. Finally, this paper summarizes the potential of bi- and multi-static SAR systems and gives an outlook on the TanDEM-X mission.**

Keywords – Synthetic Aperture Radar (SAR), Digital Beamforming, Bi- and Multi-Static Radar, Waveform diversity.

I. Introduction

SAR plays already a major role in a wide spectrum of applications as for environmental monitoring, retrieval of bio/geo-physical parameters of land, ocean and ice surfaces, hazard and disaster monitoring as well as reconnaissance and security related applications. Today we stand at the threshold to a new era of spaceborne and airborne SAR systems. New satellite systems like TerraSAR-X, SAR-Lupe, CosmoSkymed, Radarsat-II, TanDEM-X, and Sentinel-1 will provide radar images with a resolution cell up to hundred times smaller than the one of conventional SAR systems. They will also outperform by far existing systems with respect to their imaging flexibility and interferometric modes.

Since the first spaceborne SAR system has been launched in 1978, a tremendous technological and application-related development has been achieved. Spaceborne SAR systems represent today one of the most demanding remote sensing imaging instruments in a technological sense and this poses a great challenge for the development of new concepts, techniques and technologies for future SAR systems. Today, the active antenna with transmit and receive modules (T/R modules) represents the state-of-the-art for spaceborne SAR systems. This technology allows a greater flexibility in the selection of the incidence angle range to be imaged as well as the efficient implementation of advanced SAR imaging modes like scanSAR or spotlight.

However, the user request for large swath width and the high azimuth resolution poses contradicting requirements on the design of spaceborne synthetic aperture radar (SAR) systems [1]. ScanSAR mode enables a wide imaging swath on the cost of an impaired azimuth resolution [2] and the spotlight mode allows for an improved azimuth resolution on the cost of a non-contiguous imaging along the satellite track [3]. It is, therefore, not possible to combine both imaging modes simultaneously in one and the same data take. This dilemma motivated further research towards the development of new radar techniques for spaceborne high-resolution wide-swath SAR imaging.

II. Digital Beamforming

A promising candidate for such a new radar imaging technique is digital beamforming on receive where the receiving antenna is split into multiple sub-apertures (cf. Fig. 1). In contrast to analog beamforming with conventional T/R modules, the received signals from each sub-aperture element are separately amplified, down-converted, and digitized. This enables an a posteriori combination of the recorded sub-aperture signals to form multiple beams with adaptive shapes. The additional information about the direction of the scattered radar echoes can then be used to (1) suppress spatially ambiguous signal returns from the ground in range and/or azimuth direction, (2) to increase the receiving antenna gain without a reduction of the imaged area, (3) to suppress spatially localized interferences, and (4) to gain additional information about the dynamic behavior of the scatterers and their surroundings. By this, it becomes possible to overcome the fundamental limitations of conventional SAR systems [4]-[10]. An example for the recent developments is the high-resolution wide-swath (HRWS) SAR system which combines a small transmit antenna with a large receiver array as shown in Fig. 1 ([6], [8]). The small transmit antenna illuminates a wide swath on the ground and the large receiver array compensates the Tx gain loss by a real-time digital beamforming process called scanning on receive. Multiple azimuth channels allow furthermore for the acquisition of additional samples along the synthetic aperture by employing the principle of the displaced phase centre antenna (DPCA, [4]). This enables a reduction of the pulse repetition frequency (PRF) and therefore the imaging of a wider swath without rising azimuth

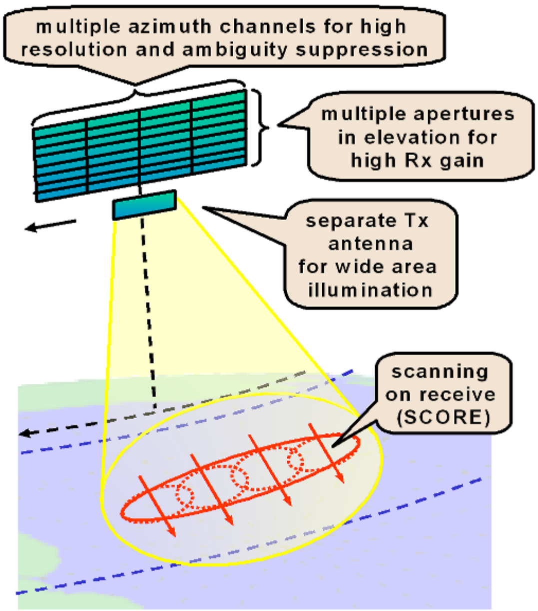

Figure 1. High-Resolution Wide-Swath (HRWS) SAR system with separate transmit antenna and scanning on receive by means of digital beamforming.

ambiguities. The combination of the azimuth signals from the multiple apertures requires the application of dedicated multi-channel SAR signal processing algorithms as introduced in [7] and further elaborated in [9] and [11].

The HRWS system concept assumes a wide area illumination by a separate transmit antenna. This enables an independent electrical design and optimization of the transmit and receive paths, but it requires also the accommodation of an additional antenna on the spacecraft and reduces the flexibility to operate the radar system in different SAR imaging modes. It is hence worth to consider also the application of digital beamforming techniques in radar systems that use the same antenna array for both the transmission and reception of radar pulses, thereby taking advantage of already existing space-qualified T/R module technology.

A novel approach to exploit the large SAR antenna array is the use of multi-dimensional waveform encoding for the transmitted radar pulses. The illustration in Fig. 2 visualizes the difference between a spatio-temporally waveform encoding (right) and a transmit pulse (left) as used in conventional SAR imaging modes and systems. A simple example for a multi-dimensional waveform encoding in space and time is a mere switching between different antenna beams and/or sub-aperture elements during each transmitted pulse. The overall PRF remains unaltered in this case. Full range resolution within each sub-beam is achieved by concatenating multiple chirp signals in a saw-tooth like frequency modulation (or any other sequence of full bandwidth and possibly even mutually orthogonal waveforms). The scheme allows a staggered illumination of a large area during each pulse, thereby supporting a systematic distribution of the available signal energy within this area. The concept of

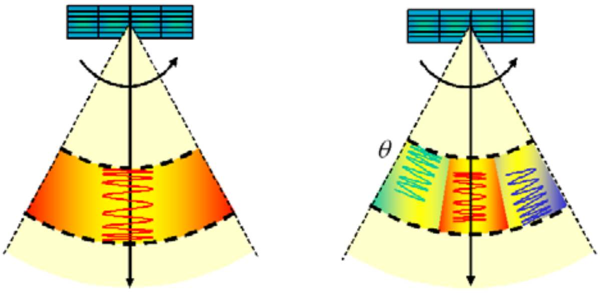

Figure 2. Different types of Tx waveforms. Left: Radar pulse as used in conventional SAR systems. Right: multi-dimensional waveform encoding of the transmitted radar pulse.

multi-dimensional waveform encoding can of course be extended to an arbitrary spatio-temporal radar illumination where each direction has its own temporal transmit signal with different power, duration, and/or phase code.

Another example for multi-dimensional waveform encoding is intra-pulse beam steering in elevation. This enables an illumination of a wide image swath with a sequence of narrow and high gain antenna beams. Such a staggered illumination is in some sense similar to the traditional scanSAR mode, with the important difference that each transmitted pulse illuminates now not only one but all sub-swaths simultaneously. The illumination sequence within each Tx pulse can in principle be arranged in any order. An interesting opportunity arises if we start from a far range illumination and proceed consecutively to near range as illustrated in Fig. 3. As a result, the radar echoes from different sub-swaths will overlap in the receiver as shown in Fig. 3 on the upper right. The overall receiving window can hence be shortened, thereby reducing the amount of data to be recorded and stored on the satellite without the necessity for real-time on-board processing. The temporal overlap of the radar echoes from the different sub-swaths is then resolved in the spatial domain by digital beamforming on receive. This a posteriori processing can be performed off-line on the ground, which has the further advantage that no information about the spatial structure of the recorded radar data will be lost, thereby enabling e.g. a suppression of directional interferences or jamming signals.

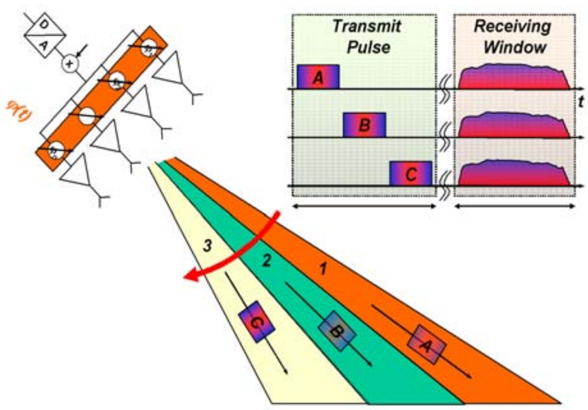

Figure 3. Intra-pulse beam-steering in elevation: The backscattered signals from different sub-swaths superimpose in the receiving window.

A direct consequence of the shortened receiving window length is the increased time to transmit multiple sub-pulses. This reduces the RF peak power requirements in the transmitter and provides further margin to switch between the sub-pulses, thereby simplifying the electrical system design. Another advantage of the staggered illumination is the reduced gain loss at the border of the swath if compared to a conventional radar illuminator. The use of variable Tx sub-pulses allows even for a flexible distribution of the signal energy on the ground. As a simple example one may consider the use of longer transmit pulses for sub-beams with higher incident angles. This illumination strategy is well suited to compensate the SNR loss due to both the typical decrease of the backscattering with increasing incident angles and the additional free space loss from a larger range. As a result, one may reduce the overall power requirements of the radar payload which in turn alleviates the thermal and electrical design of the satellite.

The systematic combination of spatio-temporal radar waveform encoding on transmit with multi-aperture digital beamforming on receive enables new SAR imaging modes for a wide range of remote sensing applications. Examples are an improved SAR system performance by increasing the number of effective phase centers, larger along-track baselines for along-track interferometry and moving object indication, and an efficient reduction of redundant information recorded by large receiver arrays.

Digital beamforming on transmit allows furthermore a flexible distribution of the RF signal energy on the ground. This enables not only a switching between different SAR modes like spotlight, scanSAR and HRWS stripmap, but it allows also for the simultaneous combination of multiple imaging modes in one and the same data acquisition. An example for such an interleaved operation is a spotlight imaging of an area of high interest in combination with a simultaneous wide swath SAR mapping for interferometric applications. This can be achieved by enhancing the multidimensional waveform encoding with additional sub-pulses that steer highly directive transmit beams to some specific areas on the ground. By this, one obtains a high Tx gain and a longer illumination time along the synthetic aperture, which will improve both the radiometric and the geometric resolution for the local areas of high interest. This is illustrated in Fig. 4 and such a hybrid mode is well suited to satisfy otherwise contradicting user requirements like the conflict between a continuous interferometric background mission and a high-resolution imaging request.

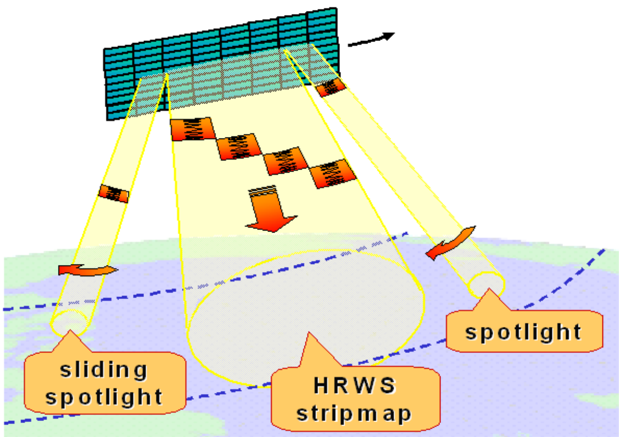

Figure 4. Hybrid SAR imaging modes using multi-dimensional waveform encoding.

III. BI- AND MULTI-STATIC SAR SYSTEMS

Bi-static radar is defined as a radar where the transmitter and receiver are spatially separated [1]. Recently, bistatic radar also received increasing interest with respect to synthetic aperture radar (SAR) and a number of spaceborne bi- and multistatic radar missions have been suggested, some of which are now under development or in planning [14]-[24]. The suggested systems may be divided into fully and semi-active configurations. In a fully active configuration, each radar has both transmit and receive capabilities as illustrated in Fig. 5 on the left. Examples for fully active systems are the multistatic TechSAT 21 constellation [16] and the TanDEM-X mission [24]. Semi-active systems combine an active illuminator with one or more passive receivers as shown in Fig. 5 on the right. Examples for semi-active systems are the interferometric cartwheel [18] and BISSAT [19].

Future semi-active SAR systems may in principle also combine multiple satellites in different orbital altitudes like e.g. a transmitter in a geostationary or geosynchronous orbit with multiple passive receivers in low earth orbit ([22], [23]). Such systems would be well suited for global monitoring with a short revisit time (e.g. < 1h) as well as for interferometric or even tomographic applications.

The development of bi-static spaceborne SAR systems is being brought forward by the TanDEM-X mission which will be the first bi-static SAR mission in space. TanDEM-X has the primary objective of generating a consistent, global digital elevation model (DEM) with an unprecedented accuracy according to the HRTI-3 specifications (2 m vertical accuracy, 90% confidence interval). The mission concept is based on a coordinated operation of two spacecraft flying in close formation to form a large radar interferometer in space. It consists of the TerraSAR-X satellite and a second, almost identical spacecraft, flying in tandem with typical distances of 250 – 500 m (see Fig. 6). In order to allow accurate phase information in the bistatic acquisition mode, the radar instruments feature a new technique for exchanging phase

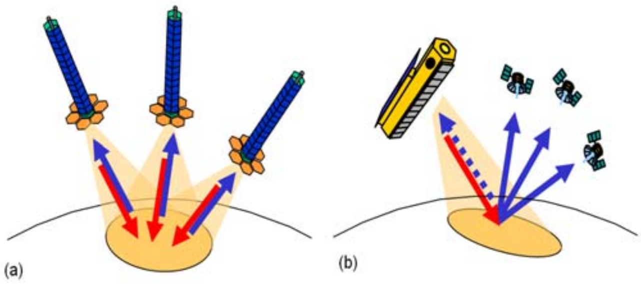

Figure 5. Fully active (left) and semi-active (right) multistatic radar systems.

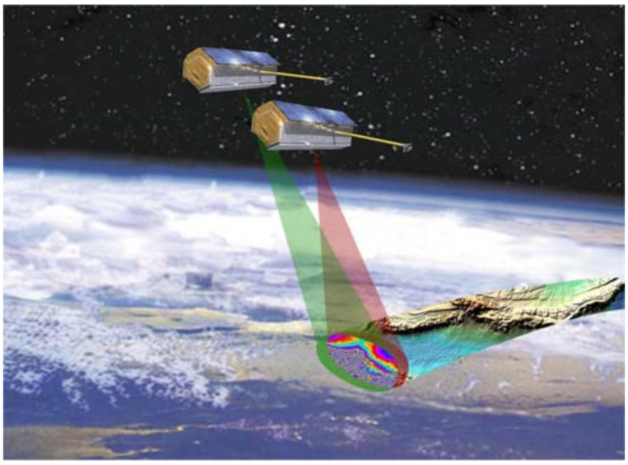

Figure 6. TanDEM-X mission with close formation flight and bi-static radar configuration for high accurate interferometric imaging.

information via dedicated microwave links. For generating the global DEM roughly 300 TByte of raw data will be acquired using a network of ground receiving stations. Processing to DEM products requires advanced multi-baseline techniques and involves mosaicking and a sophisticated calibration scheme on a continental scale. Beyond its primary mission objective of generating a global HRTI-3 DEM, TanDEM-X provides a configurable SAR interferometry platform for demonstrating new SAR techniques and applications, such as digital beamforming, single-pass polarimetric SAR interferometry, along-track interferometry with varying baseline, or super resolution. Close formation flight collision avoidance becomes a major issue and a new orbit concept based on a double helix formation has been developed to ensure a safe orbit separation.

TanDEM-X represents an important step towards a constellation of bi- and multi-static radar satellites and will provide sustained support for Germany's leading role in spaceborne SAR technologies and missions.

IV. Conclusions

This paper has summarized new techniques and concepts towards a vision of a constellation of SAR satellites for earth remote sensing. Bi- and multi-static SAR configurations in combination with digital beamforming make optimum use of the total available signal information and energy, allowing an efficient radar design for applications with user requirements for frequent monitoring, wide-swath imaging, interferometry and high resolution. Digital beamforming with multiple aperture signals allows for the efficient suppression of ambiguities, which enables new SAR systems with wide coverage and high image resolution. This avoids conflicts from operating SAR systems in mutually exclusive imaging modes such as scanSAR, stripmap and spotlight and enables regular observations of large areas. Further potential advantages of bi- and multi-static radar systems in combination with digital beamforming are enhanced MTI, efficient interference suppression, resolution enhancement and SAR tomography.

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