A Golden Age for Spaceborne SAR Systems

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Abstract— **Spaceborne Synthetic Aperture Radar (SAR) is the only imaging sensor technology that can provide all-weather, day-and-night and high-resolution images on a global scale. Today, SAR data are used for a multitude of applications ranging from geoscience and climate change research, environmental monitoring, 2-D and 3-D mapping, change detection, 4-D mapping (space and time), security-related applications up to planetary exploration. With the launch of the SAR satellites TerraSAR-X and TanDEM-X, COSMO-SkyMed constellation, Radarsat-2 as well as Sentinel-1a a new class of SAR satellites was introduced providing images with resolution in the meter regime. A paradigm shift is however taking place in spaceborne SAR systems. By means of the development of new digital beamforming and waveform diversity technologies in combination with large reflector antennas, future SAR systems will outperform the imaging capacity of current systems by at least one order of magnitude. This paper will provide an overview of the state of the art in spaceborne SAR technologies and applications, and will describe the innovative techniques and technologies that will shape its future development.**

Index Terms—**Synthetic Aperture Radar (SAR), Spaceborne SAR, Interferometry, Polarimetry, Tomography, Digital Beamforming, Digital Elevation Model (DEM).**

I. Introduction

Synthetic Aperture Radar (SAR) has entered into a golden age. More than 15 spaceborne SAR sensors are being operated today and 10 new SAR systems will be launched within the next 5-6 years [1]. SAR is predestined to monitor dynamic processes on the Earth's surface in a reliable, continuous and global way. Since the launch the first SAR satellite, Seasat, in 1978 a huge development has been achieved in technology, techniques and information retrieval algorithms [2], [3]. While the SAR development until the 90s was driven by technology, a new era started 2007 with the launch of the high-resolution SAR satellites, for which the user requirements were the main drivers for the specification, development and mission operation. This year's highlights are the launches of Sentinel-1 (C-band, first satellite of the ESA/EU Copernicus program), ALOS-2 (L-band, Japan) and PAZ (X-band, Spain). This new class of SAR satellites with T/R module technology is providing flexible imaging modes and an image resolution into the meter regime.

In Europe, much effort has been put into the development of operational services based on satellite data. The ESA/EU Copernicus program is the largest ever Earth observation program worldwide and consists of a fleet of 6 satellites for land, ocean and atmospheric monitoring. Sentinel-1a, the first satellite of the Copernicus program, was successfully launched on April 3, 2014. It consists of a C-band SAR instrument with a focus on emergency services (extreme weather, humanitarian disaster), marine environment (oil spills, ship traffic, coastal zones, ocean winds, waves and currents), land use mapping as well as climate change. Fig. 1 shows an example of the applications of Sentinel-1 related to land monitoring [4]. The main acquisition mode of Sentinel-1 is the interferometric wide swath (IW) mode which applies the azimuth beam steering concept defined as TOPS (Terrain Observation by Progressive Scans), [5]. By this, an improved imaging performance is achieved when compared to the standard ScanSAR mode, which suffers from an amplitude modulation within each azimuth burst. Sentinel-1a is the first SAR satellite to use the TOPS acquisition concept as an operational imaging mode, providing a swath width of 250 km with 5 m x 20 m resolution in dual polarization mode (HH+HV or VV+VH).

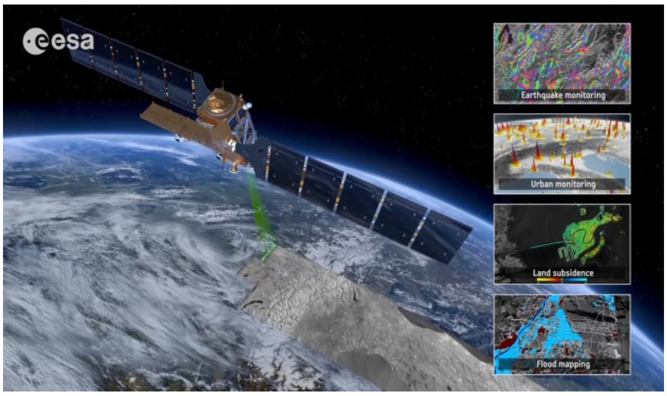

Fig 1 – Artistic view of the Sentinel-1 satellite and examples of land applications: Monitoring of earthquakes, urban areas, land subsidence and flooding mapping (© ESA).

Sentinel-1a lifetime is specified with 7 years (satellite resources available for 12 years) and is being deployed in a 12-day repeat orbit at 698 km height. Sentinel-1b, an identical SAR satellite, will be launched in 2015 and will fly in the same orbit height but 180 degrees apart from Sentinel-1a in order to provide a 6-day revisit time.

As far as the German spaceborne radar program is concerned, TerraSAR-X and TanDEM-X are the flagship projects. The next session provides an overview of the TanDEM-X mission's objectives and innovations.

II. TanDEM-X: A High-Resolution Spaceborne Radar Interferometer

The primary objective of the TanDEM-X mission is the generation of a global Digital Elevation Model (DEM) of the Earth's surface with unprecedented accuracy as the basis for a wide range of commercial applications as well as for scientific research. It is expected that this data set will become a new reference in geosciences and remote sensing applications since its 3-D information content is ca. 30 times more accurate than the presently available global scale DEM data set. The first DEM data sets are available since January 2014 and the complete DEM will be available by the end of 2015.

TanDEM-fX is the first radar interferometer in space that employs two satellites operating in a closely controlled formation flight (see Fig. 2). TerraSAR-X, the first satellite of the formation, was launched in June 2007 and is providing high-resolution X-band radar images for commercial and scientific applications [6]. TanDEM-X, an almost identical satellite to TerraSAR-X, was launched in June 2010 [7] and is equipped with an additional 30 kg cold gas tank to allow precise maneuvers for keeping the formation flight. In addition, TanDEM-X has a larger solid-state mass memory with 768 Gbit (twice the size of TerraSAR-X) to support the on-board data buffering and downlink of the large data amount during interferometric acquisitions. While both radar satellites are operated during the interferometric acquisition mode, either the TerraSAR-X or the TanDEM-X satellite is used for acquiring high-resolution 2-D radar images.

A new orbit concept, the so-called Helix orbit, has been developed for TanDEM-X which minimizes the collision risk while keeping the across-track baseline at similar values along the orbit cycles. After the launch of TanDEM-X, global DEM acquisitions started in December 2010. The first and second global coverages of the Earth's surface were completed in March 2012 and 2013, respectively. Currently, the third and the fourth interferometric acquisitions over difficult, mountainous terrain are being performed [8]. The TanDEM-X DEM is specified with 2 and 4 m relative height accuracy for flat and mountainous terrain, respectively, at 12 m posting. Large areas of Australia (see example in Fig. 3), North America and Siberia have been processed and mosaicked. DEM processing of South Africa is now being performed and will be followed by South America. The analysis of these data shows that the DEM specifications are being met and even surpassed [9]. DEM with even higher resolution (0.8 m relative vertical accuracy and 6 m posting) will be generated after the main acquisition plan is concluded in mid-2014. Besides the main objective of the mission, several innovative acquisitions are being performed with TanDEM-X to demonstrate several techniques and applications based on Along-Track Interferometry (ATI), multistatic SAR, polarimetric SAR interferometry, digital beam forming and super resolution. A dedicated 15-month science phase will start in October 2014 where the baseline values will be set to optimize the acquisition of scientific experiments and higher resolution DEM. Scientists are invited to submit proposals for obtaining DEM data for scientific applications at www.dlr.de/HR/tdmx.

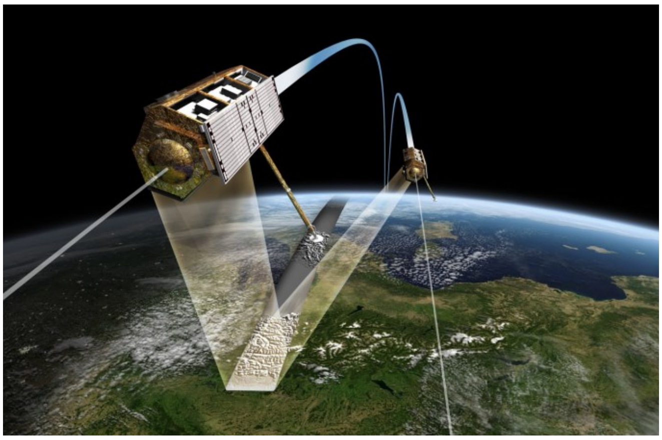

Fig 2 – TanDEM-X artistic view. With across-track baseline values ranging from 120 to 500 m a high-resolution global Digital Elevation Model (DEM) is being generated.

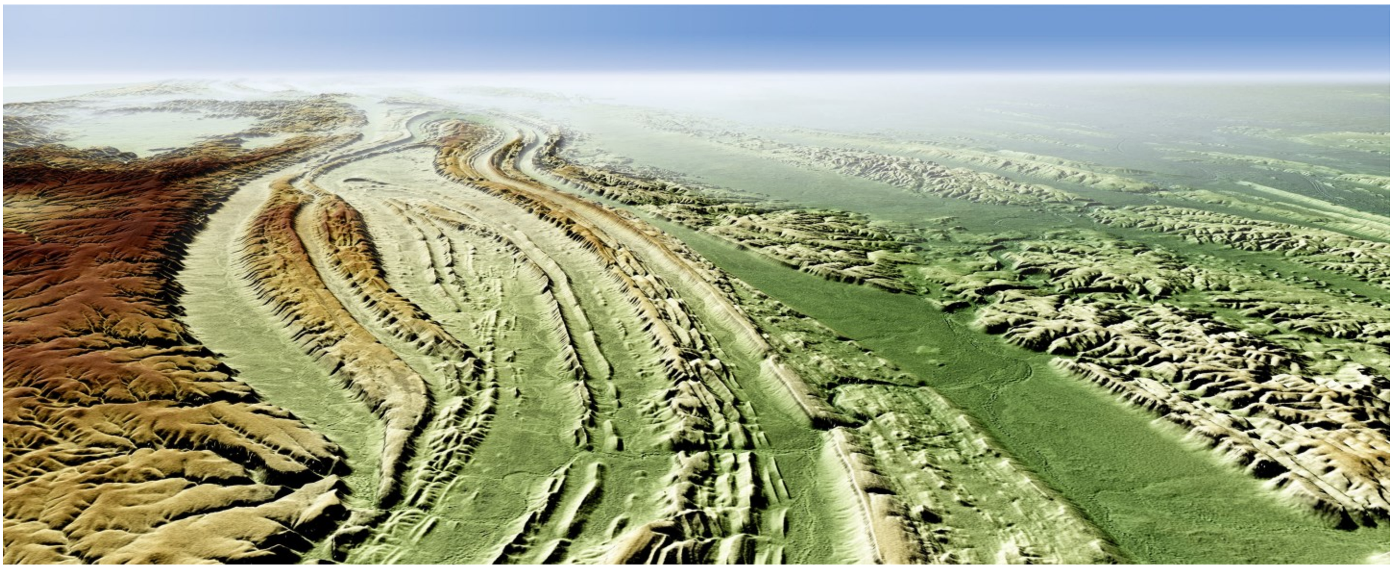

Fig. 3 - Digital Elevation Model (DEM) generated by TanDEM-X over the Finke Gorge National Park, close to Alice springs, Australia.

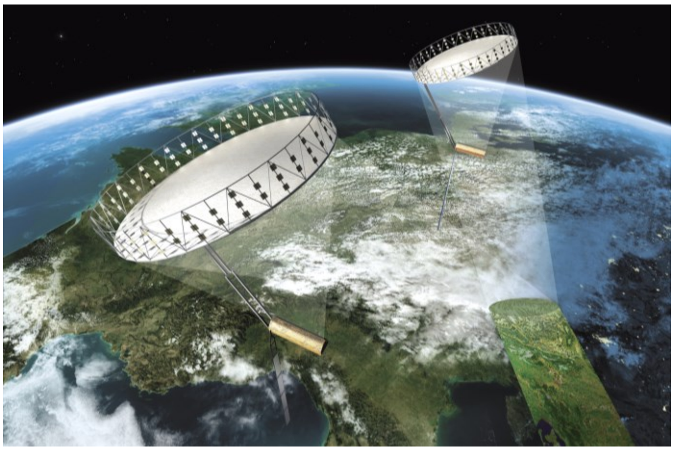

Fig 4 –Artistic view of the Tandem-L satellite formation with L-band radar for systematic monitoring dynamic processes over the Earth's surface.

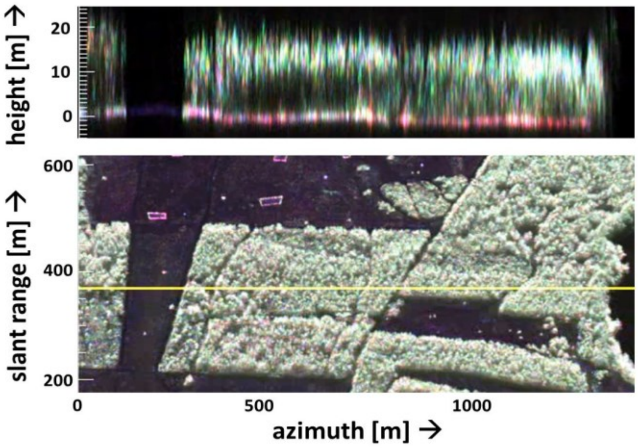

Fig 5 – Forest profile derived by polarimetric SAR tomography using DLR's airborne SAR system at L-band [11]. The forest vertical profile on the top corresponds to the yellow line shown on the SAR image. A total of 21 flight tracks were acquired with an average interferometric baseline of 20 m each. The color coding corresponds to the elements of the Pauli vector, namely, blue for the surface scattering, red for the dihedral ground-trunk interaction, and green for the volume of the canopy. Tandem-L will estimate the forest biomass from the forest height and vertical profile using polarimetric SAR tomography with a reduced number of tracks.

III. TANDEM-L

Tandem-L is a mission proposal for an innovative interferometric L-band radar instrument that enables the systematic monitoring of dynamic processes over the Earth's surface using advanced techniques and technologies [10]. The mission is science driven aiming to provide a unique data set for climate and environmental research, geodynamics, hydrology and oceanography. Important application examples are global forest height and biomass inventories, measurements of Earth deformation due to tectonic processes and/or anthropogenic factors, observations of ice/glacier velocity field and 3-D structure changes, and the monitoring of soil moisture and ocean surface currents. The Tandem-L mission concept consists of two cooperating radar satellites flying in close formation (see Fig. 4). The repeat-pass acquisition mode in combination with polarimetric SAR interferometry provides a unique data source to observe, analyze and quantify a wide range of mutually interacting processes in the bio-, litho-, hydro- and cryosphere. Fig. 5 shows the potential of polarimetric SAR tomography for the estimation of forest height and its vertical profile. By means of an allometric relation forest biomass can be estimated.

One key technology of Tandem-L is the use of a large reflector antenna in combination with digital beamforming in the feed array that illuminates the reflector. While all feed elements are used during transmission, allowing the illumination of a large image swath, 2-3 feed elements are activated during the receive window. The feed element positions are periodically shifted in synchrony with the systematic variation of the direction of arrival from the swath echoes. The advantages of this concept are manifold. First, the use of a large reflector antenna in connection with digital beamforming allows the reduction of the transmit power by a factor of 3-4 in comparison to the traditional SAR concept for the same imaging parameters. Second, it allows the mapping of a much wider swath in high resolution stripmap mode. Radar operation with a variable PRF concept, called staggered SAR, allows an imaging with 350 km swath width and 3 m x 3 m resolution [12]. The increase in imaging performance is at least one order of magnitude higher than for current SAR systems. A joint pre-phase study with JAXA has been started in 2013 and will be completed by mid-2014. The study has demonstrated a concept for a joint realization of a Tandem-L mission with an envisaged launch date by 2021.

IV. FUTURE DEVELOPMENTS

Conventional spaceborne SAR systems use a planar antenna with transmit/receive (T/R) module technology. This allows the steering of the antenna beam at different incidence angles and a great flexibility in the implementation of imaging modes for a wide range of user requirements. Typically a few hundred T/R modules are employed, with their settings being controlled by software. It is however not possible to achieve high azimuth resolution and wide swath coverage at the same time. This constrain arises from the pulsed operation of SAR systems and the sampling requirement for the Doppler bandwidth. Radar systems with very high resolution have a high Doppler bandwidth which leads to a high value for the pulse repetition frequency (PRF). This high PRF value reduces on the other hand the maximum allowable size of the swath. An increase of the swath width implies therefore in a deterioration of the azimuth resolution [15], [16].

A paradigm shift is however taking place in spaceborne SAR systems: New digital beamforming concepts will boost the performance of future SAR systems by at least one order of magnitude. A prominent example is the high-resolution wide-swath (HRWS) SAR demonstrator [13], [14] which is currently under development at EADS Astrium with support from the German Aerospace Center (DLR). This system has been specified to map a 70 km wide swath with a resolution of 1 m, thereby exceeding the number of acquired ground resolution cells of the TerraSAR-X stripmap mode (3 m resolution at 30 km swath width) by a factor of approx. 7.

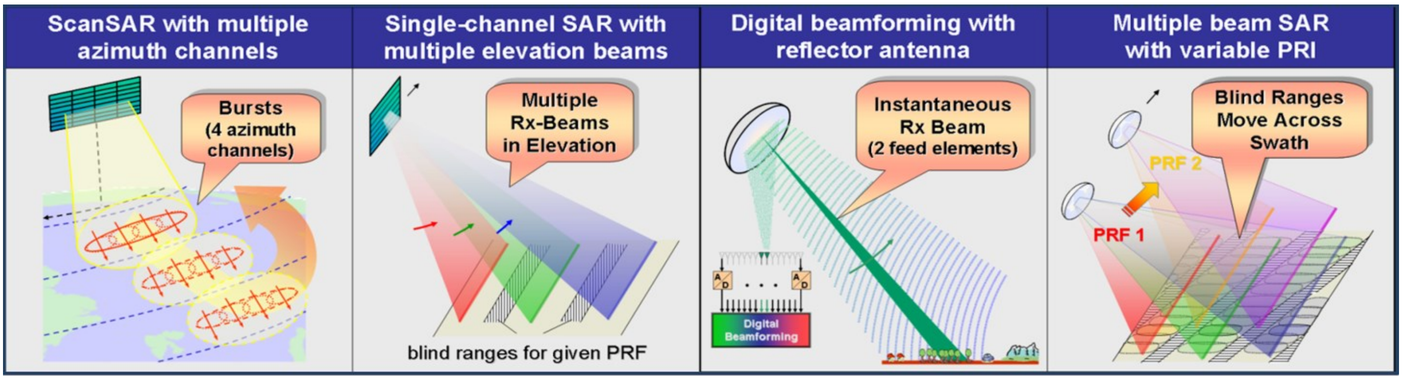

Fig 6 – Advanced concepts for high-resolution wide-swath imaging based on digital beamforming. Left and middle left: large planar array with digital beamforming; right and middle right: multichannel feed array with digital beamforming and large reflector antenna (e.g. Tandem-L).

Advanced concepts for future spaceborne SAR systems with digital beamforming technology are summarized in figure 6 and includes a ScanSAR image mode (Figure 6 left) or a simultaneous multi-beam on receive which are illuminated by a broad Tx beam (Figure 6 middle left). The broad Tx beam can be achieved by applying phase tapering, spectral Tx diversity or an illumination with a sequence of sub-pulses [15]. Moreover, digital beamforming in combination with waveform diversity and large reflector antennas provides a further extension of the imaging capability (see Figure 6 middle right and right). This imaging mode is being adopted for the mission proposal Tandem-L (cf. session III) which is distinguished by the high degree of innovation with respect to the methodology and technology.

V. Conclusions

The future for spaceborne SAR systems looks fascinating. The fast growing user community poses demanding requirements for improved imaging capabilities which push the development of new technologies with the ultimate goal to allow a wide-swath high-resolution imaging. The trend for future systems shows the need for an increased information content in SAR images that are achieved by polarimetric operation, multi-frequency radar systems, improved range and azimuth resolution, time series (frequent revisit of the same area) as well as observation angle diversity (interferometry and tomography) [1].

Multi-channel SAR systems with digital beamforming, MIMO, bi- and multi-static and large reflector antennas technologies will outperform the imaging capacity of current SAR systems by at least one order of magnitude [12], [13], [14], [15], [16]. The vision for the future development is a space-based radar observatory for the continuous monitoring of dynamic processes over the Earth, as it currently exists for weather prediction, where a network of geostationary satellites is used.

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