SPACEBORNE MULTI-BASELINE SYNTHETIC APERTURE RADAR (SAR) IMAGING

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ABSTRACT

This paper provides an overview of the state of the art and an outlook on future developments of spaceborne Synthetic Aperture Radar (SAR) systems with multi-baseline imaging capability, such as 3D differential SAR interferometry (3D-DinSAR), polarimetric SAR interferometry (Pol-InSAR), tomography (TomoSAR), and holography (HoloSAR). The goal is to fill the multidimensional data space with additional information from images with different spatial and/or temporal baselines.

***Index Terms*—** Synthetic Aperture Radar (SAR), Multi-baseline SAR Imaging, Polarimetric SAR Interferometry, SAR Tomography, SAR Holography.

1. INTRODUCTION

The trend for future SAR systems shows the need for an increased information content in SAR images which can be achieved by polarimetry, multi-frequency and/or improved range and azimuth resolution [1], [2]. In addition, temporal and spatial multi-baseline imaging increases the information content in the multi-dimensional data space and opens the door to a new class of information products [3]. This paper provides a summary of the state of the art and a perspective for future developments of space-based SAR systems with multi-baseline imaging capability. These include 3D differential SAR interferometry (3D-DinSAR), polarimetric SAR interferometry (Pol-InSAR), tomography (TomoSAR), and holography (HoloSAR). The goal is to fill the multidimensional data space with additional information from images with different spatial and/or temporal baselines. Well-known examples include across-track and along-track interferometry, providing measurements of surface topography, land deformation, ocean currents, and glacial motion. While across-track and along-track interferometry are well-established techniques and are widely used by current space-based SAR systems, new techniques like 3D-DinSAR, Pol-InSAR, TomoSAR, and HoloSAR are shaping the future development of space-based SAR.

New mission concepts for multistatic SAR configurations with distributed and sparse arrays will pave the way for this development. The multi-baseline SAR imaging can be basically divided in two different classes:

- *Temporal baseline*, i.e., acquisition of a time series from the same area with frequent revisit and with the same viewing geometry [4–7]. This well-established technique represents the state of the art for spaceborne SAR systems and can be divided into two distinguished applications: a) along-track interferometry for temporal baselines typically smaller than one day and b) differential interferometry for temporal baselines of several weeks up to years.
- *Spatial baseline*, i.e., acquisition from the same area with observation angle diversity. The associated imaging techniques are: across-track interferometry for terrain topography estimation with one or more spatial baselines (typically $1-3$ baselines, e.g., TanDEM-X [8], [9] and HRWS MirrorSAR [10]), Pol-InSAR for the characterization of the vertical structure of natural and anthropogenic volume scatterers (typically with $1-3$ baselines, [11], [12]), TomoSAR for three-dimensional imaging of natural or anthropogenic volume scatterers with several spatial baselines (typically 5 – 8 baselines, [13–16]) and HoloSAR for generating a 360° imaging view of natural and anthropogenic volume scatterers by means of multi-circular flight acquisitions (typically $5-20$ baselines, [17]).

The combination of temporal and spatial baselines using multistatic SAR configurations with large along-track baselines shall allow the retrieval of additional information products, like 3D deformation [18] as well as the simultaneous estimation of absolute differential tropospheric delays [19]. Next, the focus will be given to the new developments which are shaping the future of the multi-baseline SAR.

2. 3D DIFFERENTIAL SAR INTERFEROMETRY

While DinSAR is a well-established technique, there is a great interest in the user community for new imaging and

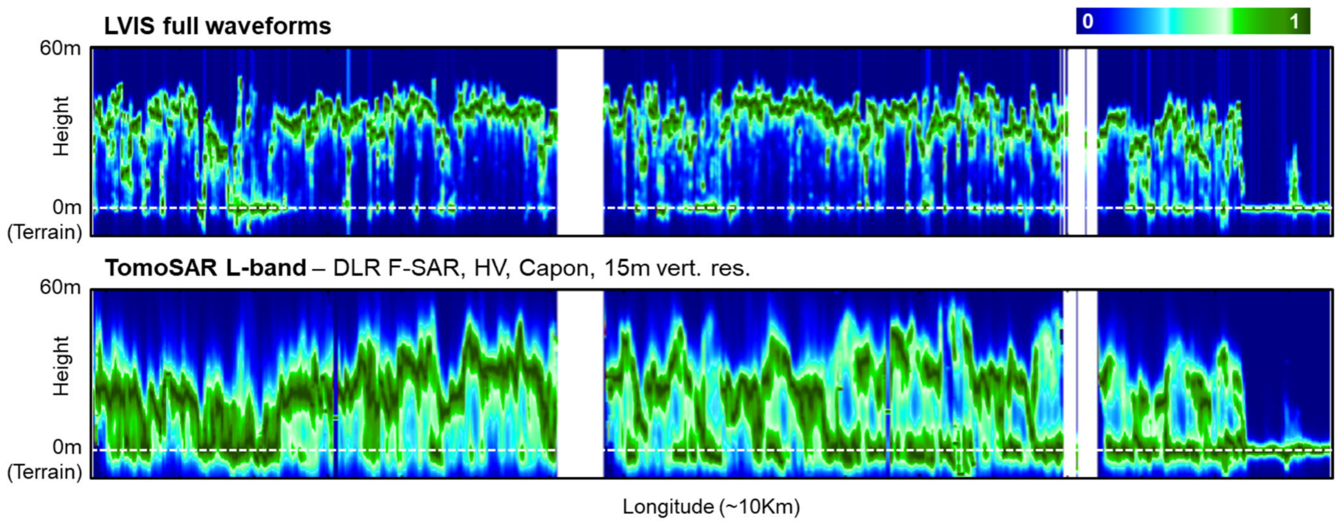

Figure 1 – Top: example of lidar waveforms acquired by NASA's LVIS sensor over dense forest stands in Lopé (Gabon). Bottom: TomoSAR L-band profiles obtained from the AfriSAR data (Capon algorithm) in HV polarization with a (Rayleigh) vertical resolution of 15 m over the same stands. The height axis is referred to the lidar terrain height.

mission concepts for 3D-InSAR. The Harmony mission [20], recently selected as ESA's Earth Explorer 10, consists of two companion satellites in formation with Sentinel-1, each of them carrying as main payload a receive-only radar instrument using Sentinel-1 as illuminator. When performing deformation measurements via differential SAR interferometry, the large squint diversity, given by the large along-track distance of 350 km between the illuminator and the receivers, will allow the retrieval of different projections of the deformation and, consequently, the possibility to obtain, for the first time, accurate 3D global deformation measurements of the Earth's surface [18]. The fact that the acquisitions are simultaneous allows the retrieval of the North-South deformation with a very high accuracy, since most of the tropospheric signal is correlated among the lines of sight and therefore cancels out for this component. For this reason, the large angular diversity can be further exploited to retrieve not only the deformation, but also the absolute differential tropospheric delay [19].

3. POLARIMETRIC SAR INTERFEROMETRY

The combination of multi-baseline interferometric acquisitions with polarimetric diversity for quantitative parameter estimation evolved from a stand-alone technique in the core element of integrative processing and inversion frameworks for the estimation of 3D vegetation and ice structure parameters [11], [12]. Pol-InSAR techniques are able today to combine multispectral interferometric acquisitions and to integrate lidar measurements in a model-based context improving significantly estimation performance. At the same time, the ability to integrate tomographic and Pol-InSAR measurements in a more general inversion framework, established in recent years, allows not only better performance in parameter estimation, but also effective design and combination of the different phases of actual and future interferometric/tomographic spaceborne missions.

4. POLARIMETRIC SAR TOMOGRAPHY

Tomography, i.e., 3D imaging via the formation of an additional aperture in across-track, allows a direct volumetric analysis of media like forests or ice sheets. Various new tomographic imaging techniques have been proposed in recent years to better suppress ambiguous responses or to better deal with small image stacks [21], [22]. Future spaceborne missions, like e.g. Tandem-L and BIOMASS, will include tomography as a mode of operation. In order to prepare such missions, accompanying airborne SAR campaigns are indispensable tools to further develop this technology and design operational information products. An example is the 2016 AfriSAR campaign in Gabon [23], which has been repeated in spring 2023. Figure 1 shows an example of tomographic AfriSAR profiles at L-band compared to lidar profiles.

5. POLARIMETRIC SAR HOLOGRAPHY

One intrinsic limitation of conventional linear SAR modes is the limited view of the azimuth look angle measurement. Since the scattering signature depends directly on the observation angle, it is not possible to fully characterize the imaged objects. An alternative to overcome this limitation is the use of wide-angular synthetic apertures, such as the holographic SAR tomography which is distinguished by flying several circular trajectories distributed in elevation, while illuminating the same area on the ground [17].

6. DISCUSSION AND CONCLUSIONS

Multi-baseline SAR imaging is a powerful technique which enables a wealth of innovative information products that cannot be extracted from single-channel SAR data. While along-track and DinSAR applications requires a temporal baseline, across-track interferometry, Pol-InSAR, TomoSAR, and HoloSAR require bistatic and/or multistatic SAR configurations to avoid temporal decorrelation between acquisitions. The 3D component of the motion can be retrieved either using bistatic and/or multistatic SAR configurations or monostatic squinted acquisitions. A cost-effective solution is achieved by partially active multi-static SAR systems. One or more satellites are transmitting and all other satellites are receiving the SAR signal at the same time [10], [24]. With this concept, existing SAR systems can be used as a transmitter, while a constellation of small, receive-only satellites can be adopted to realize the multi-baseline imaging. The formation flight can be adjusted to allow a flexible and reconfigurable constellation of small satellites, being able to adjust the baseline configuration according to the user requirements. The concept of a distributed multi-static SAR system will certainly play an important role in the vision for multi-baseline spaceborne SAR.

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