A NOVEL TECHNIQUE TO GENERATE DIGITAL ELEVATION MODELS IN A SINGLE PASS USING A CLUSTER OF SMALLSATS

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ABSTRACT

Synthetic aperture radar (SAR) interferometry is an essential remote sensing technique with a wide range of applications. Studying and monitoring dynamic processes on the Earth's surface requires digital elevation models (DEMs) at short time intervals, making distributed and multi-static SAR systems a very promising solution to this need. This work introduces a concept for distributed SAR interferometry using a cluster of smallsats with small antenna apertures operating with a pulse repetition frequency much smaller than the Doppler bandwidth and capable of single-pass DEM generation with high accuracy and robustness to phase unwrapping errors. The novelty of the proposed method is that the DEM is extracted from a tomogram formed using all available data without requiring as an intermediate step the formation of SAR images. This allows reducing the number of required satellites and obtaining increased baseline diversity at the same time. A cluster of smallsats is a very attractive low-cost solution for the implementation of future interferometric SAR missions.

***Index Terms*—**Synthetic aperture radar (SAR) interferometry, smallsats, distributed SAR, multi-static SAR, digital elevation model (DEM).

1. INTRODUCTION

Studying and monitoring dynamic phenomena on the Earth, such as melting ice, through satellite remote sensing demands continuous data time series and small revisit times [1], [2]. Synthetic aperture radar (SAR) interferometry [3] is a powerful remote sensing technique capable of supplying data with high accuracy and resolution for many such applications, but, while nowadays frequent revisit is achieved for SAR imaging through satellite constellations, it remains missing for single-pass interferometric products, such as high-quality digital elevation models (DEMs). State-of-the-art SAR interferometric systems generally require multiple passes of the satellites over the same area to generate such products, limiting the sampling frequency of any produced time series. Even TanDEM-X, a formation-flying mission capable of generating interferograms in a single pass, requires additional passes with different baselines — the spatial separation between the satellites — to produce DEMs robust to unwrapping errors and to resolve layover, for example, in mountainous areas [4], [5]. Furthermore, multi-pass systems have to deal with the fact that the imaged scene and the behavior of the atmosphere changes between different passes of the satellites. This can affect the data quality (e.g., strong rain occurs between two passes, changing the arrangement of the soil and vegetation, and so causing decorrelation between the images), introduce additional complexity (e.g., the different ionospheric delays between the passes may have to be estimated and compensated), and even prevent the generation of an unambiguous product (e.g., snow fall events that occur between two passes change the topography and may prevent the passes from being able to be used in conjunction for resolving phase unwrapping errors).

In single-baseline across-track SAR interferometry, there is a trade-off between accuracy and robustness to unwrapping errors, the former and the latter achieved with larger and smaller baselines, respectively [3]. If additional baselines are available, multiple interferograms can be formed and combined to produce a final DEM with both high accuracy and robustness. Furthermore, with multiple baselines, SAR tomography can potentially be used to resolve layover in the DEMs and also enable a wide range of applications, such as measurements of biomass from the vertical structure of forests [1]. A formation with three or more satellites separated in the across-track direction would then be capable of robustly producing highly accurate DEMs in a single pass, avoiding the drawbacks and limitations of generating a product from data acquired at different times, and enabling the generation of time series with frequent revisit, supporting applications such as glacier or permafrost monitoring [1], [6].

Instead of a formation with large satellites, this work proposes the use of a cluster of a larger number of smallsats with small antenna apertures, such that the data from each individual satellite are not sufficient to form an unambiguous SAR image, but the data from the whole cluster can be combined to produce an unambiguous and highly accurate DEM. A cluster of smallsats can be a more cost-effective and agile solution than a few large satellites [2] and has the usual advantage of distributed systems: if some of the satellites in

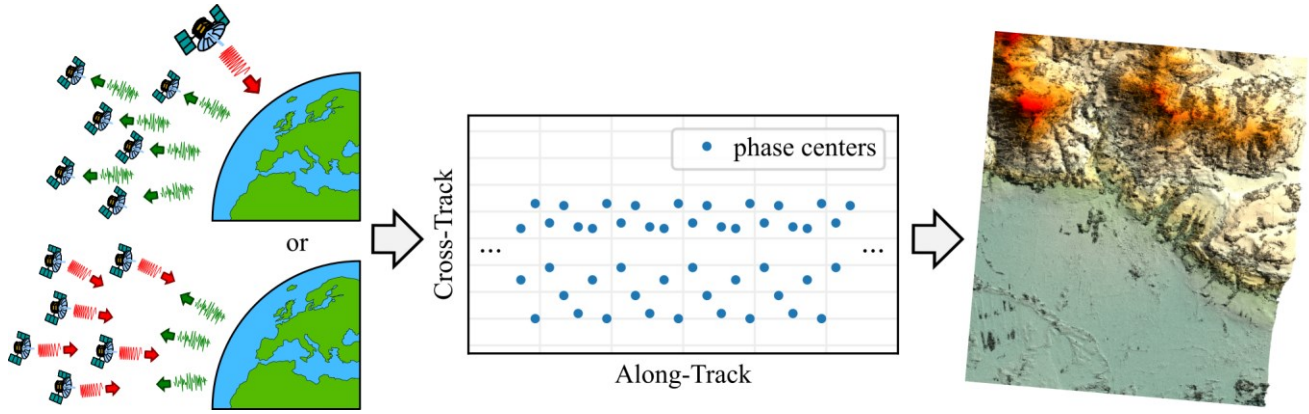

Fig. 1. A cluster of smallsats operating with a dedicated transmitter and multiple receivers (top left) or multiple transmitters and multiple receivers (bottom left). The raw data from the cluster form an array of phase centers, one for each receiver transmitter pair at each pulse, distributed in along- and across-track (center) and is processed to directly generate a DEM (right).

the cluster fail, the cluster can still generate products, albeit with some reduction in quality, and it would be financially feasible to replace the failed satellites as their individual cost is low compared to that of the whole mission. Furthermore, a cluster of many smallsats can have the flexibility to rearrange itself into different formations for other applications, such as along-track interferometry or tomography.

Distributed SAR imaging can be performed with satellites flying in a train formation [7]-[14]. SAR interferometry for robust DEM generation could then be achieved with three or more trains of satellites, each producing a SAR image, and the usual interferometric SAR processing using these images. However, if the goal is to produce a DEM, one should consider that the latter is characterized by a much lower information content with respect to the SAR images used to form it. The local spatial correlation of typical topography is in fact much larger than that of a SAR image, where the spatial correlation is low due to speckle. This discrepancy provides a hint that three or more full trains of smallsats produce data in excess of what is required for robust DEM generation. This observation was first exploited in [15], which proposes a CubeSat add-on to a bistatic SAR interferometer that provides an additional noisy SAR image with strong azimuth ambiguities which, despite its low quality, can be used to resolve unwrapping errors in the DEM produced by the system. Thus, this work proposes that the data from the entire cluster of smallsats be processed as a whole to directly generate a robust DEM from undersampled SAR data, without the intermediate step of generating high-quality SAR images. In this way, comparable DEM quality could be achieved with fewer smallsats, and the cluster is not required to be arranged in trains, so more across-track baselines can be present.

2. TOMOGRAM-BASED DEM GENERATION

The proposed system concept is a cluster of smallsats with small antenna apertures with the goal of generating robust and highly accurate DEMs. All or some of the satellites in the cluster can have pulse transmission capabilities and alternate the pulse transmission between themselves [10] or maybe all transmit simultaneously [11]. Another option is to have a dedicated transmitter satellite — which can be an existing satellite opportunistically followed by the cluster — allowing the other satellites to be receive-only [12]-[14]. As a consequence of the small antenna apertures, the proposed system observes a wide Doppler bandwidth much higher than the pulse repetition frequency (PRF). Similarly to the train formation used for SAR imaging, the proposed cluster must contain along-track baselines enabling the reconstruction of this wide Doppler bandwidth [8]-[10], but, to allow robust DEM generation, it must also contain a mix of across-track baselines. Preference should be given to large baselines, as they contribute to the height accuracy, but a sufficient number of small and medium baselines should be included to provide robustness to the final DEM. As depicted in Fig. 1, the raw data from the cluster then form a sparse array of phase centers distributed in along- and across-track and are processed to directly generate a DEM, without the intermediate step of SAR image formation.

As shown in the block diagram in Fig. 2, a DEM can be generated from the data of the cluster of smallsats through tomographic response maximization, i.e., a tomogram can be formed from the range-compressed data of the whole cluster, multilooked, and, at each pixel in range and azimuth, the DEM height is selected as the height whose value in the multilooked tomogram is strongest. The tomogram can be formed from the array of phase centers provided by the cluster through beamforming in azimuth, including the azimuth compression and the reconstruction of the Doppler bandwidth wider than the PRF exploiting the along-track baselines, and in elevation exploiting the cross-track baselines. Furthermore, multilooking the tomogram consists in averaging the squared magnitude of the looks, which, as in conventional SAR interferometry, can be taken with a moving window in range and azimuth or by separating the data into frequency bands in range and azimuth.

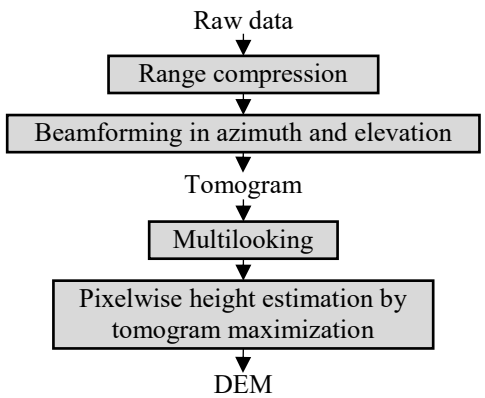

Fig. 2. Block diagram of the technique for processing the data from the cluster of smallsats to generate a DEM.

This method of DEM generation is a generalization of conventional SAR interferometry, and, in fact, in the single-baseline case the same DEM is equivalently obtained by maximizing the tomogram formed using Fourier beamforming in elevation with the two available images. More generally, in the multi-baseline case, the tomographic response maximization with Fourier beamforming in elevation is the maximum-likelihood estimator of the height under the assumption of equal interferometric coherences in all baselines. This result is proven by observing that, in that case, the log-likelihood function [16]

$$\ln \mathcal{L}(h|\boldsymbol{u}_1, \dots, \boldsymbol{u}_L) = C + \sum_{l=1}^{L} -\boldsymbol{u}_l^H e^{jFh} \Gamma^{-1} e^{-jFh} \boldsymbol{u}_l \quad (1)$$

is equal to the multilooked tomogram

$$q(h) = \frac{1}{L}\sum_{l=1}^{L} |q_l(h)|^2 = \frac{1}{L}\sum_{l=1}^{L} \boldsymbol{u}_l^H e^{jFh} \mathbf{1}\mathbf{1}^{\mathrm{T}} e^{-jFh} \boldsymbol{u}_l \quad (2)$$
$$\because q_l(h) = \mathbf{1}^T e^{-jFh} \boldsymbol{u}_l$$

but for a constant and a linear factor, where h is the height, $\boldsymbol{u}_l$ are the vectors of values of the focused data at the range and azimuth pixel in question corresponding to each satellite, l is the index of the look, L is the total number of looks, $\cdot^T$ denotes the transpose, $\cdot^H$ denotes the transpose complex conjugate, Γ is the coherence matrix, e^{jFh} is a diagonal matrix encoding the Fourier beamforming in elevation, C is a constant dependent on the coherence matrix, $\mathbf{1}$ is a vector whose entries are all 1, and $q_l(h)$ are the different looks of the tomogram.

In the presence of volume scattering, the proposed method of DEM generation will, much like in conventional SAR interferometry, yield heights related to the phase center within the volume, albeit with some accuracy degradation. The multiple baselines in the proposed system, however, can enable tomographic applications such as estimation of ground and canopy heights in a forest.

Interferograms formed from the data of any pair of smallsats in the cluster are severely corrupted by azimuth ambiguities because the system operates with a PRF much lower than the Doppler bandwidth. The proposed processing technique is a good match for this scenario because the tomogram is formed through the coherent combination of the data from the entire cluster allowing the suppression of azimuth ambiguities by exploiting the available along-track baselines.

3. SAMPLE IMPLEMENTATION

This section presents an example implementation of the proposed concept, and a simulation of the DEM generation through the tomographic response maximization method. Consider a cluster of eight smallsat SAR receivers arranged as shown in Fig. 3 and a dedicated transmitter satellite, all in helix orbits and operating at the same altitude and frequency as TanDEM-X [4]. The arrangement of the satellites evolves across the orbit, but is approximately constant within the duration of an acquisition. The smallsat receivers have rectangular antennas of length of 0.5 m, much smaller than the 4.8 m of the TanDEM-X antenna, and the dedicated transmitter satellite has a rectangular antenna of length of 2 m. With these parameters, the system observes a 3 dB Doppler bandwidth of 8634 Hz, much higher than its PRF of 3100 Hz.

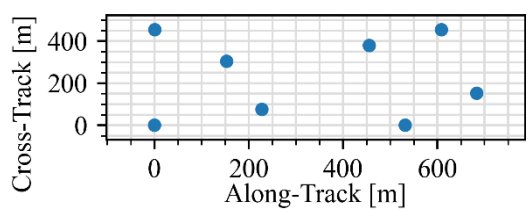

Fig. 3. Positions of the eight smallsat receivers of the cluster.

The raw data acquired by the cluster over a homogeneous scene with a flat topography including a pyramid at the center were simulated. Noise was included in the raw data with a signal-to-noise ratio of 6 dB. The data were then processed into a tomogram by a combination of multi-channel reconstruction [17] for recovering a bandwidth equal to 3 times the PRF, azimuth compression, and Fourier beamforming in elevation. The tomogram was then multilooked with a 5 × 5 moving window. Fig. 4 shows the multilooked tomogram along with the terrain topography (dashed black line) and the DEM generated by maximization of the tomographic response (white line). The generated DEM shows a good agreement with the underlying topography and the standard deviation of the height error was 0.67 m. Note, however, that there is a spike in the DEM at around -120 m in azimuth. Spikes such as this one are the result of an incorrect height ambiguity band being selected by the tomogram maximization. These errors occur occasionally but could be corrected by exploiting the high spatial

correlation of typical terrain to reject strong localized jumps in height. The aforementioned height error standard deviation was evaluated excluding these spikes.

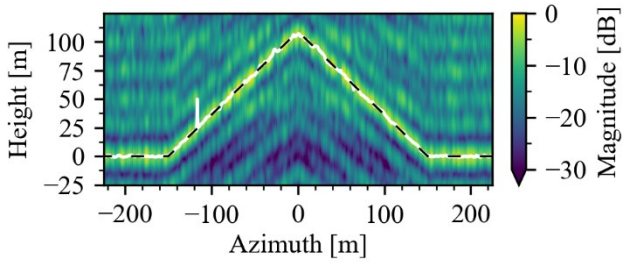

Fig. 4. Multilooked tomogram at a specific slant range formed from the data of a simulated acquisition performed by the cluster of smallsats. The dashed black line shows the terrain topography, and the white line shows the DEM generated by maximization of the tomogram.

4. CONCLUSION

This work proposes the concept of a distributed interferometric SAR system based on a cluster of smallsats with reduced antenna size that is capable of robust and accurate DEM generation in a single pass of the satellites, avoiding the drawbacks of using multiple observations separated in time. A new method for DEM generation is presented that does not require the formation of SAR images, and so does not constrain the cluster to train formations, allowing a smaller number of satellites to be used than otherwise possible.

An F-SAR experimental acquisition over mountainous terrain near Mittenwald, Germany is planned to demonstrate the proposed DEM generation technique using real multi-baseline airborne SAR data. The experiment will produce SAR data from around 10 different parallel tracks over a swath that includes areas with diverse topographies both covered and not covered by forest, allowing a comprehensive evaluation of the proposed processing for DEM generation.

This concept is a promising solution for future Earth observation missions that require single-pass generation of high-quality DEMs.

5. REFERENCES

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