Understanding Spaceborne Missions for TomoSAR Imaging with Multi-Angular Acquisitions

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Abstract

This paper presents an analysis on the achievable improvement in the range resolution for low-bandwidth space-borne systems by combining ascending and descending Tomography SAR acquisitions. The analysis is performed by means of a Multiple-Baseline Circular SAR campaign from the German Aerospace Center's F-SAR sensor over a forested area in Kaufbeuren, Germany. Splitting the circular acquisition into subapertures and combining the ones from opposite angles, ascending-descending acquisitions are simulated.

1 Introduction

Synthetic Aperture Radar (SAR) is a well-established technique where a sensor is mounted on a moving platform to acquire images of a scene. Being a radar technology, images can be acquired day and night independent on the weather conditions, which makes it suitable to better understand the dynamics of the biosphere, geosphere, cryosphere and hydrosphere.

Stripmap SAR is the most widely used imaging mode and it allows for two-dimensional azimuth and range (a, r) sensing with geometric resolutions defined by the bandwidth of the system and the physical antenna size. SAR tomography (TomoSAR) is its 3-D extension, that allows the reconstruction of a scene reflectivity along the elevation direction from multiple-pass SAR acquisitions [1]. Due to its capabilities, TomoSAR has been well accepted in the scientific community in the last years, leading to the planning and preparation of several spaceborne missions with tomographic capabilities [2] [3]. Additionally, its ability to retrieve 3-D structures from space makes it suitable for monitoring Earth's dynamic processes in the biosphere and the cryosphere, as well as urban areas.

TomoSAR still faces some limitations in order to be an operational technique. One of the most restrictive is the low geometric resolution of the three-dimensional results when using low bandwidth systems.

In this paper, this limitation is analyzed by means of a fully polarimetric airborne Holographic SAR Tomography (HoloSAR) survey [4]. HoloSAR is an innovative imaging mode where the sensor follows a cylindrical trajectory, thereby allowing the characterization of the observed scene from multiple observation angles. It is studied how this mode of acquisition can help enhance the resolution in the vertical direction z by selectively combining opposite subaperture tomograms. This is analogous to combining ascending and descending acquisitions in spaceborne SAR missions. In fact, this enhancement may be more prominent for low-bandwidth systems.

The remaining part of this paper is structured as follows. The basic theory of TomoSAR will be reviewed in section 2. Section 3 will be devoted to Multi-angular SAR. Section 4 will present an overview of the results from the fully-polarimetric data acquired with the DLR's airborne F-SAR sensor, and finally the conclusions and outlook will be discussed in section 5.

2 TomoSAR

2.1 State of the art

In conventional TomoSAR, N parallel tracks are flown over the area of interest. The signal s_n acquired at every track, and for every azimuth-ground range position in a stationary scene will be expressed as follows:

$$\begin{aligned} s_n &= exp(-j\frac{4\pi}{\lambda}r_n) \\ \mathbf{s} &= [s_1, ..., s_N]^T \end{aligned} \tag{1}$$

where r_n is the distance between every target and the n-th sensor, and λ is the wavelength. In the following, we will assume this signals to be corregistered with respect to a master track, corrected for flat earth and phase calibrated using the Singular Value Decomposition (SVD) [5] approach.

To recover the tomographic information $t(z)$ in the perpendicular line-of-sight ($LOS_\perp$) axis, direction of arrival (DOA) estimation techniques can be applied. Classical Fourier beamforming is the simplest of them:

$$\begin{aligned} t(z) &= \mathbf{a}(z)^H\mathbf{s} \\ \text{where} \quad \mathbf{a}(z) &= [a_1(z), ..., a_N(z)]^T, \\ \text{and} \quad a_n(z) &= exp(-j\frac{4\pi}{\lambda}r_n(z)) \end{aligned} \tag{2}$$

$\mathbf{a}$ is the steering vector and $r_n(z)$ is the distance from track n to position z in the $LOS_{\perp}$ axis. The Fourier resolution along this axis can be written:

$$\delta_{LOS_{\perp}} = \frac{\lambda r_0}{2L_{tomo}} \quad (3)$$

where r_0 is the distance target-master track and L_{tomo} is the length of the tomographic synthetic aperture.
Other DOA estimation methods based on the covariance matrix $\mathbf{R} = E\left\{\mathbf{ss}^H\right\}$ can be applied. Among them, Capon, MUSIC [6] and Wavelet Based Compressive Sensing [7] are the most common.

2.2 Problem statement

In this paper, we focus on the dependency of the tomographic resolution on the range resolution. Range resolution in chirp-based SAR systems is defined as

$$\delta_r = \frac{c}{2W_c} \quad (4)$$

where c is the speed of light, and W_c is chirp bandwidth. Therefore the range resolution of the system will be limited by W_c, and in low bandwidth systems such as BIOMASS [2][8], increasing the tomographic resolution will not lead to a better information retrieval, because the range-height resolution cells will be rectangular shaped ($\delta_{LOS_{\perp}} << \delta_r$) and will mix up different layers in the case of vertically distributed scenes such as forests.

3 Multi-angular TomoSAR

Exploiting the diversity of acquisitions taken from different angles has been already used in Circular SAR (CSAR) to achieve better resolution [9], in Multi-Aspect Multi-Baseline SAR Interferometry (MAMBInSAR) to improve the 3-D reconstruction accuracy of a scene [10] and in operational space-borne products to reduce the impact of shadow and layover effects [11].

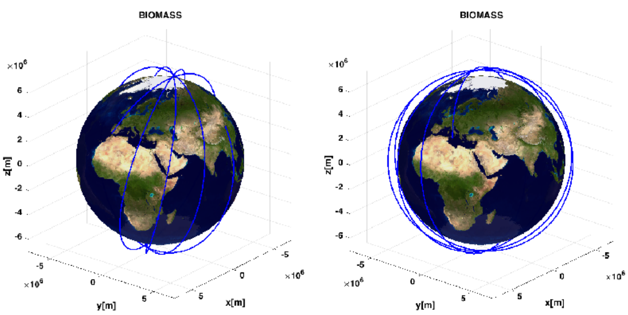

Figure 1: Representation of acquisition over Europe. The simulation represents ascending (right) and descending (left) orbits and was done with the parameters of the BIOMASS mission: dawn/dusk orbit with an inclination of 97.9°.

In this context, we propose to combine several baselines belonging to two opposite subapertures (viewing angles) in a HoloSAR campaign in order to simulate ascending/descending acquisitions and to study how merging them can help to improve the overall resolution of low bandwidth systems [5].

4 Experimental results

Data from German Aerospace Center (DLR)'s F-SAR sensor acquired over Kaufbeuren, Germany, will be used. The dataset contains 14 circular tracks at different heights over the area of interest. The scene contains several forested parts, which is the main focus in this study.

Parameter	Value
Pulse Repetition Frequency [Hz]	500
Wavelength [m]	0.23
Bandwidth [MHz]	50
Flight Radius [m]	3700
Platform Height [m]	3156 - 3355
Terrain Height [m]	780.35
Radar Speed [m/s]	29
Polarization	HH
Subaperture Size [deg]	10
Number of tracks	14

Table 1: Summary of the Airborne campaign.

The raw data of every circle n is divided into subapertures of 10 degrees each, and processed in 2-D (a, r) using Fast Factorized Back-Projection algorithm [9]. Afterwards, tomographic beamforming techniques are applied on the stack of 2-D images forming each subaperture. These techniques make use of the set of acquisitions and the precise knowledge of the sensor during each of them in order to capture the reflectivity in the direction perpendicular to the line of sight ($LOS_{\perp}$). The result of this step will be tomograms in local coordinates (a, r, z).

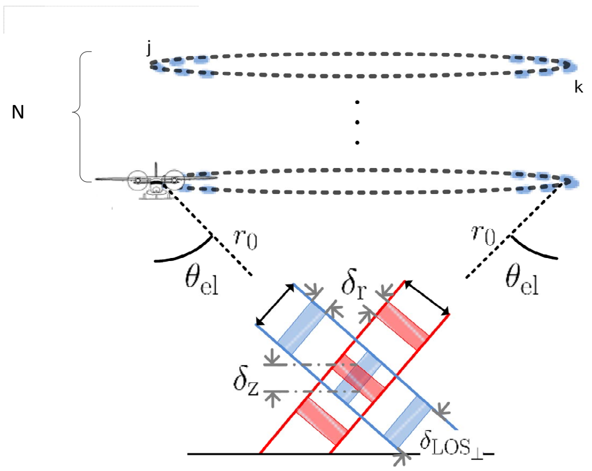

Figure 2: Holographic acquisition geometry. In blue are highlighted the opposite subapertures to combine to simulate satellite ascending-descending acquisitions.

After interpolating them to the same geocoded grid (x, y, z), the tomograms from subapertures j and k, $j \neq$

k can be combined. **Figure 3** shows the response in ground-elevation of a pixel containing an isotropic reflector (Luneburg Lens) after applying Wavelet Based Compressive Sensing beamforming for the two opposite subapertures separately, as well as for the coherent combination of both (i.e. adding together complex values of their tomograms). Compressive Sensing is used because it decreases significantly the clutter with respect to the other beamforming methods presented in section **2.1**. The combination of the signals from the opposite subapertures results in a signal with better resolution in the vertical direction z than the resolution of the subapertures separately, as it can be observed from the contour lines. The improvement is specially remarkable in the case of low bandwidth signals, as it can be seen in the bottom images of **Figure 3**. There, the original signal has been filtered down to $6MHz$ to simulate a BIOMASS acquisition, showing how the combination of opposite subapertures results in a signal with much better resolution in the vertical direction z. This suggests that fusing acquisitions from ascending and descending orbits could be used to improve the vertical resolution, particularly for low-bandwidth systems.

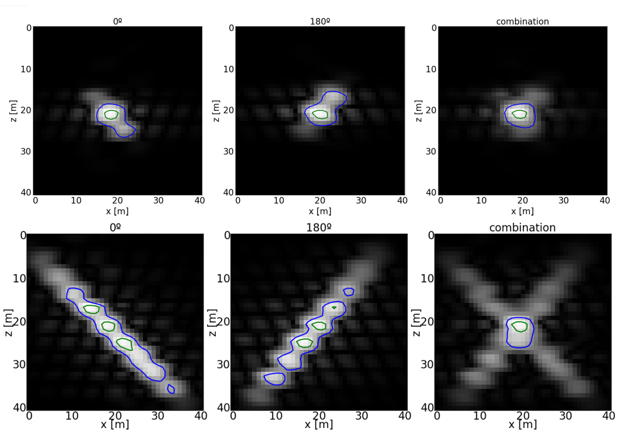

Figure 3: Impulse response of an isotropic reflector (Luneburg Lens) as seen from (left) first subaperture (center) opposite subaperture and (right) combination of both. Top row acquired at full ($50MHz$) bandwidth and bottom row with bandwidth filtered to $6MHz$

The same effect can be observed in **Figure 4**, where a field and a forested area are analyzed. In this case, the beamforming algorithm is again Wavelet-Based Compressive Sensing. Interestingly it can be observed that the quality of the resulting tomogram improves due to the combination of the opposite subapertures, reducing the noise and artifacts and increasing the number of features represented. This can be explained by the fact that the components of the target that persist independently of the viewing angle (i.e canopy, truk-ground and surface signatures), will be summed up, whereas other targets will be attenuated. In the figure it can be appreciated that fusing acquisitions from opposite viewing angles **Figure 4 d)** results in better quality tomograms compared to the fusion of perpendicular acquisitions **Figure 4 e)**. In this respect, parallel acquisition orbits, e.g., close to the Equator, will show more resolution enhancement than orbits close to the poles.

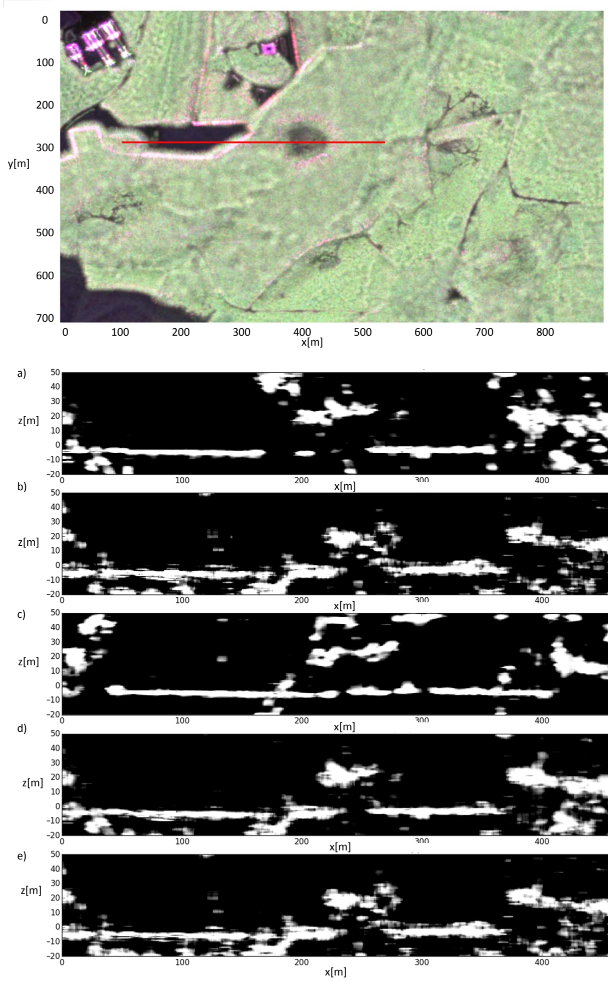

Figure 4: Top: Pauli image of the area of interest with the slice under analysis highlighted in red. The slice contains (from left to right) a bare field, some trees, another field and a dense forest. Bottom: Tomograms for a) first subaperture (0°), b) second subaperture (90°), c) third subaperture (180°), d) combination of first and second, e) combination of first and third.

5 Conclusions and future work

In this paper, the idea of using angular diversity as a way to overcome the loss of resolution in low bandwidth TomoSAR space-borne missions has been introduced. A first analysis has been conducted, using Multiple-Baseline CSAR acquisitions to simulate the effect of imaging the same area from opposite viewing angles. This acquisition geometry can be considered analogous to the one in space-borne missions when ascending and descending orbits are taken into account. Fused results for an isotropic reflector and a forested area have been presented. The main application for this technique will be for the case of high resolution in the perpendicular line-

of-sight axis and low resolution in range, as described in section **2.2**.
The usage of ascending and descending acquisitions to generate tomograms will also imply a longer integration time, and therefore a higher decorrelation between the acquisitions. In future work, this effect will be studied in the frame of 4-D Tomography (or Differential Tomography) [12][13], which allows to detect phase disturbances during time. Again the usage of CSAR data will be useful, in this case allowing to compare the Differential Tomograms generated from the integration of all the subapertures and the ones generated only from one subaperture. This continuous integration will allow a reduction of ambiguities and sidelobes, and therefore a better understanding of how 4-D Tomography can be used to estimate the temporal decorrelation.

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