# A study on irregular baseline constellations in SAR tomography

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## Abstract

SAR Tomography (SARTom) is the natural extension of SAR Interferometry (InSAR) to solve for multiple phase centers within a resolution cell and obtain the 3-dimensional (3D) representation of a scene. In order to obtain a reasonable resolution and reject ambiguities, a large tomographic aperture sampled with a sufficient number of acquisitions is required. For most applications this number represents a critical factor. Basically, the reference acquisition geometry usually assumes a regular sampling of the tomographic aperture. The potential of irregular constellations for SARTom represents a field that has not yet been completely investigated and could allow one to reduce the number of acquisitions keeping the constraint of resolution and ambiguity rejection. In this context, this paper presents a study on how irregular distributions of baselines impact the tomographic reconstruction. In particular, the acquisition geometry will undergo a minimum redundancy design in term of baselines, in order to estimate the elements of the sample covariance matrix. The study is applied on simulated as well as on real data acquired at P-band by the E-SAR system of the German Aerospace Center (DLR).

## 1 Introduction

SARTom makes it possible to obtain a complete 3D representation of the scene. In [1] the first demonstration of airborne SAR tomography has been carried out and the main constraints in terms of resolution and ambiguity rejection have been analyzed. SAR tomography can be performed by means of the standard Fourier beamforming and with super-resolution techniques like Capon and MUSIC that allow to outperform the Fourier resolution and reduce sidelobes [2, 3].

The main disadvantage of SARTom concerns the number of acquisitions required to perform the reconstruction. On one hand side a large tomographic aperture has to be spanned to obtain a reasonable resolution and on the other hand side a sufficient sampling along such an aperture, resulting often in a large number of acquisitions, is required to avoid aliasing. In [4] a technique has been presented to reduce the number of acquisitions when subspace methods are applied on data which were acquired with a regular acquisition geometry. The potential of irregular constellations for SARTom represents a field that has not yet been completely investigated and which could improve the quality of the 3D reconstruction without increasing the number of observations. Preliminary analyses concerning data acquired with irregular acquisition geometries can be found in [5, 6]. In [7] a method to design an *optimal* tomographic constellation by means of singular values decomposition (SVD) has been proposed.

Irregular constellations are of interest especially for future multistatic spaceborne SAR systems. The degrees of freedom that these systems will offer (flexible geometry, reduced repeat cycle, mono-, bi- and multistatic imaging) will allow new possibilities in acquiring data and combining them to retrieve the desired information. A cost-effective system would consist of a main satellite that illuminates the area of interest and several receive-only micro-satellites [8]. Such a system allows one to realize a complete tomographic constellation with just one or two passes. For such a purpose, the geometry analyzed in this paper is based on the minimum redundancy array (MRA) theory [9].

## 2 Minimum redundancy arrays

MRAs allow one to obtain one sample of the interferometric pair for missed baselines. In this way, a sample covariance matrix of interferograms can be estimated allowing SAR tomography with a reduced number of passes.

Let us consider an MRA with 3 elements with an aperture length equivalent to a 4 element linear array (Figure 1). For the sake of simplicity, the first track will be assumed to be the master one.

The missed interferometric pair $1-3$ with a baseline $2d$ will be substituted by the pair $2-4$. The vector $\mathbf{y}$ used to build the interferometric covariance matrix has the expression:

$$\mathbf{y} = [(s_1 s_1^*), (s_1 s_2^*), (s_2 s_4^*), (s_1 s_4^*)]^T, \tag{1}$$

where $s_i$ stands for the $i^{th}$ SAR acquisition, $(\cdot)^*$ represents the complex conjugate of the argument and $[\cdot]^T$ the transpose of the considered vector.

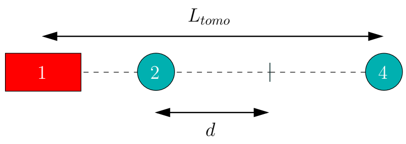


**Figure 1:** Tomographic constellation of 4 virtual elements obtained from 3 acquisitions. The location of the tracks follows the MRA theory.

The resulting covariance matrix $\mathbf{R_{MRA}}$ has the expression reported in (2) and the related interferometric steering vector has the form:

$$\exp\left(-j\frac{4\pi}{\lambda}\left[\,0,\ d\ sin(\theta_0),\ 2d\ sin(\theta_0),\ 3d\ sin(\theta_0)\,\right]^T\right) \quad (3)$$

where $< \cdot >$ stands for the spatial average, $d$ and $\theta_0$ represent the baseline and the considered look angle, respectively.
Extending this theory to the SARTom case and assuming a tomographic aperture regularly sampled in 7 points, it is possible to build an equivalent minimum redundancy array with only 4 elements. The resulting geometry is depicted in Figure 2 and the achievable baselines are reported in table 1.

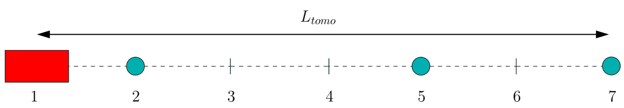


**Figure 2:** Tomographic constellation designed by means of the MRA theory. The 4 element array is equivalent to a 7 element array in terms of its aperture and the possible correlation lags.

| **MRA constellation** | |
|---|---|
| Baseline | Track combination |
| $d$ | 1-2 |
| $2d$ | 5-7 |
| $3d$ | 2-5 |
| $4d$ | 1-5 |
| $5d$ | 2-7 |
| $6d$ | 1-7 |

**Table 1:** Baseline lengths and track combinations for a minimum redundancy array design of the tomographic constellation of Figure 2.

Due to the fact that super-resolution methods require the sample covariance matrix to be applied, this paper investigates how minimum redundancy arrays can be exploited to estimate the elements of such a matrix.

## 3 Simulation

In this section results related to simulated data are reported. Firstly a single point target scenario is considered. The location of such a target is at a height of $0m$. The tomographic constellation corresponds to the one of Figure 2. The realized virtual regular constellation is characterized by a baseline of $d = 10m$ (distance between track 1 and track 2). The spanned tomographic aperture is $60m$. The platform is acquiring data at L-band ($23cm$) at an altitude of $h = 3500m$ and the considered ground-range location is $3500m$. The tomographic focusing has been carried out by means of the Fourier and the Capon beamforming. The results are reported in Figure 3.
The location of the ambiguities is at $60m$, resulting from the minimum baseline of $10m$. The resolution is around $10m$ that corresponds to the one achievable by means of the total aperture. These results imply that with these $N = 4$ acquisitions the ambiguity rejection and resolution requirements are successfully matched. The price to pay is obviously related to higher sidelobes provoked by the non-regular sampling along the tomographic aperture.
For the second scenario several point targets simulate a distributed scatterer characterized by two main phase centers (e.g. vegetation case). One phase center is located at $h = 0m$ (ground) and the other at $h = 10m$ (canopy). The system parameters coincide with those related to the previous point target example.
The results of the tomographic focusing are reported in Figure 4. Also for this last case it is possible to observe that ambiguity rejection and resolution requirements are respected allowing one to easily identify the location of the two phase centers.

## 4 Real data

The considered real data have been acquired at P-band ($0.86m$ wavelength) by the E-SAR system of DLR in October 2008. The test site is located in northern Sweden, and it is close to city of Umeå. The acquired constellation is depicted in Figure 6, that represents the plane perpendicular to the flight direction.

$$\mathbf{R_{MRA}} = \left\langle \begin{bmatrix} |s_1|^2|s_1|^2 & |s_1|^2(s_1s_2^*)^* & |s_1|^2(s_2s_4^*)^* & |s_1|^2(s_1s_4^*)^* \\ (s_1s_2^*)|s_1|^2 & |s_1s_2^*|^2 & (s_1s_2^*)(s_2s_4^*)^* & (s_1s_2^*)(s_1s_4^*)^* \\ (s_2s_4^*)|s_1|^2 & (s_2s_4^*)(s_1s_2^*)^* & |s_2s_4^*|^2 & (s_2s_4^*)(s_1s_4^*)^* \\ (s_1s_4^*)|s_1|^2 & (s_1s_4^*)(s_1s_2^*)^* & (s_1s_4^*)(s_2s_4^*)^* & |s_1s_4^*|^2 \end{bmatrix} \right\rangle \quad (2)$$

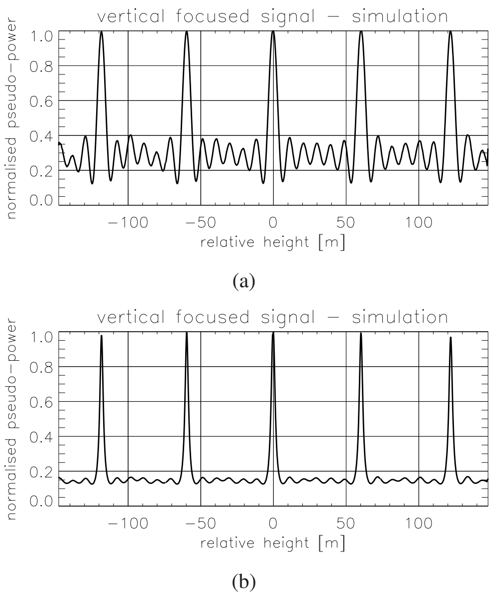


**Figure 3:** Tomographic reconstruction of a point target located at $0m$ with $N = 4$ tracks distributed with minimum redundancy. The spanned tomographic aperture is $L_{tomo} = 60m$. (a) Fourier, (b) Capon beamforming.

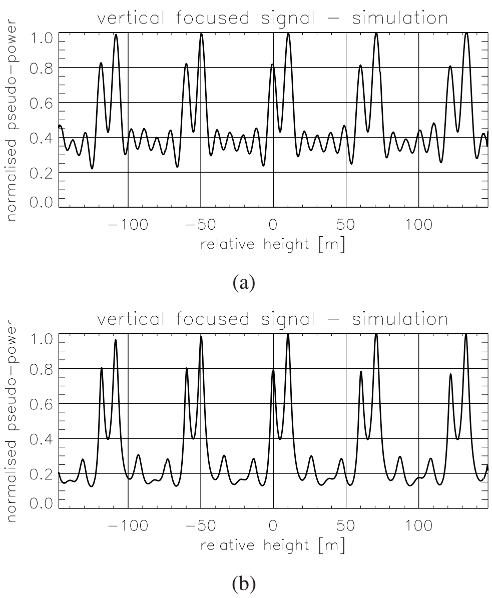


**Figure 4:** Tomographic reconstruction of a distributed scatterer (forest) with two phase centers viewed by the same minimum redundancy constellation of the point target case.(a) Fourier, (b) Capon beamforming.

The data acquired during this campaign have to be used for both tomographic and PolInSAR investigations as part of BIOMASS project [10]. As one can observe, the first 6 acquisitions[1] are regularly distributed. These have been fixed from PolInSAR requirements. The remaining 3 additional acquisitions[2] have been placed following a minimum redundancy array philosophy. In particular, the acquisitions related to the missing baselines (represented by red crosses) can be estimated by the other acquisitions.

For example, the missing baseline of 192m (blue square), can be estimated from two interferometric combination $i_1 = s_8 s_0^*$ related with the baseline $288m$ and the couple $i_2 = s_7 s_6^*$ related with the baseline 96m. Therefore, the combination $i_1 i_2^*$ has the information of the baseline 192m.

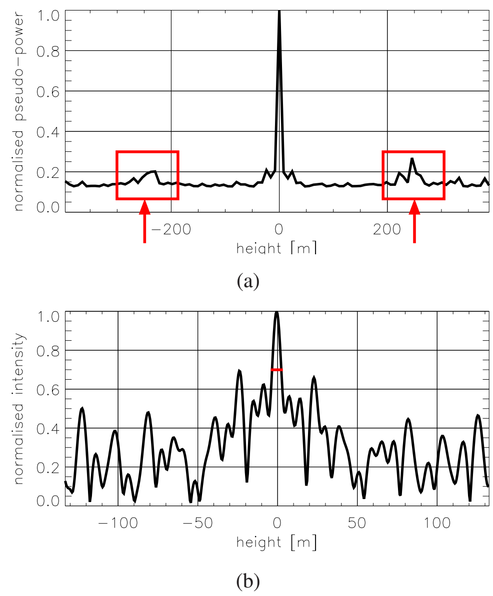


**Figure 5:** Tomographic reconstruction of a flat terrain (single layer scenario). The ambiguities are located at a height of $250m$ as shown in the reconstruction (a) performed with the MUSIC algorithm. The resolution corresponds to $7m$ as shown in the reconstruction (b) obtained by means of the Fourier beamforming.

Let us now analyse the tomographic reconstruction. The considered profile is located at a slant-range coordinate of $5100m$, corresponding to a look angle of $\theta_0 = 42^{\circ}$. The smallest baseline of $d = 8m$ allows one to define the location of the ambiguities at a height of $250m$.

In order to experimentally verify this, a bare surface has been analysed. Such a scatterer represents a point target scenario in the vertical direction, since it is the only contribution. Moreover, in order to detect for the single bounce scattering mechanism, the tomographic reconstruction has been carried out in the Pauli1 component. The tomographic vertical profile is shown in Figure 5(a) and is obtained by means of the MUSIC algorithm. In order to check the resolution of such a MRA tomographic constellation, the same scenario has been reconstructed by means of the Fourier beamforming (Figure 5(b)). The expected

[1]Funded under ESA contract no. 22052/08/NL/CT.
[2]Funded under EMRS-DTC contract no. EMRS/DTC/4/90.

vertical resolution, predicted for the full tomographic aperture, corresponds to $7m$ and it matches the actual one, as it is possible to observe from the red line in Figure 5(b).
The Fourier profile allows one to quantify the price to pay from an irregular MRA acquisition in terms of higher sidelobes. However, as shown with the simulated (Figure 3(b)) as well as in the real data (Figure 5(a)), if super-resolution methods are applied, the quality of the reconstruction improves and the features of interest can be detected.
A tomogram of a forested area close to the considered profile is reported in Figure 6. The processing has been carried out by means of the Capon beamforming.

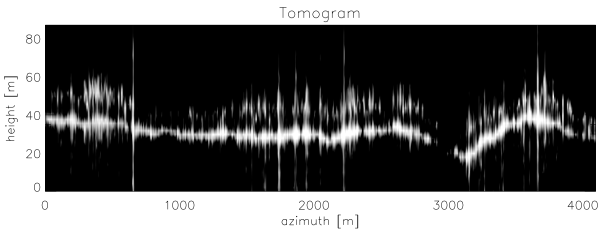


**Figure 6:** Tomogram of a forested area carried out by means of the Capon beamforming. The canopy and the ground contributions are easily identified.

One can observe how the contribution of the vegetation can be recovered as well as the ground beneath the canopy.

# 5 Conclusion

This paper presents a study on irregular distribution of baselines along the tomographic aperture. In particular the performance of minimum redundancy arrays is considered. Despite the fact that the missing baselines, estimated by means of a MRA constellation, cannot accurately represent the actual ones because of the difference in the line-of-sight, the analysis carried out shows that, if such constellations are implemented, the trade-off between number of acquisitions and resolution can be achieved.
The goal of this paper is two-fold: firstly to demonstrate that once the tomographic aperture is fixed, a reduction of the number of the required regular acquisitions can be performed keeping resolution and ambiguity rejection requirements.
Secondly, if the number of acquisitions is kept constant, it can be shown that a track distribution with a minimum redundancy allows one to outperform any regular constellation built with the same number of acquisitions in terms of such parameters.

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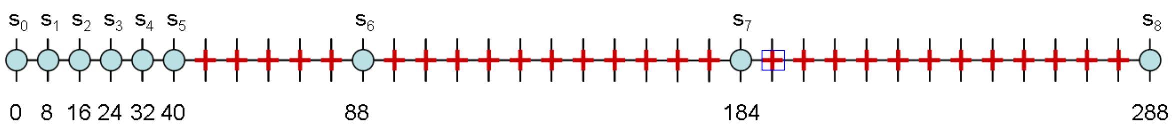


**Figure 6:** Tomographic constellation of 9 images ($s_0, \cdots, s_8$) at P-band. Acquired track (blue circles) and virtual tracks (red crosses). The baselines are indicated in meters beneath the circles.