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# Enhanced Range Migration Algorithm for sub-mm resolution imaging at 120 GHz

Carré Barnabé  
Lytid SAS  
IMS Laboratory  
Talence, France  
b.carre@lytid.com

Chopard Adrien  
Lytid SAS  
Talence, France  
a.chopard@lytid.com

Guillet Jean-Paul  
IMS Laboratory  
Talence, France  
jean-paul.guillet@u-bordeaux.fr, 

Gellie Pierre  
Lytid SAS  
Montrouge, France  
p.gellie@lytid.com

**Abstract**—A 3D close range Synthetic Aperture Radar system based on the Range Migration Algorithm and working with an affordable and compact Si-Ge Frequency Modulated Continuous Wave radar unit operating at 120 GHz with 19.5 GHz bandwidth is presented. A new method for enhancing lateral resolution combined with a normalization procedure is proposed leading to 0.33 central wavelength resolution. Lateral resolution is compared to a focusing lens system. An object of interest is displayed to reveal Synthetic Aperture Radar advantages in term of lateral resolution and depth of field for Non Destructive Testing and inspection.

**Index Terms**—Synthetic Aperture Radar, Range Migration Algorithm, Frequency Modulated Continuous Wave, Non Destructive Testing, Si-Ge radar

## I. INTRODUCTION

Imaging resolution and depth of field are limited when employing standard single point Terahertz (THz) imaging using focusing lenses. A diffraction-limited resolution up to, approximately, only a wavelength, is reachable with a high numerical aperture focusing system.

Synthetic Aperture Radar (SAR) technique is featured in this paper as an option for increasing resolution and depth of field at sub-Thz frequencies. Combining affordable and compact Si-Ge Frequency Modulated Continuous Wave (FMCW) Radar, with 3D close range SAR provides enhanced imaging performances, typically for Non Destructive Testing (NDT).

Close range SAR with Si-Ge radar transceiver operating from 210 GHz to 252 GHz with 42 GHz bandwidth has been conveyed by [1] reaching 1mm lateral resolution which correspond to  $0.77\lambda_{c,231GHz}$ .

The 120 GHz radar sensor employed in this paper is the TRA\_120\_045 [2] operating with 19.5 GHz bandwidth. The Range Migration Algorithm (RMA) is implemented for the focusing of SAR open-beam data-sets [3]–[5]. This algorithm is improved by a new enhancing resolution method (eRMA) and is complemented with a normalization procedure. The resolution improvement is featured through comparison with standard RMA and focused imaging. The combination of high resolution and large depth of field is explored through a sample of interest.

## II. RANGE MIGRATION ALGORITHM

A diagram of the algorithms steps is provided in Fig. 1. The RMA starts with a 2D spatial Fourier transform to

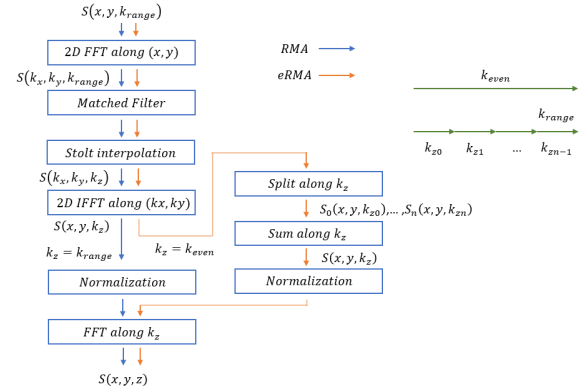


Fig. 1: Diagram of the eRMA

convert spatial data dimensions toward the lateral wavenumber domain. Then, a matched filter :  $\Phi_{MF} = e^{-i\sqrt{k_{range}^2 - k_x^2 - k_y^2} R_c}$  is applied in order to correct the phase due to the scan procedure. With, in FMCW operation,  $k_{range} = \frac{4\pi}{c}(f_c + [-\frac{BW}{2}, \frac{BW}{2}])$ ,  $k_{x,y} = [-\frac{\pi}{res_{x,y}}, \frac{\pi}{res_{x,y}}]$ ,  $R_c$  the sample distance,  $BW$  the radar bandwidth,  $c$  the speed of light,  $f_c$  the radar central frequency,  $res_{x,y}$  the azimuth scan resolutions. Subsequently, the Stolt interpolation compensates the range curvature of all the data with the following substitution :  $k_{MF} = \sqrt{k_{range}^2 - k_x^2 - k_y^2} \rightarrow k_z$ . A 2D inverse Fourier transform transpose back the dataset in the spatial domain.

A normalization procedure can take place in temporal domain. The normalization transfer function is  $S_{norm} = \frac{S - S_{back}}{S_{ref} - S_{back}}$  [6] with a reference  $S_{ref}$  signal of a perfectly reflective area and a background  $S_{back}$  signal of the focused image. The normalization procedure enhance the dynamic range and remove the imperfections of the radar, which conduct to better image quality. The last Fourier transform convert data in range domain for azimuth and range visualization.

The  $k_z$  vector chosen for the Stolt interpolation has to be equally spaced and to cover the maximum of the  $k_{MF}$  vector domain. Usually, for RMA,  $k_z = k_{range}$  is used and mainly integrate low spatial frequency contents. Due to the  $k_{MF}$  value at high azimuth spatial frequencies, most of the high frequency contents, are outside of the  $k_z = k_{range}$  domain. The Stolt interpolation will then ignore those high frequencies, resulting

in a deterioration of the lateral resolution of the image.

To counter this loss of information, a wider vector :  $k_z = k_{even}$  can be chosen through an artificial higher bandwidth, to intersect a larger portion of the  $k_{MF}$  domain and take higher spatial frequencies into account. However, no signal normalization can be performed due to the lack of information in  $S_{ref}$  and  $S_{back}$  outside of the  $k_{range}$  domain.

To overcome this problem, the temporal signal can be split in groups over bandwidth equivalent wavenumber sections  $k_{zi}$ , such that  $k_z = [k_{z0}, k_{z1}, \dots, k_{zn-1}]$ , with  $k_{zn-1} = k_{range}$  and  $n$  the number of subdivisions, described in Fig. 1. Then, the groups can be coherently summed together, creating a temporal signal containing the full range of spatial frequencies at once. Optionally, a pondered sum can be performed as an equivalent operation to Fourier spatial filtering. Finally, the normalization procedure can be applied to this signal.

### III. IMAGING PERFORMANCES

In order to determine the achievable spatial imaging resolution with this radar unit and with eRMA processing, an USAF resolution test chart has been scanned at  $R_c=10$  cm. For comparative purposes, the chart is also imaged with a standard focused imaging system using a 50.8 mm diameter and 50 mm focal length lens. The lateral resolution has been characterized with the method described in [6].

With the focusing system displayed in Fig. 2b, an optimal resolution of 2.52 mm is reached on element -3;5, equivalent to  $1.05\lambda_c$ . The usual RMA procedure is employed in Fig. 2c, the -2;4 element is resolved and correspond to 1.4 mm resolution and  $0.58\lambda_c$ . Finally, with the eRMA procedure, see Fig. 2d, a 0.8mm resolution is achieved on element -1;3, equivalent to  $0.33\lambda_c$ . With a standard focusing system, to reach the same resolution as the eRMA it would need an unachievable 1.5 numerical aperture and would lead to an unpractical 0.42 mm depth of field. Otherwise, it would require a 375 GHz radar to achieve the same resolution with a focused system.

To demonstrate advantages of SAR technique, particularly for depth of field, a sample of interest is displayed in Fig. 3. The sample is a 7cm thick board game, with two dices, in blue and red dotted lines in Fig. 3a. They are both distinguishable on the reconstruction in Fig. 3b and Fig. 3c even at 3.3 cm depth difference.

### IV. CONCLUSION

The gain of lateral resolution and depth of field by a SAR system using compact Si-Ge FMCW radar for close range NDT imaging has been exposed. A new enhancing lateral resolution method for Range Migration Algorithm reaching  $0.33\lambda_c$  resolution with this radar has been presented.

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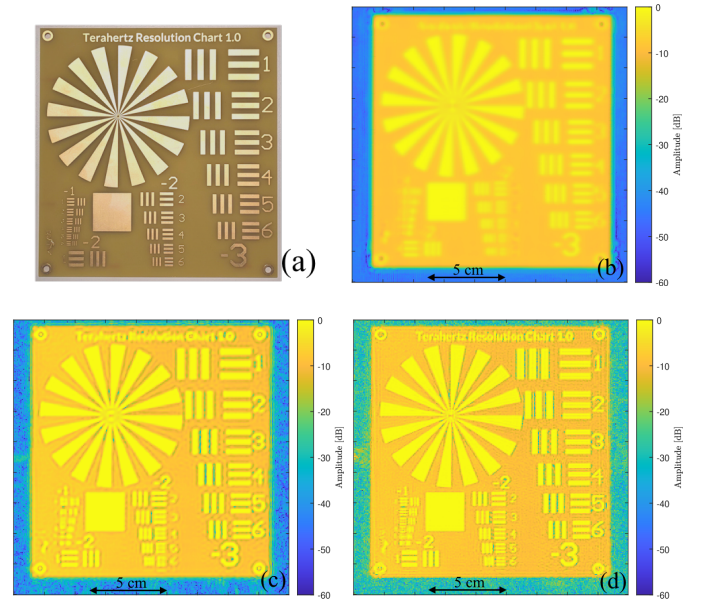


Fig. 2: USAF resolution test chart (a) Photography; (b) Scan with a focused imaging system, (c) SAR Scan with RMA procedure; (d) SAR Scan with eRMA procedure

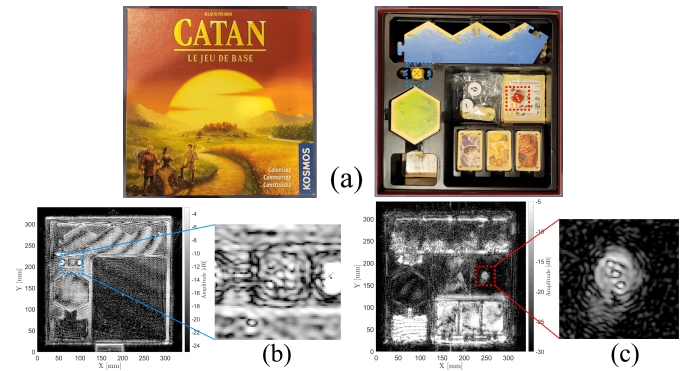


Fig. 3: Catan's board game (a) Photography of the closed package and box contents, blue and red dotted line showing two dices; (c) Slice of a reconstruction with eRMA at 14 mm under the box packaging, blue dotted line showing number 5 dice; (d) Slice of a reconstruction with eRMA at 47 mm under the box packaging, red dotted line showing number 3 dice

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