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A Transverse Spectrum Deconvolution Technique for MIMO Short-Range Fourier Imaging

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Abstract—The growing need for high-performance imaging tools for terrorist threat detection and medical diagnosis has led to the development of new active architectures in the microwave and millimeter range. Notably, multiple-input multiple-output systems can meet the resolution constraints imposed by these applications by creating large, synthetic radiating apertures with a limited number of antennas used independently in transmitting and receiving signals. However, the implementation of such systems is coupled with strong constraints in the software layer, requiring the development of reconstruction techniques capable of interrogating the observed scene by optimizing both the resolution of images reconstructed in two or three dimensions and the associated computation times. In this paper, we first review the formalisms and constraints associated with each application by taking stock of efficient processing techniques based on spectral decompositions, and then, we present a new technique called the transverse spectrum deconvolution range migration algorithm allowing us to carry out reconstructions that are both faster and more accurate than with conventional Fourier domain processing techniques. This paper is particularly relevant to the development of new computational imaging tools that require, even more pronouncedly than in the case of conventional architectures, fast image computing techniques despite a very large number of radiating elements interrogating the scene to be imaged.

Index Terms—MIMO radar, microwave imaging, millimeter wave radar, multistatic radar.

I. INTRODUCTION

In many civilian and military applications, regions of interest need to be surveyed to gather useful information that is invisible to optical imaging systems. The use of electromagnetic radiation is often justified in these practical scenarios where nondestructive detection is required, measuring the interaction of the waves with the medium under test. In particular, the microwave range is of interest for imaging and has many advantages over other frequency bands, benefiting from the advanced maturity of the active devices required for the generation and measurement of waves and the high transmittance coefficient of common materials compared to that of the optical domain. The resolution of imaging systems is related to the diversity of information measured in time and space. Ideally, broadband and densely sampled antenna arrays emitting high-frequency and ultrawideband signals should, therefore, be used to minimize the size of point spread functions in range and cross-range [1]. However, the hardware complexity inherent in signal generation and measurement is dissuasive in many applications. This problem is exacerbated by multiple-input multiple-output (MIMO) systems, where independent transmitters and receivers are needed to improve the resolution of radar images compared with single-input multiple-outputs (SIMO) and multiple-input single-output (MISO) systems of the same number of radiating elements [2]. In this paper, innovative techniques have been proposed in recent years to take advantage of these constraints and increase the efficiency of imaging systems. A first category of solutions is based on the recent introduction of compressive sensing allowing for the efficient implementation of sparse arrays [3]–[5]. This approach exploits the inherent spatial structure of the imaged objects and scenes to reduce the number of signal samples measured over time, frequency, and space. A second category is based on the use of frequency-diverse radiating structures capable of encoding and multiplexing transmitted and/or received signals into a reduced number of compressed waveforms [6]–[10]. Simplifying the hardware associated with imaging systems, MIMO architectures can be more realistically applied to many applications requiring a large number of radiating elements interacting with each other, providing both fast measurements and access to high-resolution images.

Recent advances in MIMO imaging by the scientific community—particularly in the constrained framework of short-range applications—have made it possible to significantly improve the speed of associated imaging algorithms. These techniques, initially applied to SAR, SIMO, and MISO systems, are notably based on the spectral decomposition of measured radiation, taking advantage of the use of fast Fourier transforms implemented in this paper. Given the dispersion relation of plane waves deduced from the wave equation, rapid backpropagation can therefore be calculated in k-space by a technique called the range migration.
algorithm (RMA) [11], [12]. This approach is particularly effective when combined with Stolt interpolations to rapidly transform the frequency dimension of the measured signals into range information, however introducing sometimes distortions in the computed images. In [13], this principle is extended to short-range MIMO systems, deriving an appropriate dispersion relation from a stationary phase approximation of the measured signal expression. This analysis will serve as a central pillar for the method proposed in this paper, showing that a physical interpretation of the interaction between the plane waves emitted and received by the MIMO array with the Fourier domain reflectivity function of the imaged scene can allow faster reconstructions, less memory-intensive, and of comparable quality. It is also interesting to be able to propose more intuitive tools in order to facilitate the comprehension—and possibly the teaching—of the complex processing techniques applied in this paper. An illustration based on the use of Moiré patterns is thus proposed in this framework to represent the asymptotic developments of complex integrals on which this technique is based.

The motivations for this paper are also based on the emerging field of computational imaging, where problems similar to those encountered in the case of conventional MIMO architectures are studied. Frequency-diverse radiating metasurfaces are engineered in this paper to achieve the coding and multiplexing of the transmit and receive waves into a limited number of frequency-dependent signals (Fig. 1). It has been shown in [14] and [15] that it is possible to factorize the sensing matrix encountered in computational imaging applications to separate the reconstruction stage of compressed signals from the backpropagation stage. This trick allows the implementation of conventional techniques whose formidable efficiency is based on the implementation of fast Fourier transforms. Although the full development of mathematical derivations associated with these computational techniques is outside the scope of this paper, it seemed important to justify the importance of developing new advanced processing techniques.

The rest of this paper is organized as follows. Section II is an introduction to the general formalism associated with MIMO imaging systems. Here, we confine ourselves to short-range applications, recalling in particular the principle and limitations of the RMA as described in [13]. A new technique is introduced in Section II. Its main objective is to overcome the limitations associated with the interpolation step necessary for the proper functioning of the RMA in its current form, proposing a new approach essentially based on a physical analysis of the way in which an MIMO system interrogates the spectrum of the object to be imaged in the region of interest. This technique is finally applied to various numerical simulations in order to highlight the contributions allowed by them and its possible limitations. Finally, Section IV will then provide an overview of all the elements introduced in this paper and identify elements that could lead to future studies to further improve MIMO imaging techniques.

II. MIMO NEAR-FIELD IMAGING PROBLEM

A generic MIMO setup is presented in this section for the introduction of the proposed image reconstruction method. Since most applications require a compatibility with ultrawideband signals to optimize the range resolution, this constraint will be considered for the validation of this algorithm. A couple of 2-D arrays are considered for this study (Fig. 2). The transmit array is made of \( n_{x_t} \times n_{z_t} \) isotropic radiating elements uniformly spaced in the plane \( y = 0 \) at locations defined by the vectors \( x_t, z_t \). Reciprocally, the receive array is made of \( n_{x_r} \times n_{z_r} \) uniformly spaced in the plane \( y = 0 \) at locations defined by \( x_r, z_r \). These antennas are interacting with a target centered at the location \( (x_c, y_c, z_c) \).

The target reflectivity function \( \sigma(r) \) can be estimated from the measured signals \( s(x_t, z_t, x_r, z_r, f) \), accounting for the interaction between all possible pairs of transmitting and receiving elements at each frequency. Using the first-order Born approximation and a scalar approximation of Maxwell’s equations, the expression of the measured signals can be
expressed as

$$s(x_t, z_t, x_r, z_r, f) = \int \frac{1}{16\pi^2} e^{-jkR_t} \sigma(r) e^{-jkR_r} d^3r$$

(1)

where \( r \) is the vectorized target space defined by the triplet of coordinate \((x, y, z)\). \( R_t \) and \( R_r \) are the Euclidean distances between the antennas and the target space, given by

$$R_t = \sqrt{(x_t - x)^2 + (y^2 + (z_t - z)^2)$$

(2)

$$R_r = \sqrt{(x_r - x)^2 + (y^2 + (z_r - z)^2).$$

(3)

A first estimation of the reflectivity function can intuitively be obtained by implementing a Kirchoff migration. A double summation is computed over the radiating aperture spaces \( r_1 = (x_t, z_t) \) and \( r_2 = (x_r, z_r) \) for each voxel \( r \) of the scene for compensating the phase induced by the propagation

$$\hat{\sigma}(r) = \int \int s(x_t, z_t, x_r, z_r, f) e^{j2\pi f_c(R_t + R_r)} dr_1 dr_2 df.$$

(4)

Despite the apparent simplicity of implementing this method, the computational time required to obtain a 3-D image using large antenna arrays is prohibitive in many applications. It is particularly interesting in this paper to move toward the use of backpropagation techniques in the Fourier domain. It is then possible to formalize the interaction of the reflectivity function of the scene with the emitted and received plane waves. It is necessary to start by expressing the signals received in the plane wave domain by means of Fourier transforms

$$S(k_x, k_z, k_x, k_z, k) = \tilde{\mathcal{F}}_{4D}(s(x_t, z_t, x_r, z_r, f))$$

(5)

where \( \tilde{\mathcal{F}} \) is the Fourier transform operator. The frequency dimension is expressed as a function of the wavenumber \( k = (2\pi f/c) \). The stationary phase method used in [13], partially adapted from [12], leads to a simplified representation of the measured signal \( S \), approximated in the \( k \)-space domain as

$$S = \frac{-\pi}{k_y k_z} \int \int \sigma(x, y, z) e^{-j(k_x^2 + k_z^2)z} e^{-j(k_x x + k_z z)} d^2r$$

(6)

with

$$k_y = \sqrt{k^2 - k_x^2 - k_z^2}$$

(7)

$$k_z = k_x + k_y$$

(8)

$$k_x = k_x + k_y$$

(9)

$$k_y = k_z + k_y$$

(10)

$$k_z = k_z + k_z.$$  

(11)

The reflectivity function \( \hat{\sigma}_{conv}(x, y, z) \) can thus be estimated in this paper by computing the following 3-D Fourier transform:

$$\hat{\sigma}_{conv}(x, y, z) \propto k_x k_y \int \int \int S(k_x, k_z, k_x, k_z, k) e^{j k_x x} e^{j k_y y} e^{j k_z z} dk_x dk_y dk_z$$

(12)

A 3-D representation of the target space can be obtained in the \( k \)-space by interpolating the 5-D matrix computed with a 4-D Fourier transform applied to the measured signals. This step allows for a merging of the transmitted and received plane waves, considering the dispersion relation deduced from the stationary phase approximation developed in [13]. However, this last step is crucial and represents the most time-consuming process in this algorithm, especially for large arrays of unequal sizes where prior zero padding and spatial interpolation are required to work with suitable plane wave grids. Sparse arrays have been implemented in the MIMO systems to mitigate this computational limitation, exploiting the complementary spatial diversities of the transmit and receive arrays to ensure a full \( k \)-space coverage [19], [20] enabling the development of appropriate rapid processing techniques in this paper [21]. Furthermore, the recent development of compressive systems allowing for the multiplexing of a very large number of transmitted and received waveforms [14], [22] helped overcoming the hardware limitations inherent to high-resolution systems, leading to a growing need of efficient MIMO algorithms compatible with large and densely populated antenna arrays.

Before presenting a new technique to optimize the performance of the conventional MIMO RMA algorithm, it would seem useful to illustrate the origin of the efficiency of this technique, whose mathematical complexity tends to distract from an intuitive understanding. In this paper, a simple illustrative experiment is presented: a transmit antenna is placed facing a receive aperture (Fig. 3).

The measured signals are represented in the plane wave space to represent the impact of a source translation in a plane parallel to the aperture. In order to illustrate simply how the RMA works, this simplistic case, with no real practical value, is studied by calculating the spectrum of plane waves

$$S(k_x, k_z) = \tilde{\mathcal{F}}_{2D}(s(x, z))$$

of the signals received by the radiating aperture, for two locations \( r_1 = (0, y_0, 0) \) and \( r_2 = (x_2, y_0, z_2) \) of the isotropic source, for a given frequency \( f_0 \) corresponding to a wavenumber \( k_0 = 2\pi f_0/c \) (Fig. 4). The phase distribution computed for the two locations of the transmitter can be compared to that of range matching term \( \exp(-jk_0 y_0) \), where \( k_y = (k_0^2 - k_x^2 - k_z^2)^{1/2} \) is the dispersion relation corresponding to this simple setup.

In this scenario, an RMA image reconstruction is performed by calculating the correlation between the resulting plane wave spectrum and a reference signal \( \exp(-jk_0 y_0) \) based on the dispersion relation, recalling the principle of holography [23].
The location of the radiating source can finally be computing with a 2-D inverse Fourier transform

\[ \hat{\sigma}(x, z)_{r_1} = \frac{1}{2} \left( \int S(k_{x}, k_{z})_{r_2} \exp(j k_{x} y_0) df \right). \]  

With this pointlike radiating element, the correlation between the plane wave spectrum of the measured signal and the reference signal having given rise to a phase distribution similar to a plane wave, and the final Fourier transform then converts this frequency information into the spatial position of the transmitting antenna (Fig. 5). As all these illustrations have been presented as part of a single-frequency measurement, it is only possible to resolve this element according to the transverse dimensions, parallel to the radiating aperture. The transmit antenna range can then be determined by performing a broadband measurement, summing the different frequency reconstructions in each plane in a coherent manner.

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This development highlights an important fact. It is necessary to preserve the 1/R amplitude function to obtain a compact form as presented in (14).

A. Principle of the RMA TSD

Section II provided a visual interpretation of how RMA works, confirming the importance of having a reference function adapted to each antenna array architecture. The key element of this technique is the dispersion relation, the expression of which is obtained in the case of an MIMO architecture by asymptotic development of the integral expression of measured signals ([13] and Appendix). This calculation also highlights the interaction between the transmitted and received plane waves, forming composite wave vectors described by (7)–(11). The most crucial part of the technique proposed in [13] corresponds to the interpolation step allowing the combination of which may possibly be nonuniform, imposing additional interpolation steps slowing down the computation of images. It is proposed to simplify this step by developing a matrix technique to interrogate the transverse components of the spectrum of the scene to be imaged. This technique is first explained by means of an illustration (Fig. 8).

This technique is based on interrogating the reflection function of the target represented in the plane wave domain. Each element of the matrix $S(k_x, k_z, f)$ physically corresponds to the interaction between the radiation patterns generated in the desired independent directions (represented here by the transverse components of the wave vectors). The spatial limitations and sampling of the antenna arrays used for transmitting and receiving do not allow the interrogation of infinitely fine spectral lines. This approach then makes it possible to take into account, and even to exploit, the diversity of the radiated plane waves interacting with the unknown response of the target to be imaged. Considering radiation patterns $P_t(k_x, k_z)$ and $P_r(k_x, k_z)$ obtained by computing Fourier transforms of the array sampling functions and the analysis presented in Fig. 8, the expression of signals in the k-space is then written as the following convolution products:

$$S = \int_{k_x} \int_{k_z} P_t(k_x - k_{x_s}, k_z - k_{z_s}) \times S_{c}(k_x, k_z) dk_x dk_z$$

where $S_{c}(k_x, k_z)$ is the remapped signal expression expressed in the k-space. If the samplings of the transmit and receive antenna arrays are separable functions, one can express
the radiation patterns as
\[ P_t(k_x, k_z) = P_{t,x}(k_x) P_{t,z}(k_z) \]  
(16)
\[ P_r(k_x, k_z) = P_{r,x}(k_x) P_{r,z}(k_z). \]  
(17)
The different functions are then factorized so as to group together the same variables
\[ P_t(k_x, k_{x1}, k_{x2}) = P_{t,x}(k_x - k_{x1}) P_{t,z}(k_{x2}) \]  
(18)
\[ P_r(k_z, k_{z1}, k_{z2}) = P_{r,z}(k_z - k_{z1}) P_{r,z}(k_{z2}). \]  
(19)
leading to the simplified expression of
\[ S_c(k_x, k_z, k) \]  
(20)
It is then possible to write a matrix formalism to express the link of \( S_c \) and \( S \) for each wavenumber \( k \), with
\[ \bar{P}_x \in \mathbb{C}^{n_{k_x} \times n_{k_x}}, \bar{P}_z \in \mathbb{C}^{n_{k_z} \times n_{k_z}} \]  
and \( \bar{S}(k) \in \mathbb{C}^{n_{k_x} \times n_{k_z} \times n_{k_x} \times n_{k_z}} \). The dimensions \( k_x \) and \( k_z \) are thus discretized in uniformly sampled vector, defining the maximum extension of the imaging domain. Equation (20) is then expressed as
\[ \bar{S}(k) = \bar{P}_x \bar{S}_c(k) \bar{P}_z. \]  
(21)
The expression of \( \bar{S}_c(k) \) for each value of \( k \) thus takes the following form:
\[ \bar{S}_c(k) = \bar{P}_x^+ \bar{S}(k) \bar{P}_z^+ \]  
(22)
where the symbol \( \dagger \) stands for the pseudoinverse operator. 
This approach, referred as transverse spectrum deconvolution (TSD), has multiple advantages compared with conventional techniques based on the interpolation of transverse wave vectors.

1) This transformation does not depend on the sampling of transverse wave vectors and therefore does not require signal preconditioning.
2) The transfer matrices \( \bar{P}_x \) and \( \bar{P}_z \) do not depend on frequency or wavenumber. This greatly reduces the memory and time consumption of the algorithm, which requires only a single calculation of the pseudoinverse of small matrices with respect to those of the \( S \) signal. This approach makes computing highly parallelizable and particularly suitable for array programming languages.
3) This formalism remains fully compatible with the use of nonuniform antenna arrays that remain separable functions. A precalculation of the \( \bar{P}_x^+ \) and \( \bar{P}_z^+ \) matrices or the use of nonuniform fast Fourier transform nuFFT can speed up digital processing, without requiring the use of interpolation of the associated signals.
4) This approach makes it possible to consider the interaction of the scene with all the transmit and receive plane waves emitted for each beam formation, exploiting all the secondary lobes which usually represent elements that are detrimental to image quality.

The differenct dimensions of the scene to be imaged are directly defined by sampling the vectors \( k_x \) and \( k_z \) on which the radiation patterns are calculated, avoiding the use of zero padding on 5-D matrices that already represent a certain constraint on memory consumption.

This last step of the calculation finally made it possible to move from a 5-D signal \( \bar{S}(k_x, k_{x1}, k_{x2}, k_{z1}, k_{z2}, k) \) to a remapped signal with only three uniformly sampled dimensions \( S_c(k_x, k_z, k) \). In accordance with conventional approaches, it is then possible to use the dispersion relation determined using the asymptotic calculations presented in the Appendix to express the third dimension of \( S_c \) as a function of the longitudinal projection of the wave vector \( k_i \) instead of the wavenumber \( k \). The expression \( k_i \) is given in the following:
\[ k_i = \sqrt{k_x^2 - k_y^2 - k_z^2} \]  
(23)
The plane wave components having been expressed according to the same vectors \( k_x \) and \( k_z \), it is then possible to obtain a simplified expression of \( k_y \)
\[ k_y = 2\sqrt{k_x^2 - k_i^2 - k_z^2}. \]  
(24)
The reflectivity function of the target can finally be estimated
\[ \hat{\sigma}_{\text{tds}}(x, y, z) = \int_{k_x} \int_{k_z} \int_k 4\pi^2 \bar{S}_c(k_x, k_z, k) \exp(jk_{x1}x + k_{z1}z + k_{y1}y) \]  
(25)
The numerical computation of this expression can still be quite slow when working with large antenna arrays due to the nonuniform sampling of the matrix \( k_y \) preventing from implementing fast Fourier transforms. This problem can be alleviated by using the Stolt interpolation, consisting in resampling the matrix \( S_c(k_x, k_z, k) \) over uniform grids fitting a uniformly sampled vector \( k_y \), leading to \( S_{\text{st}}(k_x, k_z, k_y) \). The association of the proposed technique with the Stolt interpolation is referred to as TSDi in this paper. Finally, the reflectivity function can be estimated using a 3-D inverse fast Fourier transform
\[ \hat{\sigma}_{\text{tds}}(x, y, z) = \mathcal{F}^{-1}_{3D}(S_{\text{st}}(k_x, k_z, k_y)). \]  
(26)

The different algorithms studied in this paper are summarized in the form of a diagram presented in Fig. 9.

A new implementation of RMA adapted to MIMO systems has been proposed. The numerical and experimental validations of this technique are presented in Section III-B in order to highlight the advantages and disadvantages of this approach compared with the existing techniques.

**B. Numerical Validation**

A first validation is carried out using a numerical simulation to measure the interaction of antenna arrays with target points. Such an approach will make it possible to highlight the computing times, memory consumption, and spatial resolutions obtained in the case of the application of RMA as defined in [13] and using the approach proposed in this paper. The system proposed for the study of these algorithms consists of two monostatic arrays (identical and sharing the same coordinates) used in transmission and reception. The simulation is carried out in the K-band (18–26 GHz) using an antenna spacing of \( 0.8c/f_{\text{max}} = 9.2 \text{ mm} \) in the transverse
Fig. 9. Comparison of the conventional MIMO RMA algorithm with the proposed TSD method. It is possible to implement this approach with a DFT or to speed up its execution with Stolt trilinear interpolation.

Fig. 10. Illustration of the proposed MIMO imaging simulation for the validation of this new imaging technique. An array of \(40 \times 40\) antennas used in both transmission and reception is used to reconstruct the image of these nine source points.

Directions \(x\) and \(z\). The arrays are placed in the plane \(y = 0\), while nine target points are arranged around a distance of \(y = 0.5\) m (Fig. 10). Target spacing is chosen so as to draw a square of \(3 \times 3\) elements separated by 5 cm in transverse dimensions. The four targets located on the corners of the square are placed at \(y = 0.045\) m, the central element at \(y = 0.55\) m, and the four elements remaining at \(y = 0.55\) m. For this first simulation, antenna arrays are made up of \(n_{ba} = 40\) antennas per side, corresponding to the interaction between \(n_{ba}^4 = 2.56\) million elements measured by this MIMO system.

Interaction is measured between transmitters and receivers for each of the 20 frequency points uniformly sampling the 18–26-GHz operating bandwidth. This matrix is then used to calculate an image using the conventional implementation of the RMA MIMO algorithm proposed in [13]. The result of the implementation of this first approach is shown in Fig. 11.

It can be seen that the reconstructed image has an uneven amplitude distribution with an energy concentration on the central target (used as a stationary phase point) and on the four points furthest away from the array. It is necessary to specify at this stage that the raw matrix is used and zero padding has not been implemented. For comparison purposes, the same matrix is again used for the implementation of the proposed method. For this first example, the pseudoinverses of the radiation matrices \(\bar{P}_x\) and \(\bar{P}_z\) are simply calculated by using matched filtering, such as \(\bar{P}_x^+ = \bar{P}_x^H\) and \(\bar{P}_z^+ = \bar{P}_z^H\), where \(^H\) is the conjugate-transpose operator. The results are presented in Fig. 12.

In this configuration and despite the absence of zero padding, the amplitude distribution appears more uniform across the space. This difference is directly related to the use of interpolation techniques in the conventional approach, allowing to merge the different transverse wave vectors, which can introduce distortions in the reconstructed images. In order to highlight these differences, two transverse views of the reconstructed images \(\hat{\sigma}_{\text{conv}}\) and \(\hat{\sigma}_{\text{tsd}}\) are presented in Fig. 13.

It can be observed that the position of the targets on the corners undergoes a small translation from their real locations in the case of the conventional approach, where the proposed technique allows a correct estimation of the positions of the targets, forming a square of \(3 \times 3\) elements separated by 5 cm along \(x\) and \(z\). The proposed approach thus offers a better
In Fig. 7, the upper bound of the range resolution can be approximated as
\[ \delta_l \approx \frac{c}{\lambda_{\text{min}}} R/(2 L_{x,z}) \]
where \( L_{x,z} \) are the aperture dimensions along the \( x \) and \( z \) directions, and is in good agreement with the results obtained with the proposed method. In the case of depth resolution, 12.8 mm is obtained for the proposed approach implemented with a direct Fourier transform (DFT), 17.8 mm for the TSD associated with an interpolation step and a fast Fourier transform, and 19 mm in the case of conventional technique. A model based on the bandwidth \( B \) is usually considered for estimating the range resolution, as \( \delta_l \approx \frac{c}{2B} = 18.7 \) mm. This result is in good agreement with the resolution obtained with the conventional method.

Considering the shells formed in the \( k \)-space represented in Fig. 7, the upper bound of the range resolution can be defined as \( \delta_k = 2\pi/(2k_{\text{max}}) = c/f_{\text{max}} = 11.5 \) mm. The resolution obtained by applying the proposed technique is thus closer to this theoretical limit by an improved exploitation of the frequency components of the measured signals.

The performance of these three algorithms is now compared. The matrix technique proposed in this paper has the advantage of reducing the memory required for the proper functioning of the program, as well as the associated computational times, especially when the number of radiating elements of the considered arrays is important. A comparison of the image computing time is thus proposed, varying the number of antennas used in transmission and reception arrays. To limit the number of variables in this study, we are still using a monostatic system, made up of a square array used for both transmission and reception, with the number of antennas per side denoted \( n_{ba} \). This study is carried out for \( n_{ba} \) ranging from 10 to 40 antennas per side of the arrays, leading to matrices of \( n_{ba}^4 \) elements for each of the 20 frequency points of the operating K-band. The calculation times are thus compared for the processing of 10 000–2.56 million equivalent radiating elements, obtained by combining all pairs of transceivers. The calculations are carried out with MATLAB, using a computer equipped with 16 GB of RAM and a six-core 3.5-GHz CPU. The results of this study are presented in Fig. 15.

The substitution of the interpolation of transverse spectral components by fusion achieved with a matrix technique not only optimizes the accuracy and resolution of reconstructed images but also allows for faster image computation up to a ratio of 75 for the largest case computed with \( 40^4 \) equivalent radiating elements.

To conclude this study, a more realistic scenario is investigated, simulating the interaction with a mannequin carrying a firearm at the belt level, imported from an STL file. The simulation is carried out according to the numerical models described in [26] and [27] by computing the electric fields radiated by a set of magnetic dipoles in the target space. This choice is justified in metasurface-based computational imaging applications to convert measured or analytically derived tangential electric fields into secondary sources injected in the numerical solver. The target under consideration consists of 67 455 facets chosen small enough with respect to the dimensions of the radiating aperture to be able to apply a physical optics approximation [28].

The contribution of each facet is thus calculated according to its orientation and dimension following a square cosine model. The qualitative validation of such an approach with
experimental results can be found in [26] and [27]. A simulation is carried out considering a 2-D MIMO antenna array formed by $71 \times 71$ elements, in which each antenna element operates in the monostatic mode, with a spatial sampling of $0.7\lambda_{min} = 6.92$ mm and placed at 1 m from the target (Fig. 16). These simulations are carried out in the frequency domain over 18–26-GHz frequency uniformly sampled by 48 points (Fig. 17).

Before analyzing the simulation results, it is important to identify the approximations that were considered for their computation. These simulations are based on the first Born approximation and do not take into account multipath phenomena. In an experimental application and under unfavorable body postures, it may be possible to observe artifacts caused by these multiple bounces, particularly between the legs and under the arms of the mannequin. However, the use of polarimetric information in such a context [17] could help to identify and filter these detrimental effects [29].

The simulated mannequin is made of metal facets with a reflection coefficient of 0.8 to match the average reflectivity of a human body [27]. Any depolarization or delay phenomenon related to the dielectric nature of a real human body is therefore not taken into account in this simulation [30]. As the impact of additive noise is rarely negligible for this type of application, it is also proposed to illustrate the impact of this effect on reconstruction under relatively unfavorable conditions. A signal-to-noise ratio (SNR) of 3 dB is thus considered for this study. This SNR is calculated from the energy of the strongest signal, determining the variance of the zero mean Gaussian noises added to all the measurements.

The volumetric reconstructions presented correspond to isosurfaces extracted at $-6$ dB from each image, previously normalized in amplitude. The color code corresponds to the depth of the reconstructed surfaces, allowing the presence of the firearm to be identified, as well as the position in space of the limbs of the target. These visualizations are simplified by representing only a 2-D view of the reconstructed information, keeping only the elements with the strongest linear magnitude as a function of depth, corresponding to the right-hand images of Fig. 17. One might notice that the trilinear interpolation step used for the TSDi technique adds distortions compared with the results obtained by simple TSD. It would be possible to limit the occurrence of such distortions by using more advanced interpolation techniques, but their interest would quickly be questionable if the associated calculation times are examined. The addition of Gaussian noise to the signals has a clearly visible impact on the volumetric reconstruction of the image by TSDi compared with the results obtained for an infinite SNR. The extraction of the isosurface is affected by the presence of a speckle making it a little more difficult to identify the object carried by the target. The depth information
computing method according to the needs of each application it is possible to adapt the antenna array architecture and the reconstructed images. Not sacrificing the accuracy and resolution of estimations.

limitations imposed by conventional imaging techniques while is intended to overcome memory and computational time systems was presented in this paper. This new breakthrough

large number of antennas and large volumes to be imaged. The spatial dimensions are expressed in the Fourier domain

S

\left( x, z, x_r, z_r \right) = \int \frac{\alpha \left( r \right) e^{-jkR_{r}} e^{-jkR_{t}}}{16\pi^2 R_{t}} d^3 r \tag{27}

with

\begin{align*}
R_{t} & = \sqrt{\left( x - x_{t} \right)^2 + y^2 + \left( z - z_{t} \right)^2} \\
R_{r} & = \sqrt{\left( x - x_{r} \right)^2 + y^2 + \left( z - z_{r} \right)^2} \\
R & = \sqrt{x^2 + y^2 + z^2} \\
dV & = \partial x \partial y \partial z. \tag{31}
\end{align*}

The spatial dimensions are expressed in the Fourier domain in order to consider the interaction between the emitted and received plane waves and the target to be imaged

S(k_{xt}, k_{zt}, k_{x}, k_{z}, k) = \tilde{S}_{4D} \left( s(x, z, x_r, z_r, k) \right). \tag{32}

A review of all the elements necessary to understand MIMO processing techniques was proposed, identifying the crucial points necessary for an intuitive presentation of this complex technique based on asymptotic developments of complex integrals. It was then possible at this stage to propose a new reconstruction method in the field of plane waves based on a physical interpretation of the interaction between the radiation of the imaging system and different targets. A numerical study revealed significant time savings in computation between the proposed method and the conventional approach proposed [13], particularly when imaging systems include a large number of antennas and large volumes to be imaged. Although these antenna array architectures are not commonly used for the usual MIMO imager implementations as they would be very expensive and would present a significant redundancy of measured information, new implementations based on the use of various frequency-diverse antennas directly face these challenges. Further studies will be carried out in the future to identify possible new optimizations of this technique. Fast Fourier transforms now represent the largest fraction of the computational time of this approach, so it will be possible to accelerate these processes by adapting these computations on field-programmable gate array (FPGA) or GPU instead of the simple multicore CPU used for this proof of principle [31]. It will also be possible to parallelize the reconstruction of radar images by separating them into a set of subdomains centered around different stationary phase points following the technique presented in [32], allowing at the same time to reduce the distortions applied to the elements reconstructed far from the stationary phase point.

IV. CONCLUSION

An imaging technique applied to MIMO imaging systems was presented in this paper. This new breakthrough is intended to overcome memory and computational time limitations imposed by conventional imaging techniques while not sacrificing the accuracy and resolution of estimations. A review of all the elements necessary to understand MIMO Fourier processing techniques was proposed, identifying the crucial points necessary for an intuitive presentation of this complex technique based on asymptotic developments of complex integrals. It was then possible at this stage to propose a new reconstruction method in the field of plane waves based on a physical interpretation of the interaction between the radiation of the imaging system and different targets. A numerical study revealed significant time savings in computation between the proposed method and the conventional approach proposed [13], particularly when imaging systems include a large number of antennas and large volumes to be imaged. Although these antenna array architectures are not commonly used for the usual MIMO imager implementations as they would be very expensive and would present a significant redundancy of measured information, new implementations based on the use of various frequency-diverse antennas directly face these challenges. Further studies will be carried out in the future to identify possible new optimizations of this technique. Fast Fourier transforms now represent the largest fraction of the computational time of this approach, so it will be possible to accelerate these processes by adapting these computations on field-programmable gate array (FPGA) or GPU instead of the simple multicore CPU used for this proof of principle [31]. It will also be possible to parallelize the reconstruction of radar images by separating them into a set of subdomains centered around different stationary phase points following the technique presented in [32], allowing at the same time to reduce the distortions applied to the elements reconstructed far from the stationary phase point.

TABLE I

<table>
<thead>
<tr>
<th>Computation Times of the Images Presented in Fig. 17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array Size</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>71 x 71 array - TSD RMA</td>
</tr>
<tr>
<td>71 x 71 array - TSDi RMA</td>
</tr>
</tbody>
</table>

APPENDIX

In this section, it is proposed to study, in a comprehensive manner, the asymptotic development of the integral equation of the signals received by an MIMO array using the stationary phase method. In addition to the pedagogical value of this development when combined with the intuitive illustrations given in Figs. 4–6, it makes it possible to highlight a certain number of calculation steps that are eluded in [13] for compactness concerns. A fraction of these developments can be found in [12] and [33], although initially applied to a synthetic aperture radar.

To the best of our knowledge, all asymptotic developments proposed in this field are based on a simplified derivation of the measured signals, considering that amplitude terms have a negligible usefulness in comparison with phase terms and can thus be removed. It is shown in this section that it is necessary to keep the decay term $1/R$, evaluated at the stationary phase point so that the final expression converges toward a form very close to that given in the references mentioned earlier. From a physical point of view, the conservation of the amplitude term also seems justified insofar as this information remains of particular interest in the context of imaging applications in the Fresnel zone.

We start the calculations from the initial formalism of the MIMO signal simplified according to a scalar field approximation and to the first-order Born approximation

$S(x, z, x_r, z_r, k) = \int \frac{\alpha (r) e^{-jkR_{r}} e^{-jkR_{t}}}{16\pi^2 R_{t}} d^3 r$ \tag{27}

with

$R_{t} = \sqrt{(x - x_{t})^2 + y^2 + (z - z_{t})^2}$ \tag{28}

$R_{r} = \sqrt{(x - x_{r})^2 + y^2 + (z - z_{r})^2}$ \tag{29}

$R = \sqrt{x^2 + y^2 + z^2}$ \tag{30}

$dV = \partial x \partial y \partial z$. \tag{31}

The spatial dimensions are expressed in the Fourier domain in order to consider the interaction between the emitted and received plane waves and the target to be imaged

$S(k_{xt}, k_{zt}, k_{x}, k_{z}, k) = \tilde{S}_{4D} (s(x, z, x_r, z_r, k))$. \tag{32}
The development of the expression of this signal makes it possible to factorize the transmission and reception terms

\[
S = \int_r \int_{A_t} \int_{A_r} \frac{\sigma(r) e^{-jk_{z_1}z_1} e^{-jk_{x_1}x_1}}{16\pi^2 R_t R_r} dA_t dA_r d^3r 
\]

\[
= \int_{A_t} e^{-jk_{x_1}x_1} e^{-jk_{z_1}z_1} dA_t 
\]

\[
= \int_{A_r} e^{-jk_{x_2}x_2} e^{-jk_{z_2}z_2} dA_r 
\]

\[
e^{-jk_{x_1}x_1} e^{-jk_{z_1}z_1} \frac{1}{R_t} e^{-jk_{x_2}x_2} e^{-jk_{z_2}z_2} dA_r 
\]

where the surface elements of the transmit and receive apertures are \(dA_t = \partial x_1 \partial z_1\) and \(dA_r = \partial x_2 \partial z_2\), respectively. The integrals \(E_t\) and \(E_r\) share the same mathematical form that can be simplified using the method of stationary phase. These expressions are developed here with a generic index \(i\) standing for \(t\) or \(r\)

\[
E_i(k_{x_i}, k_{z_i}, k) = \int_{A_i} \frac{e^{-jk_{x_i}x_i}}{R_i} e^{-jk_{z_i}z_i} \partial x_i \partial z_i 
\]

The evaluation of this integral is carried out using asymptotic development. It is therefore necessary to express this expression in a particular oscillatory integral form

\[
E_i(k_{x_i}, k_{z_i}, k) = \int_{A_i} \int_{A_i} \frac{e^{-jk_{x_i}x_i} e^{-jk_{z_i}z_i}}{\sqrt{(x_i-x)^2 + y^2 + (z_i-z)^2}} \partial x_i \partial z_i 
\]

with

\[
\Phi = \sqrt{(x_i-x)^2 + y^2 + (z_i-z)^2} - \frac{k_{x_i}}{k} x_i - \frac{k_{z_i}}{k} z_i 
\]

\[
R = \sqrt{(x_i-x)^2 + y^2 + (z_i-z)^2}. 
\]

The factorization of the wavenumber \(k\) makes it possible to introduce a phase term \(\Phi\) that varies slowly with respect to the frequency. This development makes it possible to realize an asymptotic expansion of the integral, considering that the most significant contributions arise a saddle point called the stationary phase point \((x_s, z_s)\), and defined as

\[
\frac{\partial \Phi}{\partial x_i} \bigg|_{x_s, z_s} = 0 
\]

\[
\frac{\partial \Phi}{\partial z_i} \bigg|_{x_s, z_s} = 0. 
\]

A second-order 2-D Taylor expansion of \(\Phi\) is calculated at the stationary phase point \((x_s, z_s)\)

\[
\Phi \approx \Phi(x_s, z_s) + \frac{\partial^2 \Phi}{\partial x_i^2} \bigg|_{x_s, z_s} (x_i-x_s)^2 + \frac{\partial^2 \Phi}{\partial z_i^2} \bigg|_{x_s, z_s} (z_i-z_s)^2 
\]

\[
\Phi \approx \Phi(x_s, z_s) + \frac{\partial^2 \Phi}{\partial x_i^2} \bigg|_{x_s, z_s} (x_i-x_s)^2 
\]

\[
+ \frac{\partial^2 \Phi}{\partial z_i^2} \bigg|_{x_s, z_s} (z_i-z_s)^2 
\]

\[
\Phi \approx \Phi(x_s, z_s) + \frac{\partial^2 \Phi}{\partial x_i^2} \bigg|_{x_s, z_s} (x_i-x_s)^2 
\]

\[
+ \frac{\partial^2 \Phi}{\partial z_i^2} \bigg|_{x_s, z_s} (z_i-z_s)^2 
\]

\[
\Phi \approx \Phi(x_s, z_s) + \frac{\partial^2 \Phi}{\partial x_i^2} \bigg|_{x_s, z_s} (x_i-x_s)^2 
\]

\[
+ \frac{\partial^2 \Phi}{\partial z_i^2} \bigg|_{x_s, z_s} (z_i-z_s)^2 
\]

The expression of \(x_s\) and \(z_s\) can first be obtained from the first derivatives vanishing at the stationary phase point

\[
\frac{\partial \Phi}{\partial x_i} \bigg|_{x_s, z_s} = \frac{x_s-x}{\sqrt{(x_s-x)^2 + y^2 + (z_s-z)^2}} - \frac{k_{x_i}}{k} = 0 
\]

\[
\frac{\partial \Phi}{\partial z_i} \bigg|_{x_s, z_s} = \frac{z_s-z}{\sqrt{(x_s-x)^2 + y^2 + (z_s-z)^2}} - \frac{k_{z_i}}{k} = 0. 
\]

Equations (44) and (45) then lead to the following coupled equations:

\[
(x_s-x)^2 = \frac{k_{x_i}^2}{k^2-k_{x_i}^2} (y^2 + (z_s-z)^2) 
\]

\[
(z_s-z)^2 = \frac{k_{z_i}^2}{k^2-k_{z_i}^2} (y^2 + (x_s-x)^2). 
\]

The resolution of this last equation system makes it possible to determine the expression of the coordinates of the stationary phase point, extracting the positive roots for each case

\[
x_s = x + \frac{k_{x_i}}{\sqrt{k^2-k_{x_i}^2}}. 
\]

\[
z_s = z + \frac{k_{z_i}}{\sqrt{k^2-k_{z_i}^2}}. 
\]

The second derivatives \(\partial^2 \Phi/\partial x_i^2\), \(\partial^2 \Phi/\partial z_i^2\), and \(\partial \Phi/\partial x_i \partial z_i\) can now be evaluated, reminding that \(\Phi = -(x_i-x)^2 + y^2 + (z_i-z)^2)^{1/2} - (k_{x_i}/k)x_i - (k_{z_i}/k)z_i\)

\[
\frac{\partial^2 \Phi}{\partial x_i^2} = \frac{\partial}{\partial x_i} \left( \frac{x_i-x}{\sqrt{(x_i-x)^2 + y^2 + (z_i-z)^2}} - \frac{k_{x_i}}{k} \right) 
\]

\[
= \frac{y^2 + (z_i-z)^2}{((x_i-x)^2 + y^2 + (z_i-z)^2)^{3/2}}. 
\]
Similarly, we evaluate the second derivative of the phase term according to $z_i$
\[
\frac{\partial^2 \Phi}{\partial z_i^2} = -\frac{y^2 + (x_i - x)^2}{((x_i - x)^2 + y^2 + (z_i - z)^2)^2}.
\]
(52)

The last second derivative $\frac{\partial^2 \Phi}{\partial x_i \partial z_i}$ is finally evaluated
\[
\frac{\partial^2 \Phi}{\partial x_i \partial z_i} = \frac{\partial}{\partial z_i} \left( \frac{z_i - z}{\sqrt{x_i^2 + y^2 + z_i^2}} \right) = \frac{(x_i - x)(z_i - z)}{(x_i - x)^2 + y^2 + (z_i - z)^2}.
\]
(53)

These three derivatives are finally evaluated at the stationary point
\[
\frac{\partial^2 \Phi}{\partial x_i^2} \bigg|_{x_i, z_i} = \frac{k^2 - k_{x_i}^2}{y} \sqrt{k^2 - k_{x_i}^2 - k_{z_i}^2} \frac{k^3}{k^3},
\]
(55)

\[
\frac{\partial^2 \Phi}{\partial z_i^2} \bigg|_{x_i, z_i} = \frac{k^2 - k_{z_i}^2}{y} \sqrt{k^2 - k_{x_i}^2 - k_{z_i}^2} \frac{k^3}{k^3}.
\]
(56)

Finally
\[
\frac{\partial^2 \Phi}{\partial x_i \partial z_i} \bigg|_{x_i, z_i} = -\frac{(x_i - x)(z_i - z)}{((x_i - x)^2 + y^2 + (z_i - z)^2)^2}.
\]
(57)

\[
\left( \frac{\partial^2 \Phi}{\partial x_i \partial z_i} \bigg|_{x_i, z_i} \right)^2 = y^{-2k-6} k_{x_i}^2 k_{z_i}^2 \frac{k^3}{k^3}.
\]
(58)

Finally, it is necessary to evaluate the expression of the amplitude term $R(x_i, z_i)$, as well as the expression of the phase term at the stationary point $\Phi(x_i, z_i)$
\[
R(x_i, z_i) = \sqrt{(x_i - x)^2 + y^2 + (z_i - z)^2} k_y
\]
(60)

\[
\Phi(x_i, z_i) = -\frac{(x_i - x)^2 + y^2 + (z_i - z)^2 - k_{x_i}^2}{k} x_i - \frac{k_{z_i}^2}{k} z_i
\]
(62)

\[
= \frac{k - (k_{x_i}^2/k) - (k_{z_i}^2/k)}{\sqrt{k^2 - k_{x_i}^2 - k_{z_i}^2}} y - \frac{k_{x_i}^2}{k} x_i - \frac{k_{z_i}^2}{k} z_i.
\]
(63)

The magnitude and phase term evaluated at the stationary point can then be extracted from the integral
\[
E_i = \frac{e^{jk\Phi(x_i, z_i)}}{R(x_i, z_i)} \mid_{z_i} I_k
\]
(64)

with $\alpha = -\frac{\partial^2 \Phi}{\partial x_i^2} \bigg|_{x_i, z_i}$, $\beta = -\frac{\partial^2 \Phi}{\partial z_i^2} \bigg|_{x_i, z_i}$ and $\gamma = -\frac{\partial^2 \Phi}{\partial x_i \partial z_i} \bigg|_{x_i, z_i}$.

Having $\alpha \beta > \gamma^2$ and $\alpha < 0$, (64) then takes the following form [35]:
\[
E_i = \frac{j2\pi}{k} R(x_i, z_i) \left| e^{jk\Phi(x_i, y_i)} \right| \left( \left| \frac{\partial^2 \Phi}{\partial x_i^2} \right|_{x_i, z_i} \frac{\partial^2 \Phi}{\partial z_i^2} - \left| \frac{\partial^2 \Phi}{\partial x_i \partial z_i} \right|_{x_i, z_i} \right)^{1/2}
\]
(66)

\[
= \frac{j2\pi}{k} \sqrt{k^2 - k_{x_i}^2 - k_{z_i}^2} \frac{k^2 y}{k^2 - k_{x_i}^2 - k_{z_i}^2} \exp \left( -j \left( \frac{k^2 - k_{x_i}^2 - k_{z_i}^2}{\sqrt{k^2 - k_{x_i}^2 - k_{z_i}^2}} y + k_{x_i} x + k_{z_i} z \right) \right)
\]
(67)

\[
= \frac{-j2\pi}{k} \sqrt{k^2 - k_{x_i}^2 - k_{z_i}^2} \exp(-j k_{x_i} x) \exp(-j k_{z_i} z).
\]
(68)

Finally, we recall the initial expression of the MIMO signal $S(k_{x_i}, k_{z_i}, k_x, k_z, k)$ expressed in the $k$-space, as well as its equivalent expression obtained by applying the stationary phase method
\[
S = \int_r \frac{\sigma(r)}{16\pi^2} \int_{A_r} e^{-jkr_r} e^{jk_{x_i} x} e^{jk_{z_i} z} dA_r \left( \int_{A_r} e^{-jkr_r} e^{jk_{x_i} x} e^{jk_{z_i} z} dA_r \right) \ d^3r
\]
(69)

\[
= \frac{4\pi^2}{16\pi^2 k_y k_{y_i} k_{y_z}} \int_r \sigma(r) e^{-jkr_y} e^{-jkr_z} e^{-jkr_x} e^{-jkr_{y_i}} e^{-jkr_{z_i}} e^{-jkr_{y_z}} \ d^3r
\]
(70)

\[
= \frac{1}{4k_y k_{y_i} k_{y_z}} \int_r \sigma(r) e^{-jkr_y} e^{-jkr_z} e^{-jkr_x} \ d^3r
\]
(71)

where the association of transverse components corresponding to the plane waves emitted and received gives rise to new projections of composite wave vectors interrogating the target space, matching the expressions given in [13]
\[
k_{y_i} = \sqrt{k^2 - k_{x_i}^2 - k_{z_i}^2}
\]
(72)

\[
k_{y_z} = \sqrt{k^2 - k_{x_i}^2 - k_{y_z}^2}
\]
(73)

\[
k_z = k_{y_i} + k_{y_z}
\]
(74)

\[
k_y = k_{y_i} + k_{y_z}
\]
(75)

\[
k_z = k_{y_i} + k_{y_z}
\]
(76)

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REFERENCES


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