Compressive Sensing Techniques for mm-Wave Non-Destructive Testing of Composite Panels

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Abstract—This paper presents imaging results from measurements of an industrially manufactured composite test panel, utilizing two introduced algorithms for data post-processing. The system employs a planar near-field scanning set-up for characterizing defects in composite panels in the 50–67 GHz band, and can be considered as a complementary diagnostic tool for non-destructive testing purposes. The introduced algorithms are based on the reconstruction of the illuminating source at the transmitter, enabling a separation of the sampled signal with respect to the location of its potential sources; the scatterers within the device under test or the transmitter. For the second algorithm, a $L_1$-minimization problem formulation is introduced that enables compressive sensing techniques to be adapted for image retrieval. The algorithms are benchmarked against a more conventional imaging technique, based on the Fourier Transform, and it is seen that the complete imaging system provides increased dynamic range, improved resolution and reduced measurement time by removal of a reference measurement. Moreover, the system provides stable image quality over a range of frequencies.

Index Terms—Non-destructive testing, compressive sensing, imaging, source reconstruction, millimeter wave, planar scanning.

I. INTRODUCTION

Non-destructive testing (NDT) is the science and practice of evaluating various properties of a device under test (DUT) without compromising its utility and usefulness [1]. Applications where NDT is used are for example welding inspection and structural evaluation of composite materials [1, 2]. Composite structures, manufactured with low permittivity and low loss materials such as honeycomb or foam, are increasingly utilized in, e.g., aircraft structural components and radomes [3], and in order to conduct NDT on such structures, the method of choice must be capable of detecting defects related to low conductivity and inhomogeneity.

In recent years, millimeter wave (mm-wave) (30 – 300 GHz) imaging has attracted much attention as an electromagnetic testing technique for NDT applications [2–6]. High resolution imaging is possible at these frequencies due to the inherent short wavelengths. Other advantageous properties of mm-wave imaging systems are: low power consumption, compact size, low weight, and that they can easily be integrated into existing industrial scanning platforms [4]. Millimeter-wave NDT is particularly well-suited for inspection of composite structures since it has been proven useful for detection of material inhomogeneities, disbonds, delaminations and inclusions in low loss dielectrics [6, 7]; all potential defects in composite structures. For example, in [8] it was shown that subsurface voids in insulating foam were detectable in a wide range of the mm-wave spectrum.

A near-field mm-wave imaging system can either operate in reflection, such as in security applications [2, 9], or in transmission as in radome diagnostics [10] and near-field antenna measurements [11]. The spatial sampling of the scattered signals can be acquired either through mechanical scanning [11] or electronic scanning by utilizing antenna arrays [2]. Much time can be saved if an electronic scan can be performed, but at mm-wave frequencies it is non-trivial to develop cost-effective imaging arrays of high complexity. This complexity can be reduced by performing a one-dimensional (1D) raster scan using a 1D imaging array, which provides a good compromise between complexity and scan time [12]. Depending on the application, either a single frequency or a broadband electromagnetic signal is used to illuminate the object. In this work, the focus is on transmission based near-field scanning systems. These systems traditionally utilize either planar, cylindrical or spherical scanning [11, 13, 14].

Once the signals have been acquired over a given spatial area, the aim is to reconstruct the unknown sources on a given surface. This is an inverse problem which has traditionally been solved using reconstruction in the Fourier domain, commonly referred to in literature as time reversal, digital beam forming (DBF), aperture synthesis, back propagation, back projection or migration technique [15, 16].

Alternatively, Compressive Sensing (CS) based processing techniques could be used for image retrieval if the inverse problem could be modelled as an underdetermined linear system [17–19]. The strategy is to formulate the relation between the data and unknowns as a linear mapping, modelled by a rectangular matrix, and where the unknown vector has only a few non-zero entries with respect to a defined basis. Since the industrial manufacturing standard is good, existing defects in composite structures would be few and CS processing techniques would be adaptable to the problem at hand. Furthermore, the theory behind CS states that, if adapted to a sparse problem, the sought after solution can be recovered using far fewer samples than what is classically required by...
the Nyquist theorem [20], allowing for a potentially reduced measurement time as the number of required data samples decreases.

The characteristics of CS have resulted in a fast development in a variety of applications related to electromagnetics [20] such as: array synthesis [21], antenna diagnostics [22], direction-of-arrival estimation [23], ground penetrating radar [24], and inverse scattering [25–27]. The state-of-the-art within CS techniques for microwave imaging includes a variety of formulations to target specific problems and improve performance; wavelet basis functions for CS and total-variation CS can be adapted to solve problems with non-sparse scatterers (with respect to a pixel basis) [28–30]. Additional examples are the contrast field based CS [31] applicable to weak scatterers and multi-task Bayesian CS [32].

As spatial resolution, the achievable dynamic range and overall measurement time for acquiring data is generally considered the main measures of performance of an imaging system [2], mm-wave imaging using CS offers a promising foundation for further development of electromagnetic testing techniques for NDT applications.

In this paper, we introduce a mm-wave imaging technique based on CS that aims at: (1) reducing the required measurement time by removal of a reference measurement, and (2) improving the dynamic range compared to the conventional imaging technique based on time reversal of the measured fields. A 50 – 67 GHz imaging system is constructed using a planar near-field scanning set-up, and is then applied to industrially manufactured composite test panels. The technique could be seen as a complement to currently used diagnostic tools used in industry such as ultrasonic testing.

The technique is developed in two steps, where first a source separation algorithm is introduced that separates the components of the scattered signal related to the defects in the DUT from the total received signal by subtracting the illuminating field. This implies that no reference measurement is needed. After the illuminating field has been subtracted, a weak scattered field from a few sparse defects is acquired. This linear inverse problem is then formulated in a CS sense in order to improve the dynamic range.

II. ALGORITHM DESCRIPTIONS

For clarity, the notation used in the rest of this paper is summarized here: boldface uppercase and boldface lowercase are used for matrix- and vector notation, respectively.

A. Measured Signal

The measured signal is sampled at a distance $z$ from the illuminating antenna over a finite rectangular aperture. The sampling is performed over a uniform rectangular grid, and the measured signal for each fixed frequency in the corresponding grid point can be represented as the sampled signal $s$ (a complex number at each spatial grid point):

$$s(x_i, y_j, z) = s(x_1 + (i - 1)\Delta, y_1 + (j - 1)\Delta, z)$$

$$i = 1, 2, \ldots, N_x,$$

$$j = 1, 2, \ldots, N_y.$$  \hspace{1cm} (1)

Here, $\Delta$ is the sample increment in the $x$- and $y$-direction, and $(x_1, y_1)$ is the grid point in the lower left corner of the grid. The aggregated samples of the signal (or field) in the measurement plane for each fixed frequency is represented as a $N_m \times 1$ column vector, where $N_m = N_x N_y$.

B. Time Reversal Technique

For a measured signal $s(x, y, z_2)$ sampled continuously at a fixed distance $z = z_2$, the time reversal technique exploits the Fourier transform and its inverse in order to translate the signal between different $xy$-planes [15]. The signal’s spatial spectrum at $z = z_2$ is

$$S(k_x, k_y, z_2) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} s(x, y, z_2)e^{ik_x x + ik_y y} dx dy,$$ \hspace{1cm} (2)

where $k_x$ and $k_y$ are the $x$- and $y$-component of the wavenumber, respectively. In the spectral domain, the signal can be translated to a $xy$-plane closer to the source using a simple exponential, i.e., the signal’s spectrum at $z = z_1$ is:

$$S(k_x, k_y, z_1) = e^{ik_x d} S(k_x, k_y, z_2).$$ \hspace{1cm} (3)

Here, $k_x = \sqrt{k^2 - k_y^2 - k_z^2}$, $d = z_1 - z_2 < 0$ and $k = 2\pi f/c$ with $f$ being the frequency and $c$ being the speed of light in air. Applying the inverse Fourier transform yields the signal in the spatial domain $s(x, y, z_1)$. For discrete signals, the usage of the discrete versions of the Fourier transform and its inverse allows for the time reversal technique to be efficiently implemented using Fast Fourier Transform (FFT) algorithms. Aliasing can be avoided by choosing the sample increment as $\Delta \leq \lambda/2$ in accordance to the Nyquist criterion. In the set-up considered in this paper, the choice of $\Delta$ can be relaxed as discussed further in Sec. III.

In order to retrieve the vector field components from the measured signal, it is necessary to compensate for the probe that samples the signal. The probe correction, explained in detail in [11, 33], is based on the a priori knowledge of the receiving characteristic of the probe. Using an open-ended waveguide, the far-field in the spectral domain can be modelled using formulas in [34]. The procedure can be used in order to extract either a scalar field or a vector field where the vector field extraction requires two independent measurements of the same signal. These are commonly chosen as the co-polarized and cross-polarized measurements. If the field is normalized with that obtained from a reference measurement, the time reversal technique can be applied for image retrieval of a DUT containing defects.

C. Source Separation Algorithm

A general model of the imaging set-up with appropriate field vectors and operators defined is seen in Fig. 1. As depicted in the figure, for a single frequency the field extracted from the corresponding discrete samples in the measurement plane is assembled into the $N_m \times 1$ vector $b_m$. The $n_m$:th entry of $b_m$ corresponds to the field value in the spatial grid point $(x_i, y_j)$ with $n_m = (j-1)N_x + i$ in relation to the introduced indices in (1). In order to expand the field in an arbitrary plane,
all surfaces of interest are discretized into rectangular mesh cells with rooftop functions acting as local basis functions. The operator $A_{ij}$, constructed analogously to conventional method of moments [35], thus maps the currents in plane $j$ to the field in plane $i$.

The scattered field from the defects is assumed to be orders of magnitude smaller in amplitude compared to the total field in the measurement plane in the sense that critical defects (e.g., delaminations and debonding) have only a minor impact on the electromagnetic properties of the DUT. The measured field $b_m$ can then be decomposed into the illuminating field $b_2$ from the antenna and the slab of the DUT, and the scattered field $b_s$ arising only from the interior defects:

$$b_m = \tilde{b}_m + b_2. \quad (4)$$

Using (4), $\tilde{b}_m$ can be extracted if $b_2$ can be estimated appropriately. This is done by finding the currents on the antenna aperture represented by the $N_a \times 1$ vector $x_a$, using the operator $A_{20}$ (size $N_m \times N_a$). A singular value decomposition (SVD) is applied to $A_{20}$:

$$A_{20} = U\Sigma V^H. \quad (5)$$

Here, $U$ and $V$ are unitary matrices, and $\Sigma$ is a diagonal matrix containing the non-zero positive singular values of $A_{20}$. The normalized singular values are truncated according to a prescribed threshold $\tau$, selected by means of the $L$-curve criterion [36]. The pseudo inverse is then constructed as [37]:

$$A_{20}^+ = V\Sigma^+ U^H. \quad (6)$$

Here, $\Sigma^+$ is a diagonal matrix, with all entries corresponding to singular values whose normalized value is below $\tau$ set to zero. The remaining entries contain the reciprocal of the corresponding singular value. Applying $A_{20}^+$ to the measured field $b_m$ yields

$$x_a = A_{20}^+ b_m, \quad (7)$$

and the field contribution from the antenna, $b_2$, is found as:

$$b_2 = A_{20} x_a. \quad (8)$$

After finding $b_2$, the analysis is restricted to the scattered field $\tilde{b}_m$, where the source separation algorithm utilizes the time reversal technique to retrieve the final image in the DUT plane. The CS algorithm introduced in the upcoming section, is instead based on the formulation of the $L_1$-minimization optimization problem. The partitioning of the field as a result of the source separation is illustrated in Fig. 2.

### D. Compressive Sensing Algorithm

The CS algorithm utilizes the SPGL1 Matlab solver based on the general basis pursuit denoise (BPDN) $L_1$-minimization problem [38,39]. For a single frequency, the target image can be acquired from the scattered field $\tilde{b}_m$, by finding the corresponding scattered field $b_1$ in the DUT plane. The initial optimization problem is then formulated as:

$$\begin{align*}
\text{minimize} & \quad \|b_1\|_1 \\
\text{subject to} & \quad \|A_{21} b_1 - \tilde{b}_m\|_2 \leq \sigma.
\end{align*} \quad (9)$$

The choice of the user-defined threshold $\sigma$ is discussed in the final part of this section. In order to reconstruct properties of the defects rather than the scattered field $b_1$, we introduce the scattering amplitudes $s$ as

$$b_1 = B_1 s, \quad (10)$$

with

$$B_1 = \text{diag}(b_1) = \begin{bmatrix}
0 & 0 & \ldots & 0 \\
0 & b_{1,2} & \ldots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \ldots & b_{1,N_1}
\end{bmatrix}$$

representing the incident field on the panel at $z = z_1$ from the antenna, see Fig. 1. $N_1$ spatial grid points are assumed in the DUT plane. Using $x_a$ and the operator $A_{10}$ (size $N_1 \times N_a$), and, $b_1$ can be found through

$$b_1 = A_{10} x_a. \quad (11)$$

The scattering amplitudes $s$ comprise $N_1$ unknowns, induced by the scatterers in the DUT plane. In a pixel basis, only few non-zero elements would be needed to represent the defects if their physical size is on a wavelength scale. This would correspond to defects no larger than a few centimeters when considering the $60\text{GHz}$ band; a reasonable scenario since
industrial manufacturing processes rarely results in large-size fabrication errors. The optimization problem then reads:

$$\text{minimize } ||s||_1 \text{ subject to } ||A_{21}B_1s - \tilde{b}_m||_2 \leq \sigma. \quad (12)$$

The incident field, expressed in $B_1$, is not uniformly distributed over the DUT plane which results in a non-uniform weighting of the scattering amplitudes in this formulation. To re-compensate for this effect the final formulation is obtained as:

$$\text{minimize } ||s||_1 \text{ subject to } ||B_{2,\text{inv}}A_{21}B_1s - B_{2,\text{inv}}\tilde{b}_m||_2 \leq \sigma, \quad (13)$$

where $B_{2,\text{inv}}$ represents the magnitude of the inverse of the incident field in the measurement plane:

$$B_{2,\text{inv}} = \begin{bmatrix} |b_{2,1}|^{-1} & 0 & \ldots & 0 \\ 0 & |b_{2,2}|^{-1} & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & |b_{2,N_m}|^{-1} \end{bmatrix}.$$

1) Choice of the threshold $\sigma$: For a known field $\tilde{b}_m$, an estimate of the scattering amplitudes $\hat{s}$ is retrieved by time reversing $\tilde{b}_m$ using the adjoint operator $A_{21}^*$:

$$B_1^*\hat{s} = A_{21}^*\tilde{b}_m. \quad (14)$$

By applying $A_{21}$ to $B_1\hat{s}$, the estimated scattered field in the measurement plane $\hat{b}_m$ is found as:

$$\hat{b}_m = A_{21}B_1\hat{s} = A_{21}A_{21}^*\tilde{b}_m. \quad (15)$$

Finally, the threshold is chosen as

$$\sigma = ||\tilde{b}_m - \hat{b}_m||_2 = ||(1 - A_{21}A_{21}^*)\hat{b}_m||_2. \quad (16)$$

This choice of $\sigma$ is stable, and the performance of the algorithm would not be compromised by small fractional changes to this value.

2) Comment on implementation: Given that the measurement and DUT plane are discretized identically, it follows that $A_{21}$ is a block Toeplitz matrix. Due to the large number of grid points necessary for a reasonable resolution, it is not desirable to compute the complete matrix operator. Rather, $A_{21}$ can be extended to a circulant matrix due to its Toeplitz characteristic, and the general linear operations $A_{21}x$ and $A_{21}^*b$ can instead be evaluated efficiently in a matrix free way using an FFT algorithm [37,40].

III. PERFORMANCE

The three implemented algorithms are:

1) The time reversal technique, as described in Sec. II-B. This technique employs time reversal of the field $b_m$ in the measurement plane with DUT present and a free space reference. The final image is obtained after normalization with the free space field back-propagated to the DUT plane.

2) The source separation algorithm. This algorithm utilizes source separation to estimate the scattered field $\tilde{b}_m$ in the measurement plane (Sec. II-C), and thereafter employs time reversal of $\tilde{b}_m$ (Sec. II-B) in order to retrieve the final image.

3) The CS algorithm. This algorithm utilizes source separation to estimate the scattered field $\tilde{b}_m$ in the measurement plane (Sec. II-C), and thereafter employs the CS algorithm. The free space measurement data, denoted by $FS$, is associated with the dashed line.

A block diagram describing the algorithms can be seen in Fig. 3. As depicted, the top row corresponds to processing that were carried out for all measurement data. The three parallel schemes at the bottom correspond to 1) the time reversal technique, 2) the source separation algorithm and 3) the CS algorithm.
Due to the large difference in dynamic range for the different algorithms, the images from the time reversal technique and source separation algorithm are shown in Fig. 6 for customized color ranges. It is seen that the source separation algorithm provides a dynamic range of around $\simeq 20 \text{ dB}$. As Figs. 5 and 6 (a) depict the time reversed field normalized with a free space measurement ($|E_y/|E_y^{FS}|$), the shadowing effect from the resistive sheets is clearly seen as the amplitude around the defects is lower than the surrounding medium. However, both the source separation algorithm and CS algorithm act on the scattered field using (4), and consequently the images in Fig. 5 (b), (c) and Fig. 6 (b) show the resistive sheets as the maximum amplitude in the DUT plane. Truncation effects, i.e., sidelobes, arising from the finite aperture of the measurement plane can be seen for both the time reversal technique and source separation algorithm, most clearly seen in Fig. 5 (b) as the vertical- and horizontal lines springing from the resistive sheets. The sidelobes can be suppressed by applying an appropriate windowing function, reducing the effect of the finite aperture of the measurement plane, with the cost of degraded resolution. However, these sidelobes do not appear for the CS algorithm, due to the usage of operators for transforming between $xy$-planes. Moreover, the CS algorithm manages to resolve the $1 \times 1 \text{mm}^2$ ($0.2\lambda \times 0.2\lambda$) defect, whereas this defect is not detected by neither the time reversal technique nor the source separation algorithm.

### B. Measurements

Measurements were carried out in the microwave laboratory at Lund University, Sweden. The illuminating source was chosen as a $50 - 67 \text{ GHz}$ standard gain horn antenna, and an open-ended waveguide was used as the scanning probe. A single planar scan was conducted, with both horn and probe being $y$-polarized. The transmitted signal was measured using an Agilent E8361A network analyzer, and a low noise amplifier (LNA) was added on the receiver side. The transmit power was $-7 \text{ dBm}$, the intermediate frequency (IF) bandwidth was set to $300 \text{ Hz}$ and a linearly spaced frequency sampling with 201 points across the whole operational band of the horn antenna was used.

In order to acquire the necessary data as input for the algorithms, post-processing routines were employed on the measured $S_{21}$, as seen in the top row of blocks in Fig. 3. First, multipath scattering components of the signal are suppressed by applying an appropriate window function in the time domain, here chosen as a Hanning window. An interesting remark is that even with a free space path loss of $\simeq 68 \text{ dB/m}$ at $60 \text{ GHz}$, and additional losses due to reflection and surrounding absorbers, the data filtering resulted in a considerable improvement of the purity of the $S_{21}$ over the measurement aperture. Secondly, probe correction is applied in order to extract the field components from the $S_{21}$ as described in Sec. II-B. Using one planar scan, only a single scalar component may be extracted, here chosen as the copolarized component of the electric field, i.e., $E_y$ according to the alignment of the horn and the probe. It should be noted that the probe correction is not limited to a specific field or the final image due to the fact that the geometrical set-up limits the possible incident plane waves under consideration, or equivalently restricts the $(k_x, k_y)$-spectrum. Consequently, any aliasing that occurs falls outside of the wavenumber region of interest.

### A. Synthetic Data

The above described algorithms are employed on synthetic data, extracted from simulations using FEKO. This discards any deterministic measurement errors that might appear when measured data is considered, and consequently provides a proof of concept of the algorithms themselves.

The $E_y$-component (co-polarization) in the aperture of a standard gain horn antenna at $60 \text{ GHz}$ is used as the illuminating source, and three rectangular resistive sheets with $R = 100 \text{ ohm}$ represent the DUT. The set-up can be seen in Fig. 4. With labelling according to Fig. 4b, the dimensions of the resistive sheets are $1.5 \times 10 \text{ mm}^2$, $5 \times 2.5 \text{ mm}^2$ and $1 \times 1 \text{ mm}^2$.

Retrieved images using the time reversal technique, source separation algorithm and the CS algorithm can be seen in Fig. 5. As seen, for the depicted color range ($[-60, 0]$ dB), the CS algorithm provides the best dynamic range as only scattering amplitudes related to the physical dimension of the resistive sheets have non-zero entries, i.e., the sparse solution to the problem is found. The time reversal technique gives little information whereas the source separation algorithm manages to detect the defects, with noticeable low power noise present.
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Figure 5. Retrieved images at 60 GHz for the synthetic data using the three different algorithms. (a) depicts $|E_y|/|E_{yFS}|$, were $E_{yFS}$ denotes the free space reference measurement, (b) depicts $|E_y|$, and (c) depicts the absolute value of the scattering amplitudes $s$. All figures are in normalized dB-scale ($20 \log_{10}(|u|/\max(|u|))$, where $u$ is the parameter being plotted) with color range $[-60, 0]$ dB.

Figure 6. Retrieved images at 60 GHz for the synthetic data using the time reversal technique and source separation algorithm with customized color range. (a) depicts $|E_y|/|E_{yFS}|$ were $E_{yFS}$ denotes the free space reference measurement, and (b) depicts $|E_y|$. Both figures are in normalized dB-scale ($20 \log_{10}(|u|/\max(|u|))$, where $u$ is the parameter being plotted) with color range: (a) $[-5, 0]$ dB, and (b) $[-20, 0]$ dB.

Figure 7. Photo (a), and block schematic (b) of the measurement set-up. Receiving antenna is a 50 – 67 GHz standard gain horn antenna, and the transmitting scanning probe is a rectangular open-ended waveguide. Surrounding absorbers are seen in black (a).
assembling the panel. The largest dimension of all defects are between 2 – 20 mm, i.e. ranging in size from sub-wavelength to a few wavelengths of the illuminating signal. With the geometrical settings presented earlier, one planar scan took 4 h to conduct, i.e., the total measurement time for retrieving the necessary data for the different algorithms is 8 h, 4 h and 4 h for the time reversal technique, the source separation algorithm and the CS algorithm, respectively.

Fig. 10. Photo (left) and schematic (right) of the panel under test as seen from the probe. The size of the panel is 300 × 300 × 3 mm³.

IV. CONCLUSION

A complete imaging system using a planar near-field scanning set-up operating in the 50 – 67 GHz band has been

Retrieved images at \( f = 60 \) GHz using the time reversal technique, the source separation algorithm and the CS algorithm can be seen in Fig. 8. Note the customized color scale for every image, motivated by the large difference in dynamic range achieved by the different algorithms. The image quality obtained in the synthetic case is maintained for the measured data. As for the synthetic case, the CS algorithm provides the best dynamic range. The source separation algorithm and CS algorithm provide stable images regardless of the choice of frequency, demonstrated by the similarity of the equivalent images at \( f = 61 \) GHz shown in Figs. 9 (b) and (c). Errors arising from the measurement set-up can be seen to affect the image quality of Figs. 8 and 9 (a) to a larger extent, perhaps explained by the exploitation of data from two independent measurements (one with DUT present and one free space reference). Whereas the dynamic range is maintained, the color scale is different for the different frequencies in (a) in order to provide the best image. The effect of the weighting compensation introduced by the operator \( \mathbf{B}_{2, \text{inv}} \) can also be seen in Figs. 8 and 9 (c), as the scattering amplitudes for all defects are of the same magnitude unlike as in (a) and (b).
presented. Its potential as a complementary tool for industrial NDT diagnostic purposes has been validated through measurements on an industrially manufactured composite test panel using two introduced post-processing algorithms. The source separation algorithm can be regarded as a stepping-stone in the development of the more efficient CS algorithm, yet both algorithms provide noticeable enhancements compared to the more conventional time reversal technique. These enhancements include reduction of measurement time by removal of a reference measurement, increased dynamic range, and stable image quality over a range of frequencies. All three are critical measures of system performance.

It should be noted that sparsity is a relative concept in CS, and a scatterer can be sparse in some basis but not sparse with respect to another one. The pixel basis used in this work is convenient due to the small physical size of the defects under consideration.

Further development of the CS algorithm is ongoing, mainly for reduction of measurement time while maintaining image quality. The single frequency problem formulation provided in (13) allows for a straightforward extension to the multiple frequency scenario, in which data from several fixed frequencies can be utilized in order to solve for the scattering amplitudes. Potentially, this would allow for a reduction in spatial samples without compromising image quality. This implementation is currently in progress.

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References


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