Data set reduction for ultrasonic TFM imaging using the effective aperture approach and virtual sources

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ABSTRACT

The Total Focusing Method (TFM) is sometimes described in the literature as the “gold standard” compared to conventional imaging techniques. TFM is an algorithm that usually post-processes the full matrix of data, also called Full Matrix Capture (FMC). Real-time piloting of such an algorithm is heavy due to the large number of firings (N for a N-element array) and the large number of signals (N×N) to process that tend to decrease the frame rate and, consequently, the inspection speed. This problem can be overcome to some extent if only a few elements are activated which is equivalent to using a sparse array in transmit. The PSF (Point Spread Function) provides information about important images parameters: lateral resolution and contrast. An algorithm based on PSF optimization is proposed to obtain both the number of transmit pulses and the location of the active elements. However, reducing the number of emissions induces a loss in transmitted energy. To compensate it, each transmit pulse is carried out by multiple transmit elements that emulate a single “virtual” element. The method is evaluated on experimental data in a realistic NDT configuration by comparison of images obtained with FMC and SMC (Sparse Matrix Capture) acquisitions.

1. Introduction

Ultrasound methods are commonly used in non destructive testing (NDT), for example, in the field of nuclear energy and aerospace, where safety requirements are important. They may allow detection, location, identification and sizing of the flaws of mechanical parts and assemblies without altering their mechanical properties. Real-time inspection may prevent industry from failure, improve quality while limiting costs. Ultrasonic transducer arrays are more and more widespread for detection and imaging. The large number of possibilities offered by them has opened the development of various imaging methods. Among all the existing imaging techniques, the Total Focusing Method (TFM) is sometimes described as the “gold standard” compared to conventional imaging techniques [1], [2]. TFM is an algorithm that usually post-processes the full array response matrix, also called Full Matrix Capture (FMC), obtained by exciting each element of an ultrasonic phased array individually while reception is performed by all the elements. For an array of N elements, then N² signals are collected. Image acquisition speed for conventional system is determined by the number of lines in the Bscan. Reducing the number of lines by limiting the field of view and/or decreasing the lateral resolution
results in an increase of the acquisition speed. It is not the case for TFM imaging whose acquisition speed can be increased by simply reducing the number of independent firings. This is equivalent to defining a sparse array in transmit while reception is performed by either all or some of the elements of the array.

The design of sparse arrays was intensely studied in the 1990s in the medical imaging field by various authors such as Lockwood, who put forward multiple algorithmic strategies for designing periodic sparse arrays using the effective aperture function [3]. Recently, the design of sparse linear array has been transposed to NDT [4] and is still an open question. Sparse arrays for synthetic aperture imaging can be defined in several ways such as optimizing the elements weights of a sparse array where the location of the active elements is already determined [4, 5], or optimizing the location of the active elements when weights are determined [6]. In [7, 8] the optimization is simultaneously applied for locations and weights of a fixed number of active elements. The advantage provided by sparse arrays is that they reduce the amount of data to be managed by reducing the number of transmissions. This leads to two drawbacks associated with the two main types of noise: electronic and material noise. The first drawback induced by the reduction of transmit firings is that less energy is put in and thus less signals contribute to the image at each point. Assuming that noise is mainly an uncorrelated electrical one, the loss of transmitted energy results in a loss of Signal to Noise Ratio (SNR). To compensate this loss, Karaman et al. suggests the use of “virtual” sources. Each of them consists in a group of several elements time delayed to transmit a cylindrical wave, thus emulating a single “virtual” element located below the array with higher acoustic power [3, 9]. The second drawback is that the sparse transmit aperture may result in a Point Spread Function (PSF) that is worse than the one provided by a full array. This can be problematic when imaging flaws in noisy parts since the sidelobes level of a PSF characterizes material noise [10]. Thus, the sparse transmit aperture may lead to a PSF that worsens the image quality because the signal to coherent noise will be worse.

The aim of this work is to reduce the data volume to be managed in TFM imaging while limiting loss of image quality. In other words, the goal is to determine the optimal Sparse Matrix Capture (SMC) providing a TFM image equivalent to that obtained by post-processing a FMC. This paper presents a method to design a sparse array providing a TFM image close to the one obtained by post-processing a FMC. Contrary to the different approaches encountered in the literature, the proposed designing method consists in finding both accurate number and best location of active elements according to the weights applied to the full array in reception. The optimization is based on the comparison of the PSF of the sparse array with the one generated with full matrix of data. The result is then evaluated in near field condition according to NDT restrictions such as structural noise. The loss in signal due to the reduced number of firings is compensated by the use of “virtual” sources.

2. Total focusing method and point spread function

The TFM imaging technique is a synthetic focusing method applied to elementary signals acquired with a transducer array. This algorithm is generally applied to a FMC acquisition. For an array of N active elements, this acquisition is composed of the N×N stored impulse inter-element responses $s_{nm}(t)$ defined as the output of the element number $m$ when the input of the element number $n$ is a delta impulse. Once all elementary signals $s_{nm}(t)$ are stored, the principle of the TFM algorithm is to coherently sum them for each point of a Region Of Interest (ROI) [11].

Noting $T_{nm}(x, z)$ the theoretical time of flight between a pair of element (n, m) through a point P(x, z) of the ROI (see Figure 1), the image magnitude $I$ in this point may be written as:

$$I(x, z) = \sum_{nm} w_n^I(n) w_m^R(m) s_{nm}(T_{nm})$$  \hspace{1cm} (1)

where

$$T_{nm}(x, z) = \frac{R_L(x, z) + R_R(x, z)}{c}$$  \hspace{1cm} (2)

and

$$w_n^I(n) = \frac{1}{N} \sum_{n=1}^{N} w_n^I(n)$$
$R_T$ and $R_R$ are respectively the distances between the transmitter and receiver to the imaging point and $c$ is the ultrasonic velocity in the ROI. $w_n^T$ and $w_m^R$ are weights applied to the elements $n$ and $m$ respectively.

Figure 1: Array geometry

In the frequency domain equation (1) can be written as:

$$ I(x, z) = \sum_{\omega} \sum_{nm} w_n^T(n) w_m^R(m) s_{nm}(\omega) d_{nm}(\omega, x, z) $$

(3)

where $s_{nm}(\omega)$ is the frequency spectrum of array data, and $d_{nm}$ are focusing coefficients.

$$ d_{nm}(\omega, x, z) = \exp\left[ jk(R_{Tn}(x, z) + R_{Rm}(x, z)) \right] $$

(4)

Assuming that the reflectors are located in the far-field of the array (i.e. $|\vec{r}| > |\vec{r}_E|$, $|\vec{r}_E|$) and using the approximation $|\vec{r} - \vec{r}_E| \approx r - \frac{\vec{r}_E \cdot \vec{r}}{r}$ (subscript E refers to subscripts R or T), $R_T$ and $R_R$ can be written as follows:

$$ R_{Tn} = r - x_{Tn} \cdot \sin \theta $$

(5)

and

$$ R_{Rm} = r - x_{Rm} \cdot \sin \theta $$

(6)

where $x_{Tn} = |\vec{r}_T| = nd$ and $x_{Rm} = |\vec{r}_R| = md$ with $d$ the array pitch

With the previous approximation, equation (3) can be re-written as follows:

$$ I(x, z) = \sum_{\omega} \sum_{nm} e^{j2\pi x_{Tn}(n)} e^{j2\pi x_{Rm}(m)} A_{nm}(\omega, \theta) $$

(7)

where

$$ A_{nm}(\omega, \theta) = w_n^T(n) w_m^R(m) e^{-j\pi x_{Tn} \sin \theta} e^{-j\pi x_{Rm} \sin \theta} $$

(8)

The two first terms of (7) are associated with radial resolution while $A_{nm}$ is associated with angular resolution quality. This last one can be considered as the angular Point Spread Function (PSF) for a target in the $\theta$ direction. A Point Spread Function (PSF) corresponds to the response of an imaging system to a point-like target [4].
\( PSF(\omega, \theta) = \sum_{nm} A_{nm}(\omega, \theta) \)
\[ = \sum_{m=0}^{N-1} w^T(n)e^{-jknd \sin(\theta)} \sum_{m=0}^{N-1} w^R(m)e^{-jkmd \sin(\theta)} \]  \hspace{1cm} (9)

where \( \lambda \) is the wavelength.

Setting \( \sin(\theta) = 2\pi \frac{p}{Nd} \), with \( p \) denoting the frequency index, the PSF can be described as a Discrete Fourier Transform (DTF)

\[ PSF(\omega, \theta) = DTF[ w^T \otimes w^R ] \]  \hspace{1cm} (10)

The convolution product of the apodization functions applied in transmit \( (w^T) \) and in receive \( (w^R) \) is referred to as the effective aperture:

\[ e_{TR}(n) = w^T(n) \otimes w^R(n) \]  \hspace{1cm} (11)

Thus, the PSF can be obtained by Fourier transform of the effective aperture which represents an equivalent receive aperture that would produce an identical two-way radiation pattern if the transmit aperture was a point source [3], [7].

TFM achieves high resolution images in an extended area. It also provides finer characterization than other classical methods [12], [13]. However, the main drawback of TFM imaging is the large amount of data to acquire and to process for image reconstruction. This is time consuming and limits real-time application of the algorithm. This problem can be overcome to some extent if only a few elements are activated in transmission which is equivalent to using a sparse array in transmit. Image contrast and lateral resolution depend on the PSF characteristics. The main lobe width of the PSF determines the lateral resolution while image contrast depends on side lobe level. Thus, the relation between effective aperture and PSF can be used as a useful strategy for analysis and optimization of a sparse array. The PSF can be optimized by selecting the appropriate transmit and receive aperture functions. That is why, in the next section, the adopted method to design a sparse array is based on PSF optimization.

3. Optimization of a sparse array

3.1. Description of the optimization algorithm

The optimization of the sparse array consists in minimizing the number of transmit firings by determining both the accurate number and best locations of active elements according to the weights applied to the full array in reception.

Different algorithms have been proposed for optimization of the locations of a number of transmit elements already fixed. Most of them use one or two of the following criteria: maximum side lobe peak (SLP) below an acceptable value noted \( A \) and maximum main lobe width of the PSF (MLW) below a threshold \( B \). In the proposed algorithm, the number of active transmit elements and their locations are determined using three criteria, those mentioned above and a third one based on the sidelobe energy (SLE) that must be less than the value denoted \( C \). \( A, B \) and \( C \) are the different thresholds of acceptance based on characteristic of a full array radiation pattern. \( A \) is the maximum level value that maximum sidelobe peak is authorized to reach. \( A \) equals -27 dB like the higher sidelobe level measured on the PSF of a full array (reference). \( B \) is the threshold required for the main lobe width at -20 dB. To avoid too much loss of lateral resolution, \( B \) is chosen equal to 1.2 times the main lobe width of a full array radiation pattern. The maximum level of sidelobe energy (SLE), \( C \), is equal to the sidelobe energy of the radiation pattern of a full array plus 3 dB.

The optimization process of an \( N \) element array can be summarized as follows:

1. Activation of the first and the last transmit elements;
The activation of the two outer elements of the array allows maximizing the lateral resolution and speed up computation time.

2. Addition of one element to the previous sparse array;
3. Calculation of the associated radiation pattern for each possible location;
4. Determination of the best location for the added element:
   The best location is the one satisfying maximum sidelobe peak < A and providing the smaller main lobe width
5. If the PSF of the “new” array meets the three criteria:
   - SLP < A,
   - and MLW < B
   - and SLE < C
   Then the optimized sparse array is obtained;
   Else add another element to the sparse array and repeat the operation until the criteria are satisfied.

3.2. Computation and experimental results

The previous algorithm was applied to optimize the number and locations of active transmit elements on a 2-MHz array of 58 elements of 0.8 mm pitch. Only longitudinal waves are considered and the following results are obtained by using the longitudinal velocity in ferritic steel. Depending on the aperture function applied in reception, the algorithm provides different results. Thus, when no apodization is used, the optimized sparse array is constituted of 13 active elements. When a trapezoidal windowing is applied, only 6 firings are necessary. The number of active elements is lowered when applying apodization functions in reception. Indeed, they provide the advantage of lowering side lobes (contrast improvement) but on the other side they widen the main lobe width (loss of lateral resolution) [13]. Note that the trapezoidal window was chosen because it proved to be the best compromise between loss of lateral resolution and lower sidelobes, in this configuration. Other apodization windows, such as Hamming or Blackman-Harris windows, further reduce the level of sidelobes but degrade more the lateral resolution. Figure 2 shows the comparison between the PSF of a full array with the one of a sparse array apodized in reception (Figure 2 (b)) or not (Figure 2 (a)). First, a slight increase of the main lobe width can be noted (+6 % of the FMC-PSF mainlobe width) when apodization was applied. Without apodization, the PSF of the sparse array presents sidelobes lower than the one of the full array, but locally, the sidelobe level can be higher for angles greater to 30°. When a trapezoidal apodization is used, 6 firings are sufficient to obtain a PSF which envelope fits the reference’s one. Sidelobe have been attenuated by the application of the trapezoidal window to the receive elements. The use of apodization allows a good compromise between beam width, side lobe level, and number of firings.
Figure 2: Comparison of resulting PSF of a full and non apodized array and optimized sparse array. 
(a) non apodized sparse array, (b) apodized sparse array (trapezoidal apodization)

The results provided by the optimization algorithm were applied to experimental data collected on a ferritic steel sample with several Side-Drilled Holes (SDH) of 2 mm diameter and located between 30 and 60 mm away from the array (Figure 3).

The resulting images (Figure 4 and Figure 5) are obtained after TFM processing and presented on a 35 dB dynamic range. Figure 4 shows the image obtained by post-processing a FMC acquisition. It is considered as the reference image.

Figure 5 displays four TFM images resulting of post-processing of SMC acquisitions. Figure 5(a) and Figure 5(b) were obtained without apodization and with 13 firings. The location of the active transmit elements was determined by the optimization algorithm for Figure 5(a) while random sequences were used for Figure 5(b). The sequences are reported in Table 1.

Table 1: Numerical results provided by the optimizing algorithm and random sequences used get random SMC-TFM images

|                  | Optimized sequences                              | Random sequences                           |
|------------------|---------------------------------------------------|--------------------------------------------|
| **Without apodization** | 1, 13, 18, 22, 24, 30, 32, 35, 38, 44, 46, 51, 58 | 1, 2, 5, 15, 16, 25, 37, 40, 44, 49, 50, 55, 57, 58 |
| **With apodization**   | 1, 17, 29, 43, 44, 58                          | 1, 16, 34, 40, 50, 58                      |
Figure 5: Images of the ferritic steel sample obtained with (a) non apodized SMC-TFM with sequences provided by the optimizing algorithm, (b) non apodized SMC-TFM with random sequences (c) trapezoidal apodized SMC-TFM with sequences provided by the optimizing algorithm, (d) trapezoidal apodized SMC-TFM with random sequences.

When comparing Figure 5(a) and Figure 5(b), it appears that image quality of the first one is better than the second one’s. Indeed, it presents less artifact and sidelobe noise especially around the holes. This illustrates that the locations of the active transmit elements impacts the image quality. Transmit element location optimization is then necessary to limit image degradation due to less transmit events. This observation is also valid for Figure 5(c) and Figure 5(d) which SMC acquisitions were apodized with a trapezoidal window. It has been shown in section 3.1 that the use of a trapezoidal apodization lowers the number of necessary signals to make an image of acceptable quality. However, this results in more visible artifacts. Thus, Figure 5(c) presents more artifacts than Figure 5(a) that was obtained with a sparse matrix constituted with twice more transmit events. The extent to which artifacts appear depends on the dynamic range used for the images (Figure 6). But, in general, their amplitude is very low compared to the one of the flaw and do not perturb the detection when employing 30 dB dynamic range which is a representative of the one used in many industrial application [4].

Figure 6: Sparse and apodized TFM image with (a) a 35 dB dynamic range, (b) a 30 dB dynamic range
To quantify the differences between FMC-TFM images and SMC-TFM images but also between SMC-TFM images and apodized SMC-TFM images, measurements have been performed and are reported in Table 2.

Table 2: Quantitative characteristics of the ferritic steel sample TFM images.

|                          | FMC-TFM image | SMC-TFM image (no apodization) | SMC-TFM image (trapezoidal apodization) |
|--------------------------|---------------|--------------------------------|----------------------------------------|
| Number of firings        | 58            | 13                             | 6                                      |
| Increase of the          | -             | +6%                            | +6%                                    |
| mainlobe width (%)       |               |                                |                                        |
| Amplitude of hole        | 0 dB          | -13 dB                         | -22 dB                                 |
| SNR                      | 45 dB         | 40 dB                          | 35 dB                                  |
| Loss of SNR              | -             | -5 dB                          | -10 dB                                 |
| Theoretical loss of SNR  | -             | -6 dB                          | -10 dB                                 |

Figure 7(a) provides the cumulative amplitude curves of TFM images of Figure 5. For a given abscissa of a TFM image, we sum the amplitudes present on all different lines of the image. In other words, each curve is obtained by summing all the lines of the corresponding TFM image. These cumulative amplitude curves and Table 2 show that as the number of firings diminishes, the measured amplitude decreases due to the reduced transmitted energy. This results in a loss of SNR which is measured on TFM images slices like the one of Figure 7(b). The SNR was calculated as the ratio of the 50mm depth SDH maximum amplitude to the average noise level taken around the SDH and at the same depth. The experimental loss of SNR corresponds to the expected theoretical loss. Indeed, assuming uncorrelated noise, the SNR of a sparse synthetic aperture system is proportional to the square root of the product of the number of transmit events $N_t$ and the number of receive elements $N_r$ [3].

$$SNR \propto \sqrt{N_t N_r}$$

(12)
Figure 7: Quantitative measurement of TFM image quality. (a) Cumulative amplitude curves normalized by the maximum amplitude of the FMC-TFM image, (b) slice of image at z=50 mm depth, the amplitudes are normalized by the maximum amplitude of the FMC-TFM image.

Comparison of lateral resolution was performed on the images at -20 dB. In sparse-TFM images, the holes appear larger than on the FMC-TFM image. This increase amounts +6% and equals the increase of mainlobe width of the sparse array PSF measured above.

From these experimental results, it is clear that sparse-TFM image quality depends on several factors. Thus, the location of active elements must be chosen properly to avoid useless artifact and sidelobe noise. Applying weight to the elements in receive allows to lower significantly the number of firings but the main drawback is the associated loss in SNR. Indeed, the less combinations of transmit-receive elements used in the imaging algorithm, the less suppression of incoherent noise.

4. Improvement of the method and application to noisy samples

4.1. Concept of virtual sources

As seen in the previous section, the use of a single element per firing limits the acoustic power output. Furthermore, reducing the number of active transmit elements induces a loss of signal. Assuming random electronic noise, the loss of transmitted energy and signal results in a limited penetration depth and a loss of Signal to Noise Ratio (SNR). One method for increasing penetration depth and/or the SNR has been proposed by Karaman et al [9]. It consists in using multiple transmit elements for each transmit burst. The group of elements is de-focused by applying time delays. Thus, the elements simulate the radiation pattern of a single “virtual” source (VS) located above the array but with higher acoustic power (Figure 8(a)). Virtual sources can also be created under the array by applying focusing time delays to the subaperture (Figure 8(b)). The position of the VS with respect to the position of the array does not impact the detection of the flaw or the quality of the resulting TFM image if the position of the VS in the calculation of the focusing delays is taken into account.
The benefit of using “virtual” sources has been tested experimentally. First, the number of elements constituting a VS was determined by simulations performed with the CIVA platform. A perfectly spherical radiator should produce a uniform horizontal band in magnitude and constant horizontal phase bands [9]. Figure 9 provides the different simulated transmitted fields obtained when varying \( N_d \). The fields are calculated along an arc of radius \( R = 50 \text{mm} \). As expected, when \( N_d = 1 \), the magnitude band (Figure 9(a)) is horizontal since a single element produces a cylindrical wavefront. Figure 9(b) and (c) show that for small values of \( N_d \) such as \( N_d \leq 7 \), the synthesized response of VS is very close to the one corresponding to a single element (Figure 9(a)). Larger subapertures (\( N_d \geq 7 \)) produce bands that are no longer horizontal in an angular extent as large as for smaller subaperture (Figure 9(d), (e) and (f)). The response deviates significantly from a cylindrical wavefront, especially in range. Furthermore, edge wave diffraction appears and a loss of uniformity along the wavefront is measured. Thus, given the characteristics of the array probe and the results of the simulations, the optimal number of elements constituting a VS is 7.

Figure 8: Principle scheme of virtual sources: (a) the virtual source is placed above the array, (b) the virtual source is placed under the array.

Figure 9: Simulated field transmitted by \( N_d \) defocused elements. (a) \( N_d = 1 \), (b) \( N_d = 3 \), (c) \( N_d = 7 \), (d) \( N_d = 11 \), (e) \( N_d = 15 \), (f) \( N_d = 19 \).
The use of virtual sources increases the transmit power proportionally to the number of elements \( N_d \) constituting the de-focused subaperture. Karaman et al. demonstrated experimentally that if an isotropic radiation pattern is obtained from the “virtual” array, the amplitude of the resulting wave is increased in proportion of \( N_d^{1/2} \) [9]. Measurements of the mean intensity of the simulated fields verify it. Figure 10 shows that the relation between the simulated transmit wave intensity and subaperture size can be approximated as \( 1.25 \sqrt{N_d} \).

![Figure 10: Mean intensity of simulated defocused beam for different subaperture sizes](image1.png)

Figure 10 represents, for a VS constituted of 7 defocused elements, the mean amplitude distribution measured on the simulated field. It allows anticipating the fact that employing VS can increase the transmitted energy by a factor 3.4 (\( \equiv +11 \) dB) compared to the one delivered by a single element.

### 4.2. Experimental results

To demonstrate the benefit of using virtual sources, experimental testing were applied on a noisy sample. The same experimental set-up than previously was used on a cast steel sample. Figure 12(a) is a FMC-TFM image considered as the reference one. Figure 12(b) is a sparse-TFM image obtained after post-processing a SMC which sequences correspond to the ones provided by the optimization algorithm without apodization applied in reception. When comparing Figure 12(a) with Figure 12(b), it appears that the level of noise is higher in the SMC-TFM image than in the FMC-TFM image. As expected, the amplitude of the SDH is also lowered. A 13 dB loss can be measured on the echodynamic of the image (Figure 13, Table 3). Using a sparse matrix acquisition provided by a “virtual” array corrects partially this loss. Figure 12(c) was obtained by post-processing a SMC where active “virtual” elements are located at the same place that the real active elements used to get the sparse matrix acquisition of Figure 12(b). The image quality is clearly improved since the use of a “virtual” array allowed increasing the transmitted energy. Thus, slices of the resulting image almost fit the one of the FMC image (1 dB of difference). Employing virtual arrays allows obtaining images of quality similar to FMC-TFM images visually and quantitatively (Figure 13, Table 3) but with less firings.
Figure 12: Images of the cast steel sample obtained with (a) FMC-TFM, (b) real SMC-TFM, (c) virtual SMC-TFM.

Figure 13: Slice of TFM images at depth $z = 50$ mm. The amplitudes are normalized by the maximum amplitude of the FMC-TFM image.

Table 3: Quantitative characteristics of the cast steel sample TFM images

|                     | FMC-TFM image | Real Sparse-TFM image | Virtual Sparse-TFM image |
|---------------------|---------------|------------------------|--------------------------|
| Number of firings   | 58            | 13                     | 13                       |
| Amplitude of the central hole | 0 dB       | -13 dB                 | -1 dB                    |

5. Conclusion
The two-way radiation pattern of an imaging system provides information about two main image quality parameters, lateral resolution and contrast. An algorithm based on optimization of the PSF has been proposed to the design of sparse array. The results provided by the algorithm and their experimental application show that the number of firings can be reduced by at least 4 without great loss of image quality compared to full array imaging. The PSF approach is based on far-field approximation. However, it has been tested in the near field of the array and applied to TFM imaging. Thus, although a loss of amplitude can be noticed, sparse-TFM images are found to be very close to TFM images obtained by post-processing FMC. Signal loss due to the reduction of...
active transmit elements is not a problem when imaging in non-noisy components contrary to materials presenting a high level of structural noise. To overcome this, virtual sources have been used. They consist in grouping adjacent elements and applying them time delay so they simulate the radiation pattern of a single element with higher acoustical power. This solution has shown its efficiency when imaging SDH in a cast steel sample. An increase of 12 dB has been noticed leading SMC-TFM image identical to full matrix TFM image.

The work presented in this paper suggests that TFM images of good quality can be obtained without processing the full array of data. Using sparse matrix capture allows to reduce the data volume by a factor 4. Thus, processing time is reduced and real-time application of TFM imaging can be considered.

6. References

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