

Department of Electrical Engineering,
National Tsing Hua University
Special Topic on Implementation
Research Report

REFoCUS: Complete-Dataset FSA
Implementation & Validation

REFoCUS：完整資料集 FSA 實作與
驗證

Major Category: EE systems group

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Abstract

Ultrasound imaging uses focused transmit beams to focus acoustic energy in a specific target point. For this, conventional beamforming methods will use signal data that is close to the focal depth, completely disregarding any important information from outside the set focal region. Hence, decrements in image quality and signal-to-noise ratio (SNR) will occur at regions located outside the focal zone. One way to solve this issue is by acquiring the “complete dataset” which will allow us to get high image quality in regions inside and outside the focal zone. The main objective for this research project is to implement and validate a data acquisition algorithm based on the “REFOCUS” algorithm, which main goal is to completely recover the complete dataset or in other words “element-domain channel data”. This complete dataset is acquired from the focus transmit beams by emphasizing the individual element pairs contributions.

“REFOCUS” breaks down the focused transmit beam channel data into the responses from each specific array element pair. By doing so, it enables the use of full synthetic aperture (FSA) and therefore synthetic transmit focusing at any region which nullifies the focal depth artifacts that usually occur when using other conventional virtual source methods. In this research project, two main methods were proposed: a time-domain based method that uses interpolation to apply the delay and a frequency-domain based method derived by using the FAST Fourier Transform (FFT) and phase shifts.

The code implementation and validation of the refocusing algorithm was made in MATLAB with the use of the ultrasound simulation software Field II. We simulated a 96-element linear array with a center frequency of 5MHz. Field II also helped us simulate two different phantom configurations: the multiple scatterer phantom that consists of 12 scatters with 9 transmit beams, and lastly a cyst phantom that consist of a more sophisticated scatterer pattern with 72 transmit beams.

Our validation results show the outstanding similarity between our “REFOCUS” data and the ground truth data. Simpler cases manage to reached as high as a 98% correlation coefficient and more complex cases such as the cyst phantom had correlation coefficients above 82%. As for the frequency-domain methods, results demonstrate near identical correlation coefficients when compared to the time-domain method, which makes it a really viable implementation choice for this algorithm since for large datasets a frequency-domain method is usually preferred, not to mention that frequency domain allow us the use of better optimization techniques. For both the time and frequency domain methods, the beamformed images created by using the complete dataset also almost perfectly match the images created with the ground truth data, we verified this by looking at its really low mean squared errors (MSE). With the use of coarse images, we also concluded that our algorithm had decent phase alignment by showing how the image quality progressively improves as we increase the number of beams.

I believe this project successfully managed to implement and validate the algorithm’s ability to accurately acquire the complete dataset from the signal channel data of the focused transmit beams. We also manage to demonstrate an alternative method on how to perform retrospective synthetic aperture beamforming and with this it hopefully created a foundation for future medical image reconstruction investigations.

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1. Introduction

1.1 Background and Motivation

Ultrasound imaging is considered of huge importance and is vastly use in the area of biomedical imaging, this is mainly because it can provide real-time imaging of the internal anatomical structures through the use of transmission and reception of sound waves.

Ultrasound image quality depends a lot on the data acquisition and beamforming methods, which in principle joins the images of various transducer elements to form a coherent final image. State-of-art ultrasound systems are designed with complex beamforming algorithms with the objective of getting the highest spatial resolution and hence, achieving the highest possible image quality.

For most of the conventional ultrasound imaging system, focused transmit beams are commonly used to focus acoustic energy in a specific target. This focused transmit beam is implemented by properly calculating and applying custom time delays to the array elements, creating a wavefront that will converge at a target focal point. This specific method is the foundation of ultrasound imaging and while its performance on concentrating acoustic energy in a focal point is decent, this method still has some limitation. Focused transmit beams are only optimized to work efficiently in a narrow depth of field close to the point target. This implies that on regions far away form the focal point, there will be a degradation of image resolution and a decrement in the signal-to-noise ratio (SNR). These limitations are the main reason for the research and creation of complete dataset full synthetic aperture imaging methods which will allow us to obtain ideal transmit focusing at any region and at all depths.

Data acquisition on synthetic aperture methods works by obtaining the individual transmit element or sub-apertures data, making each source emit a spherical diverging wave. The coherent combination of these responses allows us to perform synthetic transmit focusing at all points in the space. The set of all of these individual transmit-receive elements responses is what we call the “complete dataset”, which give us all the data me we need to implement any kind of signal processing or image reconstruction algorithm.

Acquiring the complete dataset comes with many challenges. For example, it is known that single-element transmission will lead to lower signal amplitude that then also leads to a reduced SNR. Various methods have been proposed to boost the SNR but all of them have their own limitations such as: needing specialized hardware and modification on acquisition protocols.

1.2 “REFOCUS” Algorithm

Recently Nick Bottenus proposed a new approach on synthetic aperture data acquisition: recovering the complete dataset from focused transmit beams. This algorithm breaks down focused transmit beams into diverging waves that come from the individual transducer array elements. The key principle is realizing that each focused beam has all the information about all the transmit elements contributions, which can later be isolated by a coherent summation across various transmit events and point targets

This refocusing algorithm could be summarized in two main formulas. The first one states that for a transmit event n , the signal that is received by element R is the sum of the individual element responses with their respective delay.

$$s_{nR}(t) = \sum_{T=1}^M w_{nT} \cdot u_{TR}(t - \tau_{nT}) \quad (1)$$

In which w_{nT} is the transmit weighting, τ_{nT} would be the transmit delay, and $u_{TR}(t)$ is the individual element contribution. By removing the delay and performing an aligned coherent sum throughout all the beams, we can estimate the individual element contributions:

$$\hat{u}_{TR}(t) = \frac{\sum_{n=1}^N s_{nR}(t + \tau_{nT})}{\sum_{n=1}^N w_{nT}} \quad (2)$$

By repeating this algorithm for all the combination of the transmit-receive elements pair, we can recover the complete dataset.

1.3 Research Objectives, Project Scope and Contributions

The main objective for this project is to implement and validate the ‘‘REFOCUS’’ algorithm. I specifically aim to:

1. **Implement** both the time-domain and frequency-domain algorithms of REFOCUS.
2. **Validate** the accuracy of REFOCUS by comparing it against the ground truth from the Field II simulation
3. Analyze the **beamformed images** created by using REFOCUS and compare them against the ground truth beamformed images.
4. Employ coarse images analysis to help us **diagnose out-of-phase artifacts**.

We will use Field II ultrasound simulation toolbox to simulate three different phantom configurations with increasing computational complexity as well as also performing point spread function (PSF) analysis.

- Multiple case simulation (medium complexity): 12 point scatterers with 9 transmit events.
- Cyst phantom simulation (high complexity): sophisticated scatterer distribution with 72 transmit events
- PSF analysis: single point scatterer with 9 transmit events. 2d/lateral/axial resolution analysis

Our Field II transducer simulation set up is as follows: 96 element array, 5Mhz center frequency, 70% fractional bandwidth, and lastly a 0.154 mm element pitch. The cyst phantom will have ± 20 lateral range and a 35 to 90 mm axial range.

This project aims describe the basics of the REFOCUS algorithm for further ultrasound imaging research. It aims to shows that the complete dataset can be acquire from focused transmit beams.

2. Research Methodology

2.1 System design and Simulation Settings

The architecture for the whole system can be divided in 5 main areas: Field II simulation, REFOCUS algorithm implementation, validation algorithms, beamforming, and phase diagnosis.

Note: Though the algorithms are originally from Nick Bottenus’s paper [1]. All of the code used for the implementation and validation of REFOCUS were created by me from scratch. Regarding the Field II simulation toolbox [2], I used it as a simulation engine, but all algorithms code modules are my original work.

This project consist of a modular MATLAB framework and its architecture is as follows:

1. Simulation: Creates the ground truth channel data by using Field II ultrasound toolbox.
2. REFOCUS time/frequency: employs the individual element isolation algorithm.
3. Validation: validates the algorithms accuracy through correlation and other error metrics.
4. Beamforming: creates images from the channel data.
5. Phase diagnosis: generates coarse images that will help analyze out-of-phase artifacts.

Table 2-1 shows all the different transducer parameters [3] used for all the simulations. I chose these parameters based on real clinical ultrasound probes.

Table 2-1

Parameter	Value	Unit
Number of Elements (M)	96	elements
Center Frequency (f_0)	5.0	MHz
Sampling Frequency (f_s)	100	MHz
Element Pitch	0.154	mm
Kerf	0.014	mm
Element Width	0.140	mm
Element Height	5.0	mm
Fractional Bandwidth	0.7	-
Speed of Sound (c)	1540	m/s

Field II will provide us with the ultrasound channel data. The process is as follows:

1. Transducer Initialization: simulates 96 elements linear array transducer.
2. Impulse response: Sinusoid with 70% fractional bandwidth.
3. Excitation signal: Single cycle sinusoid at center frequency
4. Phantoms: Three different phantoms configurations: multiple scatterers case and cyst
5. Data acquisition: Ground truth complete dataset will be acquired by using function `calc_scatter_all`

Cyst phantom: A cyst phantom will be implemented to simulate realistic tissues structures. This phantom will consist of 100,000 randomly distributed scatterers which will work as background speckles. There will be 5 dark cyst circular regions which will help us simulate a hypoechoic lesion with a sequential reduction in its echogenicity. The phantom simulation will also include 5 bright circular regions that will represent hyperechoic lesions and its echogenicity will increased. The beam configuration will be optimized to cover a ± 20 lateral range and a 35 to 90 mm axial range, which will hopefully provide a dense enough spatial sampling for simulating a realistic reconstruction. Details regarding the grid configuration, corresponding amplitudes, radiuses and the multiple scatterers simulation are listed at table 2.

Table 2-2

Type	Scatterers	Beams	Characteristics
Multiple	12	9	Distributed point scatterers
PSF	1	9	Point target: (0,0,50) mm; 2D/lateral/axial resolution metrics
Cyst	100,000	72	5 dark cysts (8mm, amp 0.1-0.3); 5 bright lesions (4mm, amp 2.0-3.0); background (amp 0.8-1.2); 9x8 beam grid

2.2 REFOCUS algorithm theory

2.2.1 Time-domain Implementation:

For the time-domain implementation of REFOCUS our system uses direct interpolation for equations (1-3) from Nick Bottenus [1]:

Step 1: Define channel data

For each and every transmit event n and receiver element R :

$$s_{nR}(t) = \sum_{T=1}^M w_{nT} \cdot u_{TR}(t - \tau_{nT}) \quad (3)$$

where τ_{nT} would be the transmit delay:

$$\tau_{nT} = \frac{|O_n F_n| - |T F_n|}{c} \quad (4)$$

Step 2: Element Isolation

For each and every transmit element T and receiver R :

$$\hat{u}_{TR}(t) = \frac{\sum_{n=1}^N s_{nR}(t + \tau_{nT})}{\sum_{n=1}^N w_{nT}} \quad (5)$$

Reverse time-domain shifting is implemented with MATLAB's `interp1` function and the main objective is to align the contributions of the same transmit-receive element pair at the same time before performing a coherent sum. Figure 1 gives a visual representation of the reverse delay performed on a single scatterer simulation.

2.2.2 Frequency-domain implementation

The frequency-domain implementation of REFOCUS could be described as an FFT-based phase shifting algorithm. Each time shift in the time-domain can be represented as a phase shift with angular frequency w .

Note: for frequency-domain implementation we will also base ourselves in the equation provided in Bottenus [1]:

Step 1: Represent the individual contributions in the frequency-domain:

$$U(f, T, R) = \text{FFT}[u_{TR}(t)] \quad (6)$$

Step 2: Construct Encoding Matrix

Encoding Matrix \mathbf{H} consists of one column per transmit event and the rows represents each element's corresponding phase shift:

$$\mathbf{H} = \begin{bmatrix} e^{-j\omega\tau_{1,1}} & e^{-j\omega\tau_{2,1}} & \dots & e^{-j\omega\tau_{N,1}} \\ e^{-j\omega\tau_{1,2}} & e^{-j\omega\tau_{2,2}} & \dots & e^{-j\omega\tau_{N,2}} \\ \vdots & \vdots & \ddots & \vdots \\ e^{-j\omega\tau_{1,M}} & e^{-j\omega\tau_{2,M}} & \dots & e^{-j\omega\tau_{N,M}} \end{bmatrix} \quad (7)$$

It is important to notice that matrix \mathbf{H} might not be square or full rank. This implies that there may be more or fewer transmit events than transducer elements.

Step 3: Define channel data

The signal channel data is represented by the Fourier Transform of the recorded echoes responses. For this case we will use $\mathbf{S} = [S_1, S_2, \dots, S_N]$ which is described by the following equation:

$$\mathbf{S} = \mathbf{UH} \quad (8)$$

Step 4: Element Isolation

This process involves applying the opposite phase shift $-\tau_{nT}$ for specific transmit element T to the channel data from each transmit event n and subsequently perform a coherent sum across all the transmit events. Conjugate transpose \mathbf{H}^* will produce the phase shifts:

$$\mathbf{H}^* = \begin{bmatrix} e^{-j\omega\tau_{1,1}} & e^{-j\omega\tau_{1,2}} & \dots & e^{-j\omega\tau_{1,M}} \\ e^{-j\omega\tau_{2,1}} & e^{-j\omega\tau_{2,2}} & \dots & e^{-j\omega\tau_{2,M}} \\ \vdots & \vdots & \ddots & \vdots \\ e^{-j\omega\tau_{N,1}} & e^{-j\omega\tau_{N,2}} & \dots & e^{-j\omega\tau_{N,M}} \end{bmatrix} \quad (9)$$

Matrix \mathbf{H}^* will be directly applied to our signal channel data to estimate the individual element contribution matrix $\hat{\mathbf{U}}$:

$$\hat{\mathbf{U}} = \mathbf{SH}^* = \mathbf{U}(\mathbf{HH}^*) \quad (10)$$

Step 5: Inverse Fourier Transform

$$\hat{u}_{TR}(t) = \text{IFFT}[\hat{U}(f, T, R)] \quad (11)$$

2.3 Beamforming Techniques

We will use a total of 2 beamforming methods to analyze the image quality

Synthetic Aperture Delay-and-Sum (DAS)

$$r_P = \sum_{T=1}^M \sum_{R=1}^M \hat{u}_{TR} \left(t = \frac{|TP| + |PR|}{c} \right) \quad (12)$$

Where we will have uniform apodization.

Synthetic Aperture Delay-and-Sum (DAS) with Coherence Factor

For contrast enhancement, we will use the Coherence Factor [4] by weighting the coherent signals:

$$\text{CF} = \frac{\left| \sum_{i=1}^M s_i \right|^2}{M \sum_{i=1}^M |s_i|^2} \quad (13)$$

2.4 Time domain REFOCUS mathematical derivations

Assume an ultrasound array with M elements, such that $T, R \in \{1, \dots, M\}$ and $n \in \{1, \dots, N\}$. Our main goal is to estimate the complete dataset by isolating all of the individual element contributions $u_{TR}(t)$. For our purposes it is convenient to create a matrix $\hat{\mathbf{U}}(t)$ containing all of the possible individual element contributions. This matrix is the so called ‘‘REFOCUS estimated complete dataset’’ and will be define as:

$$\hat{\mathbf{U}}(t) = \begin{bmatrix} \hat{u}_{11}(t) & \hat{u}_{12}(t) & \cdots & \hat{u}_{1M}(t) \\ \hat{u}_{21}(t) & \hat{u}_{22}(t) & \cdots & \hat{u}_{2M}(t) \\ \vdots & \vdots & \ddots & \vdots \\ \hat{u}_{M1}(t) & \hat{u}_{M2}(t) & \cdots & \hat{u}_{MM}(t) \end{bmatrix} \in \mathbb{R}^{M \times M} \quad (14)$$

Similarly, we can define the ground truth complete dataset as:

$$\mathbf{U}(t) = \begin{bmatrix} u_{11}(t) & u_{12}(t) & \cdots & u_{1M}(t) \\ u_{21}(t) & u_{22}(t) & \cdots & u_{2M}(t) \\ \vdots & \vdots & \ddots & \vdots \\ u_{M1}(t) & u_{M2}(t) & \cdots & u_{MM}(t) \end{bmatrix} \in \mathbb{R}^{M \times M} \quad (15)$$

Our first objective is to estimate the specific individual element contribution of T^* and R which we will denote as $\hat{u}_{T^*R}(t)$, then repeating the processing for all the different element pair contribution in matrix $\hat{\mathbf{U}}(t)$

By (3) and (4) we have:

$$s_{nR}(t) = \sum_{T=1}^M w_{nT} u_{TR}(t - \tau_{nT})$$

$$\tau_{nT} = \frac{|\overrightarrow{O_n F_n}| - |\overrightarrow{T F_n}|}{c}$$

Therefore, for a specific transmit element T^* applying reverse delay to $s_{nR}(t)$ gives:

$$s_{nR}(t + \tau_{nT^*}) = \sum_{T=1}^M w_{nT} u_{TR}(t + \tau_{nT^*} - \tau_{nT}) \quad (16)$$

A coherent sum across all transmits events $n \in \{1, \dots, N\}$:

$$\sum_{n=1}^N s_{nR}(t + \tau_{nT^*}) = \sum_{n=1}^N \sum_{T=1}^M w_{nT} u_{TR}(t + \tau_{nT^*} - \tau_{nT})$$

Expanding it gives:

$$\begin{aligned} &= \sum_{n=1}^N \left[w_{nT^*} u_{T^*R}(t + \tau_{nT^*} - \tau_{nT^*}) + \sum_{\substack{T=1 \\ T \neq T^*}}^M w_{nT} u_{TR}(t + \tau_{nT^*} - \tau_{nT}) \right] \\ &= \sum_{n=1}^N w_{nT^*} u_{T^*R}(t + \tau_{nT^*} - \tau_{nT^*}) + \sum_{n=1}^N \sum_{\substack{T=1 \\ T \neq T^*}}^M w_{nT} u_{TR}(t + \tau_{nT^*} - \tau_{nT}) \\ &= \sum_{n=1}^N w_{nT^*} u_{T^*R}(t) + \sum_{n=1}^N \sum_{\substack{T=1 \\ T \neq T^*}}^M w_{nT} u_{TR}(t + \tau_{nT^*} - \tau_{nT}) \\ &= u_{T^*R}(t) \sum_{n=1}^N w_{nT^*} + \sum_{n=1}^N \sum_{\substack{T=1 \\ T \neq T^*}}^M w_{nT} u_{TR}(t + \tau_{nT^*} - \tau_{nT}) \quad (17) \end{aligned}$$

Notice how terms at $T = T^*$ are aligned in time, which implies the summation of these terms will be coherent.

Aligned terms:

$$u_{T^*R}(t) \sum_{n=1}^N w_{nT^*}$$

On the other hand, $T \neq T^*$ implies we create a set of misaligned terms which when therefore be summed incoherently.

Misaligned terms:

$$\sum_{n=1}^N \sum_{\substack{T=1 \\ T \neq T^*}}^M w_{nT} u_{TR}(t + \tau_{nT^*} - \tau_{nT}) = \text{noise} \quad (18)$$

By (17) and (18) we can state:

$$\begin{aligned} \sum_{n=1}^N s_{nR}(t + \tau_{nT^*}) &\approx \sum_{n=1}^N w_{nT^*} u_{T^*R}(t) + \text{noise} \\ &= u_{T^*R}(t) \sum_{n=1}^N w_{nT^*} + \text{noise} \quad (19) \end{aligned}$$

Compensating for apodization w_{nT^*} gives:

$$\hat{u}_{T^*R}(t) = \frac{\sum_{n=1}^N s_{nR}(t + \tau_{nT^*})}{\sum_{n=1}^N w_{nT^*}} \quad (20)$$

By (19) and (20):

$$\begin{aligned} \hat{u}_{T^*R}(t) &= \frac{u_{T^*R}(t) \sum_{n=1}^N w_{nT^*} + \text{noise}}{\sum_{n=1}^N w_{nT^*}} \\ &= u_{T^*R}(t) + \frac{\text{noise}}{\sum_{n=1}^N w_{nT^*}} \\ &\approx u_{T^*R}(t) \end{aligned}$$

Hence, we have proved equation (5):

$$\hat{u}_{TR}(t) = \frac{\sum_{n=1}^N s_{nR}(t + \tau_{nT})}{\sum_{n=1}^N w_{nT}}$$

For all $T, R \in \{1, \dots, M\}$.

We have shown that REFOCUS can successfully estimate any ground truth element pair contribution $u_{TR}(t)$ and therefore it can also estimate the ground truth complete dataset matrix $\mathbf{U}(t)$.

2.5 Validation Methods

For Individual element pair validation, four transmit-receive element pairs will be tested: (1,1),(1,2),(8,8),(1,96). For each and every pair of elements we will use 3 different metric assessments to evaluate the algorithm reconstruction accuracy. Correlation coefficients will be use to evaluate signal similarity. Mean squared error will give more insights about the average deviation between the reconstructed signals and the ground truth. Lastly, maximum error is employed to help visualize the worst-scenario errors.

In order to accurately validate the beamformed image quality, log-scaled beamformed images will have a -60 to 0 dB dynamic range for the cyst case and point spread function (PSF) analysis. This set up will allow us to visually inspect image quality and make accurate assessments of the artifact's magnitude.

For further analysis of beamformed images, a PSF analysis module will also be implemented. This module will output a 4-panel figure that will contain both ground truth and refocused 2D PSF results, and lateral/axial profile graphs for better understand of the PSF cross-sections.

Lastly, with the goal of visualizing how FSA beamforming progressively constructs the final image as we increase the beams. This project will also include a coarse image analysis module, which will help identify any type of artifacts related to our beamforming implementation techniques.

3. Experimental Results

3.1 Cyst

For testing algorithms performance, we will compare the results the echoes responses of different transmit-receive element pairs for both the cyst ground truth and REFOCUS

estimated complete dataset. Results for Tx/Rx element pairs (1,1),(1,2),(8,8),(1,96) can be seen in figure 3-1 and table 3-1 from top to bottom, respectively.

Figure 3-1

Ground truth vs Estimated

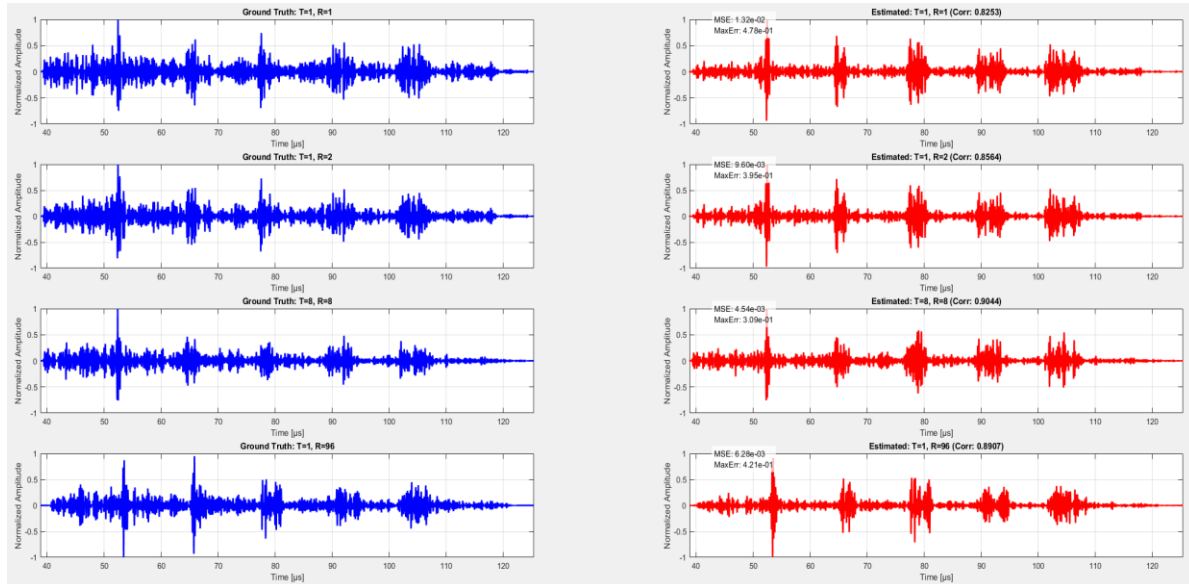


Table 3-1

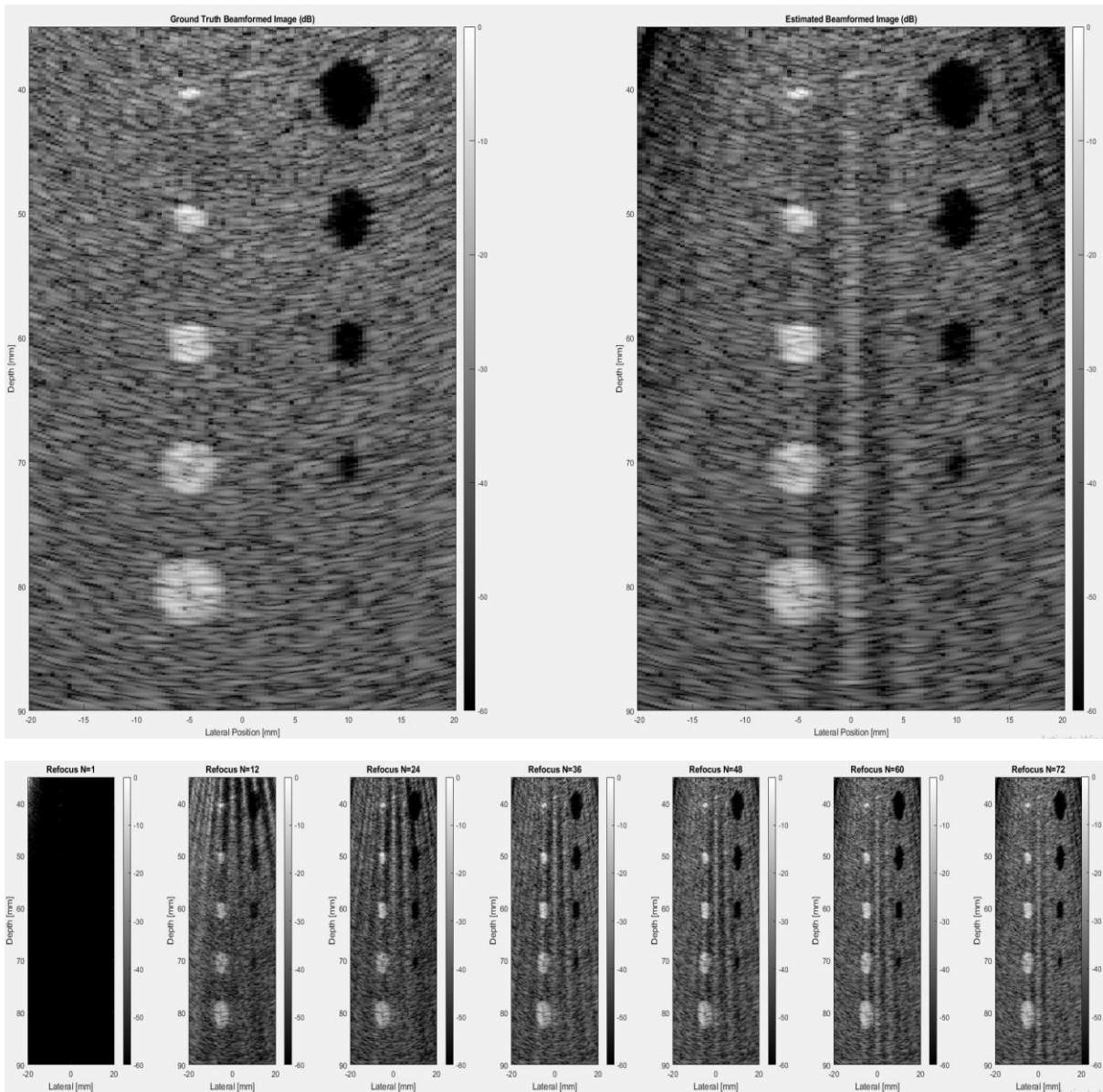
Element Pair	Correlation	MSE	Max Error
(1,1)	0.8252	1.32e-01	4.78e-01
(1,2)	0.8564	9.60e-03	3.95e-01
(8,8)	0.9044	4.54e-03	3.09e-01
(1,96)	0.8907	6.28e-03	4.21e-01

The beamforming images and coarse image analysis results are in figure 3-2.

From the beamforming results we can observe how our REFOCUS complete dataset synthetic aperture beamforming system successfully manage to generate an accurate enough cyst image. However, we can still see some line artifacts in the estimated image, specially in the top right/left corner as well as in the center. Line artifacts occur because of lack of enough simulated transmit events and elements array to cover the whole space. This is due to the high complexity of the REFOCUS algorithms which makes our system be hardware limited, only allowing us a maximum of 96-elements and 72 transmit events as mentioned before. Ideally to be able to cover the whole space on our cyst phantom we will need a total of 256-element array with 256 beams to perform a real full synthetic aperture (FSA) system. This ideal system will Our solution was to use slightly steered beams to cover the whole space with diagonal beams, (the use of diagonal beams is seen more clearly in the coarse images). However, although we manage to cover the whole space, using diagonal beams instead of straight down beams introduces line artifacts. More about our hardware and its limitations in section 3.4

Figure 3-2

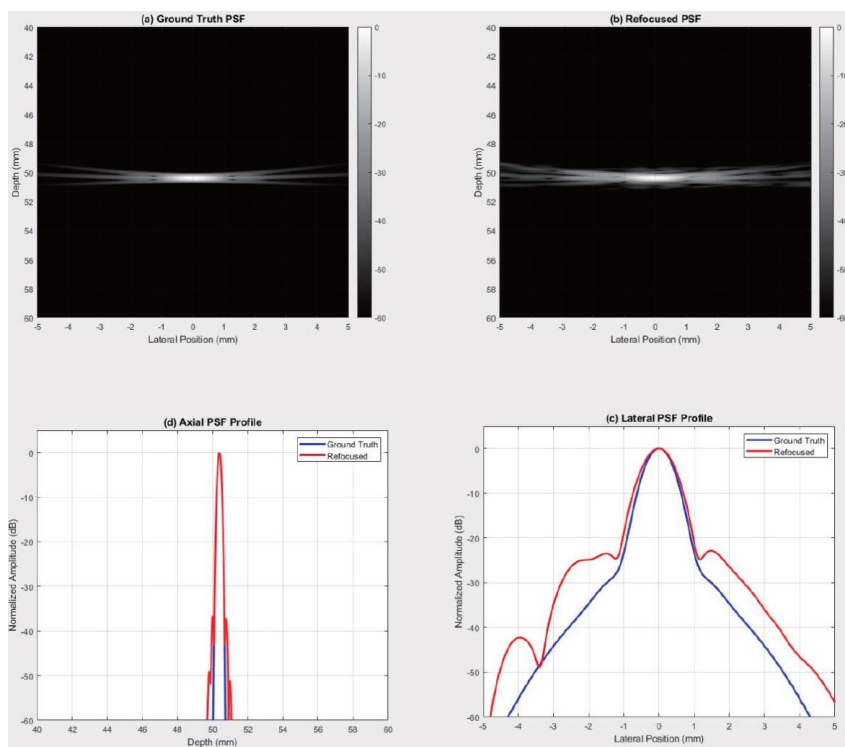
Ground truth vs Estimated (Time domain REFOCUS)



3.2 PSF

Point spread function (PSF) analysis revealed how the REFOCUS algorithm introduces sidelobes due to the out-of-phase errors. Sidelobes artifacts, can be clearly seen in the beamformed images and Lateral PSF profile (figure 3-3).

Figure 3-3: PSF analysis



3.3 Multiple point scatterers

The multiple point scatterer simulation aims to compare beamformed images generate with time and frequency domain REFOCUS's estimated complete datasets (see figure 3-4). I also intend to demonstrate how the Coherence Factor (CF) [4] can help us suppress the sidelobe artifacts previously mentioned in section 3.2 PSF (figure 3-5).

Figure 3-4

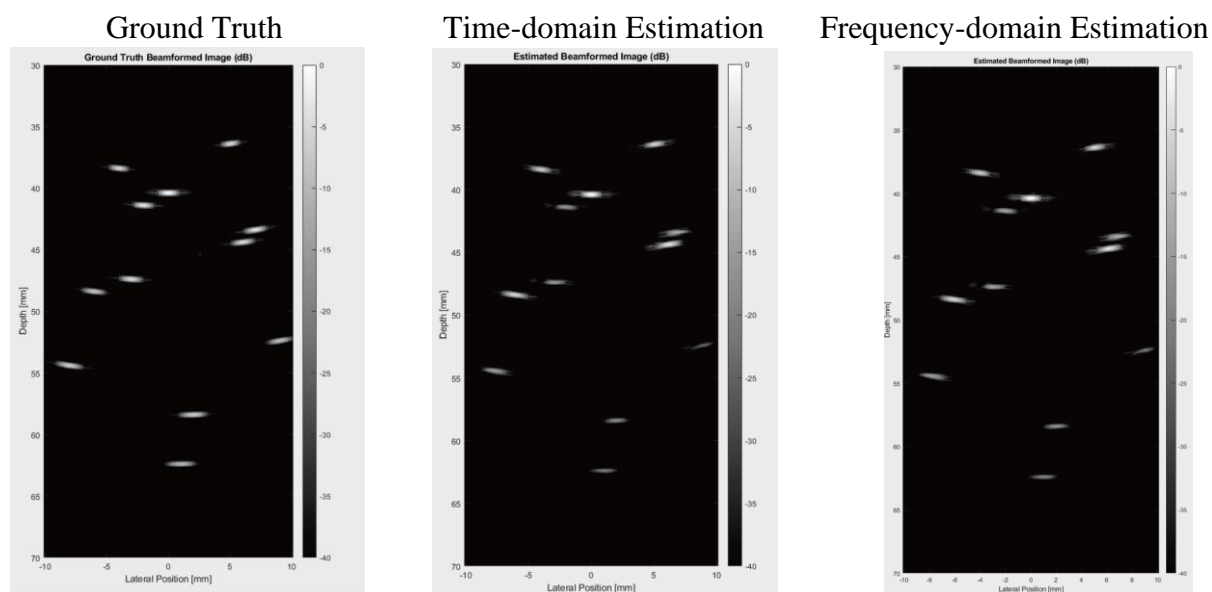
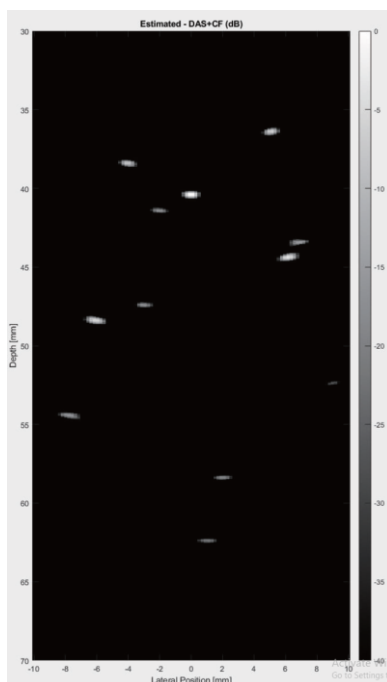


Figure 3-5

Frequency-domain Estimation + Coherence Factor (CF)



3.4 Software and Hardware

Software: The full implementation of REFOCUS was done in MATLAB R2021a using the ultrasound simulation toolbox Field II version 3.30 [2].

Hardware: Lenovo ThinkPad X1 Carbon 5th generation;
CPU intel i5-6300U, 8gb LPDDR3-1866, Intel HD Graphics 520

4. Conclusion

This implementation research project managed to test, validate and explore the limitations of the REFOCUS algorithm proposed by Bottenus's for the recovery of the complete dataset by using only focused transmit events. Time and frequency domain-based methods were implemented by using interpolation and phase shifts to calculate delays, showing how there are multiple ways to perform element isolation from focused transmit beams and therefore demonstrating how flexible the REFOCUS algorithm truly is. A fully functional framework was created in MATLAB based only on Bottenus's theoretical mathematical equations which allowed for the simulation of the algorithm.

Simulation results showed decent performance and accuracy across various types of simulation and imaging tests. Individual elements contributions more often that not exceed the 0.90 correlation coefficient for all imaging simulations with different complexity levels. Mean squared errors demonstrated how low the recovery and reconstruction error are. Sparse and dense transmit beams configuration were used to prove the high accuracy of the signal recovery process. Lastly beamformed images, although having decent results, showcased the biggest limitation of the REFOCUS algorithm, which will be the out-of-phase artifacts that cause destructive interference near bright cyst areas. This led us to discover that little phase alignment errors near high amplitude signal bright cyst can cause an uncoherent sum in regions close to this target and therefore create "dark line/streaks" artifacts. Coarse images

not only helped use analyze how image quality improves as the beam count increases, but it also further revealed the phase misaligned induced “dark lines/streaks” artifacts by showing how the image is progressively reconstructed.

Other limitations include how this is simulation-only system which doesn't include any experimental physics results where real physical ultrasound systems would be use for more accurate validation, implying that our results don't take into account real world errors such as variations on speed of sound, electronic noise and tissue attenuation. The REFOCUS algorithm also assumes the user knows the precise focal point location and speed of sound in the medium, which in the case of heterogenous tissues is highly unlikely because of the changes in acoustic velocity.

This research project completely validates that the complete data set can be acceptably recovered from focused transmit beams only, allowing synthetic aperture signal processing without the need of having specialized hardware. Being able to acquire the isolated individual element contributions from the channel data allows the use of different beamforming methods and image processing techniques. Both the frequency and time domain methods had near identical high accurate results, which not only proves both methods are mathematically equivalent, but also shows there are several ways for implementing the REFOCUS algorithm.

In conclusion, I believe this project provides many contributions for the REFOCUS algorithm implementation and testing methods, which I hope provides a basic foundation for further research in the area of computational ultrasound imaging.

5. References

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6. Project Management

Since this was an individual research project, all the different aspects of it were developed by the author. This includes any type of algorithmic research, MATLAB framework, implementation, validation, testing, and/or the documentation.

As for the MATLAB framework design, this could be divided in seven different code modules which each will independently handle different functional areas of the system. Starting with the “field2_settings.m” module, which manages the Field II simulation setup and configurations such as the impulse response definition, creation of transducers, and excitation single. The REFOCUS individual element isolation algorithm is mainly implemented in the “refocus_time.m” and “refocus_frequency.m” modules, which as their name imply, have to do with the time and frequency domain implementation of the algorithm by implementing interpolation and FFT based methods. The “validation.m” module handle the testing and validation of the accuracy on our reconstructed individual element contributions when compare to the ground truth. It computes validation metrics such as correlation coefficients, mean squared error, and maximum error. Any algorithm, technique or equation related to beamforming such as delay and sum (DAS) and coherence factor weighing, is computed by the “beamforming.m” module. For extra image analysis features this project also includes a “show_coarse_images.m” module which analyses the behavior of the image as we progressively reconstruct it, and we also included a “analyze_psf.m” module for greater understanding of the resolution characteristics and also to reveal any type of sidelobes or artifacts our ultrasound system may suffer from.

MATLAB R2021a was used as the primary development environment since it includes several useful functions such as the built-in interpolation interp1 function and plotting function. Great array computation and Fast Fourier Transform capabilities where other reasons why MATLAB was chosen for the implementation of this research project. Field II version 3.30, which is a popular ultrasound simulation toolbox, was chosen to provide us with realistic channel data and ground truth data for our REFOCUS algorithm.

Advisor Meng-Lin Li offered great guidance on various important aspects that noticeably improve the quality of the workflow. Proper spatial sampling was discussed in detail to ensure the prevention of aliasing artifacts and therefore ensure correct image reconstruction at all regions. Testing and validation methodologies were all heavily influenced by my advisor recommendation on proper methods for assessing algorithms accuracy, this includes validation techniques such as: echoes signal graphs analysis, coarse image analysis for diagnosis on out-of-phase artifacts and point spread function analysis for testing REFOCUS performance of point targets outside the focal zone. Prof. Li also provide me with feedback on report and poster structure, ensuring the appropriate use of different figures and table to effectively communicating the results of the project