Bradley University

Department of Electrical and Computer Engineering

Ultrasonic Imaging using Resolution Enhancement Compression and Synthetic Aperture Focusing Techniques

Project Proposal

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Abstract

Ever since the 1940's, ultrasonic imaging has been a key part of diagnostic medicine due to low cost, portability, and low health risks to the patient. Due to the ultrasonic mechanism, however, the resulting image may be significantly blurred by the characteristics of the system. To mitigate this effect, two different classes of imaging techniques will be utilized. Resolution Enhancement Compression (REC) is a pulse compression technique which will be used to improve the axial resolution and signal to noise ratio (SNR) of the images. To improve the lateral resolution and SNR, a variety of synthetic aperture focusing techniques (SAFT) may be used. The overall goal of this study is to investigate the effects of combining the REC technique with the various SAFT to best improve the image quality, using the MATLAB (Mathworks Inc., Natick, MA) addon Field II to produce ultrasound simulations, and a General Purpose Graphics Processing Unit (GPGPU) to reduce computation time. Improving these characteristics should allow a physician to observe smaller lesions in the tissue, potentially resulting in earlier detection of cancer.

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1 Project Description

The resolution of the image is a metric for measuring the spread of a point in the image. In the case of 2D ultrasound, there are two components to resolution. Axial resolution describes the point spread along the beam axis, while lateral resolution describes the point spread of the position parallel to the transducer surface. SNR is the traditional metric for comparing the signal strength relative to the residual echo noise, given by

$$SNR = \frac{P_s}{P_n}, \tag{1}$$

where P_s and P_n are the powers of the signal and the noise respectively.

To improve the axial resolution and SNR of the system, a novel pulse compression technique may be used. The REC technique uses the idea of convolution equivalence to effectively exchange the impulse response of the ultrasonic transducer, $h_t(n)$, with a desired impulse response, $h_d(n)$, which may have desirable qualities such as an increased bandwidth. In previous studies, the REC technique has been shown to yield remarkable increases in axial resolution by a factor of 2 [1, 2].

To improve the lateral resolution and SNR of the system, a variety of synthetic aperture focusing techniques (SAFT) will be studied. Synthetic aperture refers to artificially creating a focusing aperture by selectively choosing the transducer elements utilized on transmit and receive [3]. These signals are then recombined using delay and sum beamforming. Three different variations of SAFT are of interest:

- Generic Synthetic Aperture Ultrasound (GSAU)
- Synthetic Receive Aperture Ultrasound (SRAU)
- Synthetic Transmit Aperture Ultrasound (STAU)

These techniques complement the REC technique discussed above, which improves the axial resolution and SNR of the image. By combining REC with any of the SAFT variants, the overall ultrasound quality should be increased, leading to more accurate diagnostic images.

2 System Block Diagram

The complete system block diagram is shown in Fig. 1. Each subsystem will be analyzed in detail in the following sections.

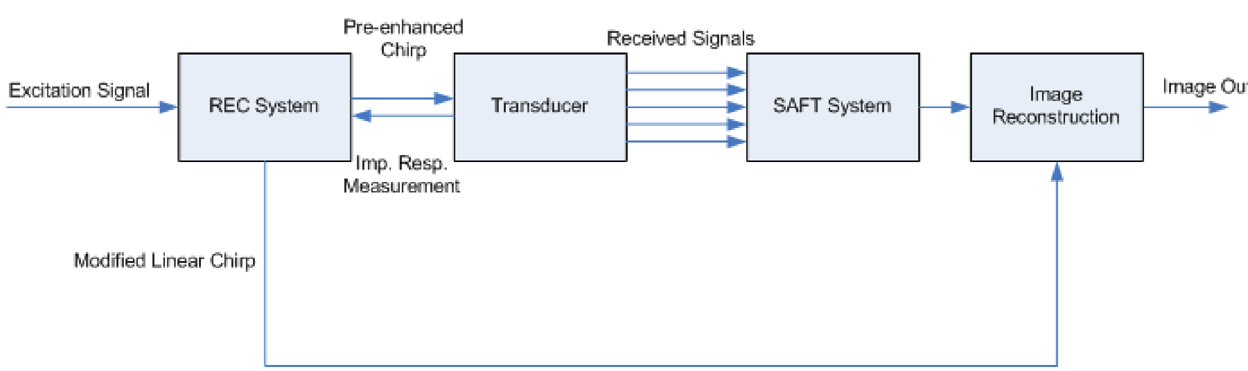


Figure 1: Top Level System Block Diagram

2.1 REC

Using the REC technique, it is possible to effectively replace the transducer's pulse-echo impulse response, $h_t(n)$, with a desired impulse response, $h_d(n)$. This desired impulse response is engineered to have more desirable properties, such as an increased bandwidth, which translates into an improvement in axial resolution [1, 2]. The driving idea behind REC is the convolution equivalence principle, which is illustrated in Fig. 2. By exciting the transducer with a pre-enhanced chirp, $v_{pc}(n)$, the resulting echo will have a response that is equivalent to a linear chirp, $v_{lc}(n)$, convolved with a desired impulse response.

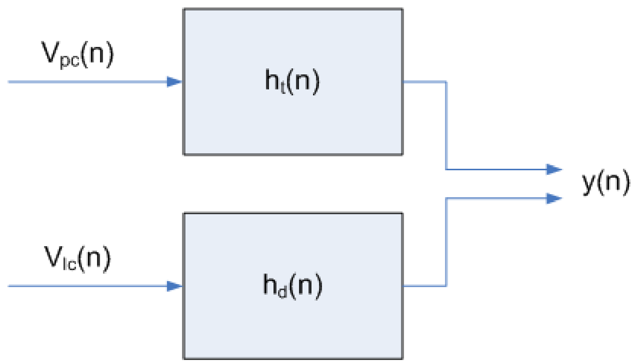


Figure 2: Illustration of Convolution Equivalence Principle

The primary task involved with the REC system is the generation of the pre-enhanced chirp. The REC system takes an unwindowed linear chirp, $v_{ulc}(n)$, as an input. This chirp is passed through a compression filter which has a frequency response given by

$$G_1(f) = \frac{H_t^*(f)H_d(f)}{|H_t(f)|^2 + |H_t(f)|^{-2}}, \tag{2}$$

where $H_d(f) = \mathscr{F}\{h_d(n)\}$, $H_t(f) = \mathscr{F}\{h_t(n)\}$, and $\mathscr{F}\{\cdot\}$ denotes the discrete Fourier transform. The expression shown in (2) is an approximation for the ideal pulse compression filter given by $G_1'(f) = \frac{H_d(f)}{H_t(f)}$, which in general cannot be used due to the potential for instability. This filtering operation will generate an unwindowed pre-enhanced chirp with spectrum denoted by $V_{upc}(f)$. The pre-enhanced chirp will then be windowed in the sample domain by a Tukey cosine window, $w(n)$, such that $v_{pc}(n)$ will be given by

$$v_{pc}(n) = v_{upc}(n)w(n). \tag{3}$$

The expression for a Tukey cosine window [1] of length N and rolloff factor α is given by

$$w(n) = \begin{cases} 1 & 0 \le |n| \le \frac{N}{2}(1+\alpha) \\ 0.5\left[\cos\left(\pi\frac{n-\frac{N}{2}(1+\alpha)}{N(1-\alpha)}\right)\right] & \frac{N}{2}(1+\alpha) \le |n| \le N. \end{cases} \tag{4}$$

However, since the Tukey window modifies the pre-enhanced chirp, convolution equivalence with $v_{ulc}(n)$ no longer holds true. Therefore, a modified linear chirp with frequency response $V_{lc}(f)$ must be generated from the pre-enhanced chirp by passing it through a second filter which has a frequency response given by

$$G_2(f) = \frac{H_t(f)}{H_d(f)}. \tag{5}$$

The block diagram for the REC subsystem is given in Fig. 3.

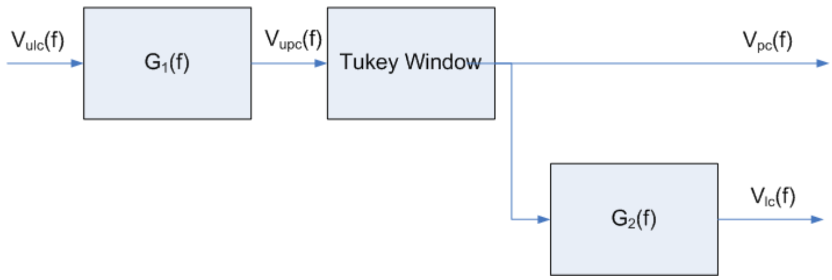


Figure 3: REC Subsystem

2.2 Transducer

The ultrasonic transducer is the component which converts electrical signals to ultrasonic pulses. For this project, a linear array transducer will be simulated. A linear array transducer is composed of several ultrasonic elements which may transmit and receive independently of one another. A depiction of a linear array transducer is shown in Fig. 4. The transducer specifications are given in Table 1.

Table 1: Transducer Specs

Center frequency:	8 MHz
Sampling frequency:	200 Mhz
Element height:	4 mm
Element width:	260 μm
Element kerf:	40 μm
Number of elements:	256
Focus:	20 mm

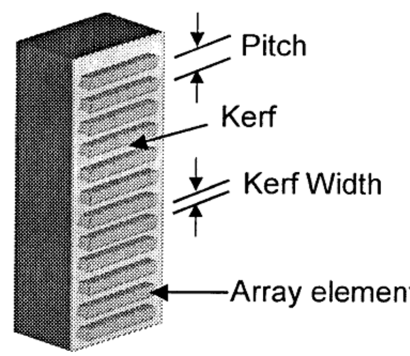


Figure 4: Linear Array Transducer [4]

2.3 SAFT

The SAFT subsystem is depicted in Fig. 5. It is composed of two parts: apodization and delay and sum beamforming. Apodization is the spatial windowing scheme that is used to shape the beam profile. This shaping is achieved by multiplying each received scan line by a different apodization coefficient in accordance with an apodization scheme. Several different apodization schemes may be studied, including rectangular, triangular, and raised cosine shapes. The overall goal of apodization is to reduce the side lobes of the scan lines, which may introduce artifacts into the image. This reduction of side lobes will come at the expense of widening the main lobe, resulting in a loss of resolution.

The second component of the SAFT subsystem is the delay and sum beamforming. Delay and sum beamforming utilizes the spatial information received in each of the scan lines to focus the image. However, because the total distance the echo pulse travels from each element to a specific point in space is different, the received signals must be delayed to compensate. The calculation of the delays will be different depending on which type of SAFT is used, and thus will be discussed in the following sections.

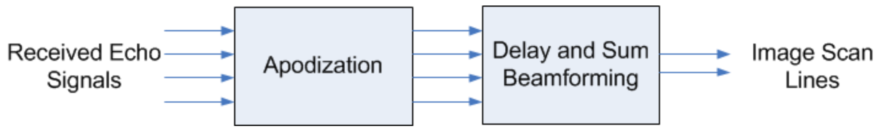


Figure 5: This diagram corresponds to a SAFT with a two element transducer. Because SAFT produces N_{xdc} copies of the image before beamforming, the number of scan lines is reduced by a factor of N_{xdc} after beamforming.

2.3.1 GSAU

The simplest type of SAFT is generic synthetic aperture ultrasound (GSAU). With the GSAU technique, each ultrasonic transducer element is utilized one at a time for both the transmit and receive operations. This results in N_{xdc} transmit events, where N_{xdc} is the number of elements in the transducer. Modeling the tissue sample as a collection of point scatterers, the received signal of the i^{th} element is given by

$$r_i(t) = \sum_p \sigma_p g(t - \tau_i) \tag{6}$$

where σ_p is the back-scattering coefficient of the tissue at the point $\vec{r_p} = (x_p, z_p)$, and $g(t)$ is the excitation signal. The delay τ_i is given by

$$\tau_i = 2\frac{|\vec{r_i} - \vec{r_p}|}{c}. \tag{7}$$

where c is the speed of sound in tissue, which is approximately 1,540 m/s. The factor of 2 present in (7) is due to the fact that the pulse travels the same distance twice round trip. By compensating for these delays in each of the received signals and summing them together, it is possible to reconstruct the image at each point $\vec{r_p}$. This technique is depicted in Fig. 6.

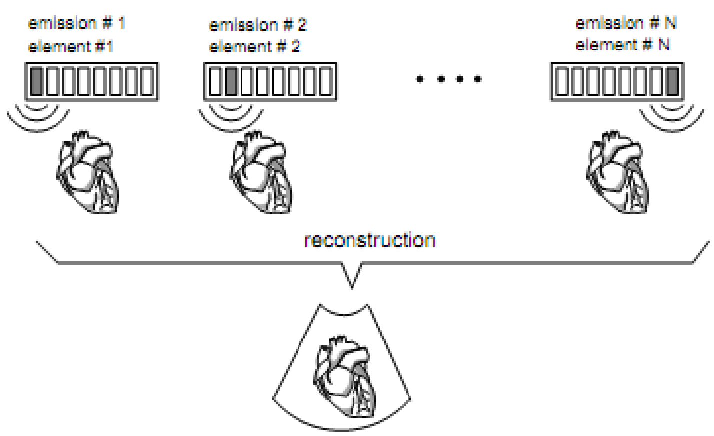


Figure 6: GSAU System [3]

2.3.2 STAU

The STAU technique differs from the GSAU technique in that instead of only receiving on one element each transmit event, it receives with all simultaneously. This adds another degree of freedom to the received signals. Thus the expression for the received signal $r_{ij}(t)$ with the i^{th} element transmitting and the j^{th} element receiving is given by

$$r_{ij}(t) = \sum_{p} \sigma_p g(t - \tau_{ij}), \tag{8}$$

where τ_{ij} is given by

$$\tau_{ij} = \frac{|\vec{r_i} - \vec{r_p}| + |\vec{r_j} - \vec{r_p}|}{c}. \tag{9}$$

The resulting signals can thus be combined into scan lines $L_i(t)$ corresponding to each event. The expression for the i^{th} scan line is given by

$$L_i(t) = \sum_{j=1}^{N_{xdc}} a_{ij} r_{ij}(t - \tau_{ij}), \tag{10}$$

where a_{ij} is the apodization coefficient for the transmit-receive pair. Once the scan lines have all been beamformed, high resolution lines $H_i(t)$ can be beamformed by summing as shown in (11).

$$H_i(t) = \sum_{i=1}^{N_{xdc}} L_i(t) \tag{11}$$

These resulting high resolution scan lines correspond to the image output. This technique is shown in Fig. 7.

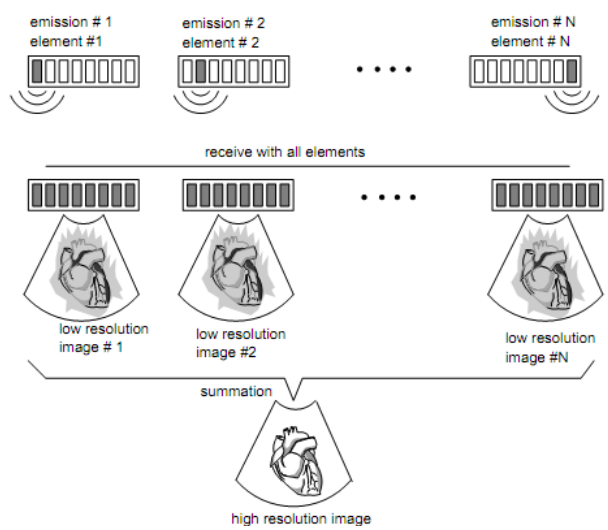


Figure 7: STAU System [3]

2.3.3 SRAU

The SRAU technique consists of transmitting on all of the elements simultaneously and only receiving on one element each transmit event. During the transmit, all of the elements focus along one scan line. The received signals are then delay and sum beamformed as was done in the STAU case to form a high resolution scan line. The process is then repeated for N_l different scan lines, which are concatenated to form an image. This is depicted in Fig. 8.

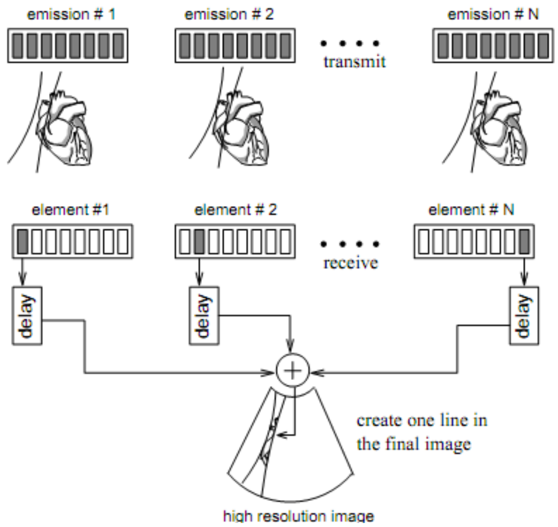


Figure 8: SRAU System [3]

2.4 Image Reconstruction System

Once the output has been fully beamformed using one of the techniques described above, the resulting output may be processed through the image reconstruction system as shown in Fig. 9.

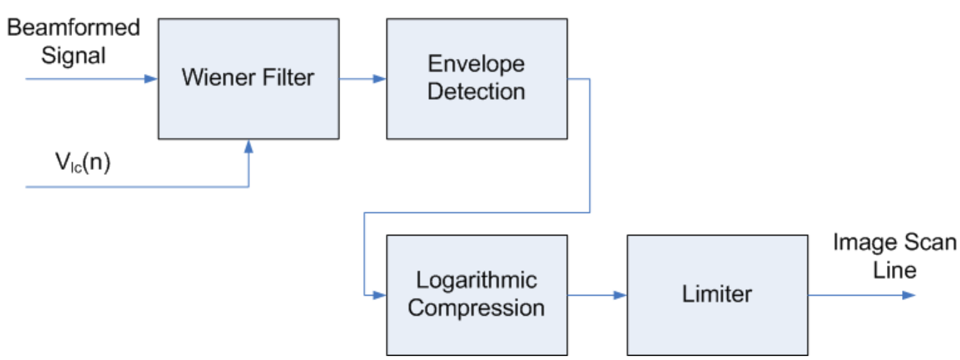


Figure 9: Image Reconstruction System

First, the beamformed signal is passed through a Wiener filter to remove the spectrum of the linear chirp. The Wiener filter will be characterized by the transfer function in (12) [1].

$$\beta_{REC}(f) = \frac{V^*_{lc}(f)}{|V_{lc}(f)|^2 + \gamma \overline{eSNR}(f)} \tag{12}$$

The γ factor is a parameter that can be tuned to fit the appropriate response, but was usually set to

1 in [1]. The $\overline{eSNR}(f)$ term describes the average eSNR per frequency channel, which is equivalent to

$$\overline{eSNR}(f) = \frac{|H_{2c}(f)|^2 E\{|F(f)|^2\}}{E\{|\eta(f)|^2\}}, \tag{13}$$

where $|F(f)|^2$ is the power spectral density (PSD) of the measured object function, $|\eta(f)|^2$ is the PSD of the noise, and $|H_{2c}(f)|^2$ is the PSD of the ensemble average of the compressed signal over noise, $h_{2c}(n) = E\{v_{PC}(n)\}$ [1]. More information about the Wiener filter chosen can be found in [1, 2].

For the envelope detection, the magnitude of complex envelope of the received signal is calculated using the `hilbert()` function in MATLAB. The resulting output is logarithmically compressed into the decibel scale via $20\log_{10}(\cdot)$. This output is then limited to a -50 to 0 dB range after normalizing all the signals to the maximum of the image.

3 Preliminary Progress

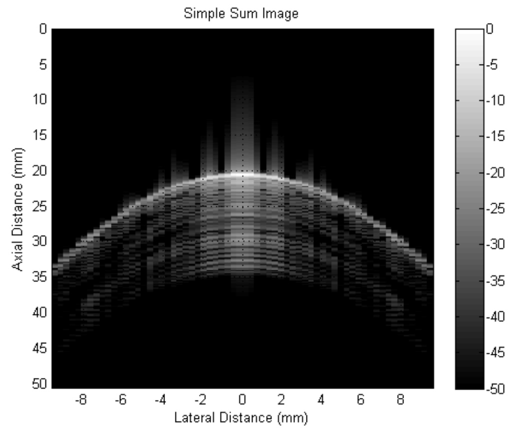
Throughout the first semester, a significant amount of progress was made in the areas of image generation and STAU.

3.1 Image Generation

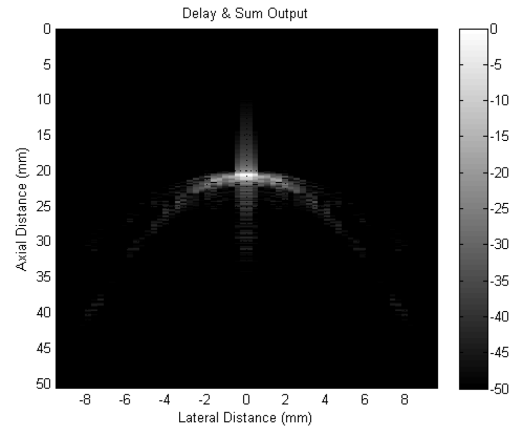
The first step to simulating an ultrasound system is to generate software to simulate the imaging process. The physical modeling of the ultrasound system response will be processed in MATLAB addon Field II, a standard tool in ultrasound simulation. The rest of the post processing necessary to generate an image consists of delay and sum beamforming, envelope detection, and logarithmic compression. The delay and sum beamforming is somewhat dependent on the type of SAFT studied, and will be the primary component of future work in the cases of the GSAU and SRAU techniques. However, both the envelope detection and logarithmic compression have been implemented successfully and are not dependent on the type of SAFT utilized.

3.2 STAU

In the case of STAU, sequential delay and sum beamforming code has been written in MATLAB. However, because this does not yet utilize the parallel processing capabilities of the GPGPU, running this code is particularly time consuming. Due to this long processing time, only a 64 element transducer has been simulated thus far using the STAU technique. Without the delay and sum beamforming, a simple sum of the STAU images produced significant glare as shown in Fig. 10a on page 8. The delay and sum output of the STAU images depicts a much more focused beam as shown in Fig. 10b.



(a) This is a simple sum of the STAU images without the delay and sum beamforming. The image of the point at 20 mm is heavily corrupted by residual echo.



(b) This is the result generated using the STAU technique. This image was taken of a point scatterer centered 20 mm away from the transducer.

4 Future Work

Future work will be done in the areas of REC and each of the SAFT variants, described in the following sections.

4.1 REC

The main components yet to be finished related to the REC system are the pre-enhanced chirp filter ($G_1(f)$), the modified linear chirp filter ($G_2(f)$), and the Wiener filter described in (12). These filters will be implemented using the Fast Fourier Transform (FFT) and Inverse FFT (IFFT) functions to generate the appropriate responses.

4.2 STAU

Future work to be done with the STAU technique includes experimental evaluation of the SNR and lateral resolution. Images with more points should also be analyzed to ensure accuracy of the imaging algorithm. Additionally, because this image was only generated using 64 transducer elements to reduce computation time during the debugging process, the same image must be processed using a 256 element transducer as previously discussed.

4.3 GSAU

The GSAU technique involves generating images by transmitting and receiving on one transducer element at a time. It would appear that Field II is capable of generating the signals for this technique, since physically this is equivalent to moving a one-element transducer by a distance equivalent to the element width for each scan. The delay and sum beamforming code may share some similarities with the STAU technique, which may make it easier to develop.

4.4 SRAU

Generation of the SRAU scan lines can be generated in a method similar to the GSAU technique described above, only using N_{xdc} element transducer. Unlike in the STAU technique, each received signal will correspond to a low resolution scan line, which then may be summed together to form a high resolution scan line after beamforming.

5 Schedule

The tentative schedule for next semester is shown in Fig. 10.

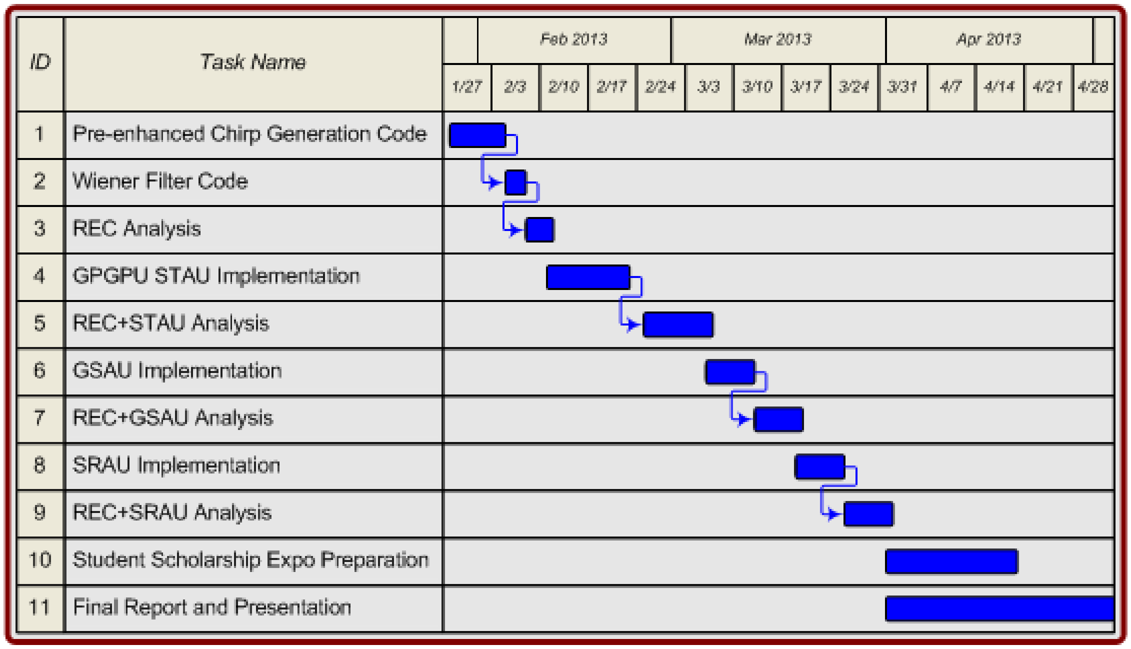


Figure 10: Tentative Schedule for Spring 2013

6 Equipment List

There are two computers in the department that need to be utilized to perform the simulations. Because Field II is only supported on Matlab 2007, a dedicated Field II machine has been set up for generating the received transducer signals. Due to the numerous computations involved in the delay and sum beamforming for a 256 element transducer, the beamforming will have to be done in parallel on a General Purpose Graphics Processing Unit (GPGPU). There is a custom built computer with an NVIDIA Quadro 5000 GPU available for this type of work, the specifications for which are available in Table 2.

Table 2: GPGPU Specifications

Number CUDA cores:	352
Graphics clock:	513 MHz
Processor Clock:	1026 MHz
Dedicated RAM:	2560 MB GDDR5

7 Acknowledgements

The author would like to thank Dr. José Sánchez for his support and guidance this semester.

8 References

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