Acoustic Lens Design
Design Description Document
URMC / Navalgund Rao

Ryan Sauer	Project Coordinator
Nancy Aguilera	Customer Liaison
Daniel Graney	Scribe
Yichen Gu	Document Handler
Prof. Wayne Knox	Faculty Advisor

Document Number 01

Revision Level	Date
K	5-5-2018

This is a computer-generated document. The electronic master is the official revision. Paper copies are for reference only. Paper copies may be authenticated for specifically stated purposes in the authentication block.	Authentication Block

Revision History

Rev	Description	Date
A	Updated PRD to fit new format and added progress made over winter break	1-21-2018
B	Updated plastic material properties,	1-31-2018
C	Added Depth of Field Test and Fresnel K-Wave	2-2-2018
D	Added Fresnel Lens Tests	2-8-2018
E	Elaborated on Fresnel Lens Testing Procedure	2-14-2018
F	Included Additional Data from Tests	2-19-2018
G	Added Fresnel Testing Results, Major formatting changes, Expanded on background section, Updated timeline,	2-25-2018
H	Added Possible Reflection Solutions, Updated References, Further updated timeline, Added Appendix IV, More Major formatting changes	2-27-1018
I	Added Final Fresnel Lens section, Added Improved Non-Fresnel Lens Design, Updated Timeline, Added Appendix V	4-1-2018
J	Major Formatting Changes, Updated many older sections, Added many new sections	5-4-2018
K	Updated K-Wave information, Conclusion written, small updates to other sections	5-5-2018

Table of Contents

Acknowledgements

Prof. Navalgund Rao

Prof. Wayne Knox

Bhargava Chinni

James Alkins

Per Adamson

Introduction

The photoacoustic imaging system has gone through several iterations as a senior design project. Previous groups have been responsible for various portions of the design process, from the laser delivery system currently used to providing a model for the 3D printed material within the Code V design software. Our current objective is to build upon these previous works to design the lens system for an imaging probe used in detection of cancer within the thyroid (in vivo) and more specifically explore the capabilities of a Fresnel lens in this configuration.

Background

As one might expect, a photoacoustic imaging system has many differences to a typical optical system. The system of this project in particular uses a laser pulse administered into a patient's thyroid, the “photo-” of “photoacoustic”, which then creates an ultrasound wave which propagates through a water-filled imaging probe and is imaged onto a transducer array via acoustic lens(es), the “-acoustic” part of “photoacoustic”.

The acoustic domain of imaging has many limitations and allowances which the optical domain does not. The most noteworthy allowance which is taken advantage of in the current system is brought on by the six-orders-of-magnitude lower speed of an ultrasonic wave in water in comparison to light in air. The acoustic transducers used in this system are able to capture images in microsecond intervals, and as such, can capture hundreds of images per single laser pulse administered, with ultrasonic waves formed from the parts of the sample closer to the imaging probe being imaged before those further from it. These images can then be processed and joined together to create a three dimensional image with different layers representing different planes within the patient's thyroid, and as such requires a lens which can perform well over a significant depth of field (around 5 to 10 mm in either direction of the image plane).

Another major difference which must be taken into consideration during the design process is the amount of signal lost when a wave passes through the lens. In optics, absorption within the lens is practically negligible when it is not wanted, while in the set up used in this project, attenuation is one of the primary concerns, resulting in thicker lenses having far less signal reaching the sensor than thinner ones. This problem brings up the question of how to minimize the thickness of the lens without having too much of a loss in image quality. Such a dilemma invites the possible usage of a Fresnel lens, which greatly reduces the overall thickness of a lens (especially off-axis) while maintaining the curvature of its surface. Fresnel lenses are primarily used in optics for illumination, as their image quality is quite limited in the optical domain, but this is not necessarily true in acoustics.

Lastly, the selection of possible materials to use in acoustics is far different than that of optics, with the main elements dictating material selection being the acoustic velocity and acoustic impedance. The ultrasonic velocity within an acoustic material is analogous to the the speed of light in an optical material, with the difference between a lens's internal velocity and the surrounding medium's dictating the curvature needed for a specific focal length, with a greater difference allowing for a lower curvature. Due to the velocity of sound in water being greater than that of the lens material, the shape of a simple lens is opposite to that of optics, with a biconcave lens having a positive focal length and a biconvex being negative. The acoustic impedance relates to how much an ultrasonic wave transmits or reflects when passing through mediums, and the ideal acoustic impedance of a lens' material in the current system being identical to that of water which would have all sound transmitting. Fortunately, the acoustic velocity and impedance required of the current system, as well as ultrasound waves being far less sensitive to surface roughness than visible light waves, allow the use of 3D printed plastics, which further allows far faster fabrication speeds and far lower costs than any well-functioning lens in optics.

Design Plan

We have two design directions. The first one is to keep the shape of the initial design and change it to be a Fresnel shape. In this case, the optical path length would not differ a lot from edge to center. The second one is to jump out of single lens system and make two lenses to split power of each surface, and if the addition of a second lens benefits the system, then we will look into incorporating the Fresnel lens structure to two lenses.

Design Constraints

The following tables show the design constraints for the project established in the Fall semester for the Product Requirement Document.

Single Fresnel Lens Design Constraints	
Lens Diameter	32 mm
Outer Edge of Lens	Additional 2 mm lip to attach to casing
Field (Image)	22.4 mm object diameter
Wavelength	150-450 μm with 300 μm as primary
Magnification	1x
Transducer Size	12.5 mm x 10.4 mm [1]
Transducer Element Size	2 mm x 2 mm [1]
Nyquist Frequency	.25 lp/mm
Elements	1
Length	< 160 mm
Object Clearance	~ 80 mm
Airspace Material	All "airspaces" are water immersed
Movability of Sensor and Lens	Adjustable during testing, fixed in final device

Laser Specifications	
Laser Used	EKSPLA Inc NT-352A[2]
Wavelength	790 nm
Laser Exposure	13 mJ / cm^2
Pulse Duration and Repetition Rate	5 ns and 10 Hz

Two Lens Design Constraints	
Lens Diameters	32 mm
Outer Edge of Lenses	Additional 2 mm lip to attach to casing
Field (Image)	22.4 mm object diameter
Wavelength	150-450 µm with 300 µm as primary
Magnification	≤ 1x
Transducer Size	12.5 mm x 10.4 mm [1]
Transducer Element Size	2 mm x 2 mm [1]
Nyquist Frequency	.25 lp/mm
Elements	2
Length	< 160 mm
Object Clearance	10 - 20 mm
Image Clearance	> 14 mm
Airspace Material	All “airspaces” are water immersed
Movability of Sensor and Lens	Adjustable during testing, fixed in final device

Customer’s 3D Printer and Plastic Specifications	
Printer Used	ProX 800 [2]
3D Printer Resolution	0.25 - 0.38 mm
Plastic Used	Accura 25 (SLA)[3]
Acoustic Velocity in Plastic	2.43 mm/µs
Acoustic Attenuation	~75% across 3 mm sample*

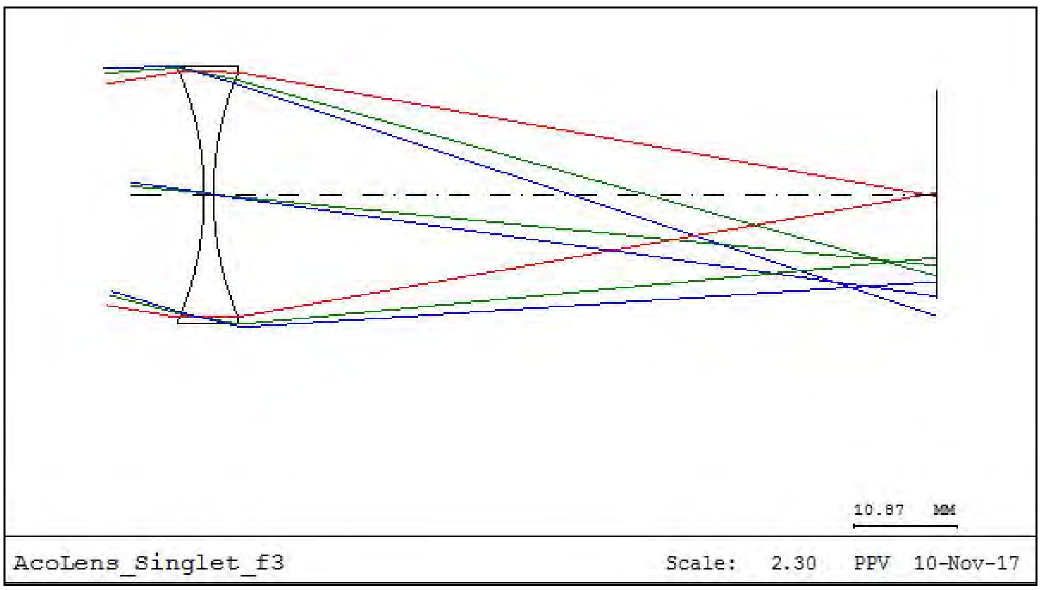
Rettner's 3D Printer and Plastic Specifications	
Printer Used	Objet 30 Pro [4]
Layer Thickness	.023 mm
Printer Resolution	X-axis: 600 dpi Y-axis: 600 dpi Z-axis: 900 dpi
Plastic Used	VeroClear
Acoustic Velocity in Plastic	2.41 mm/μs
Acoustic Attenuation	~90% across 3 mm sample*

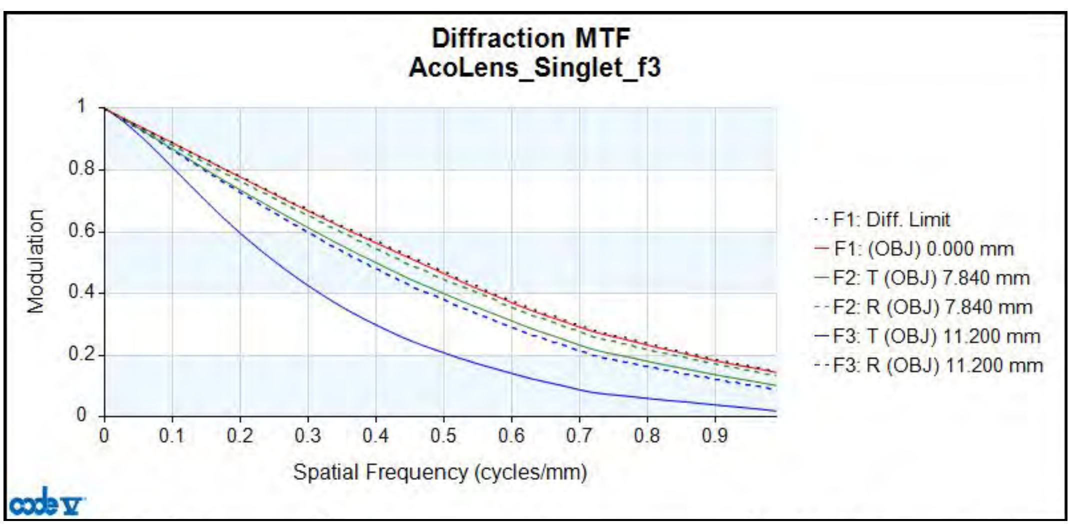
*Found experimentally with plastic test sample described later.

Starting Solution

The following are screenshots from Code V detailing the solution provided to us by Prof. Rao. It is worth noting that the Diffraction MTF for any of the segments from this point onward are not necessarily accurate, as the lenses are functioning in the acoustic domain and the software is made for the optical domain. It is included primarily as a reference.

Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	80.0000 V		Refract	O
1		Sphere	-33.5000	1.0000	'pedro'	Refract	13.5977 O
Stop		Sphere	33.5000	79.5252 S		Refract	12.9424 O
Image		Sphere	Infinity	-2.9284 V		Refract	12.8376 O
End Of Data							

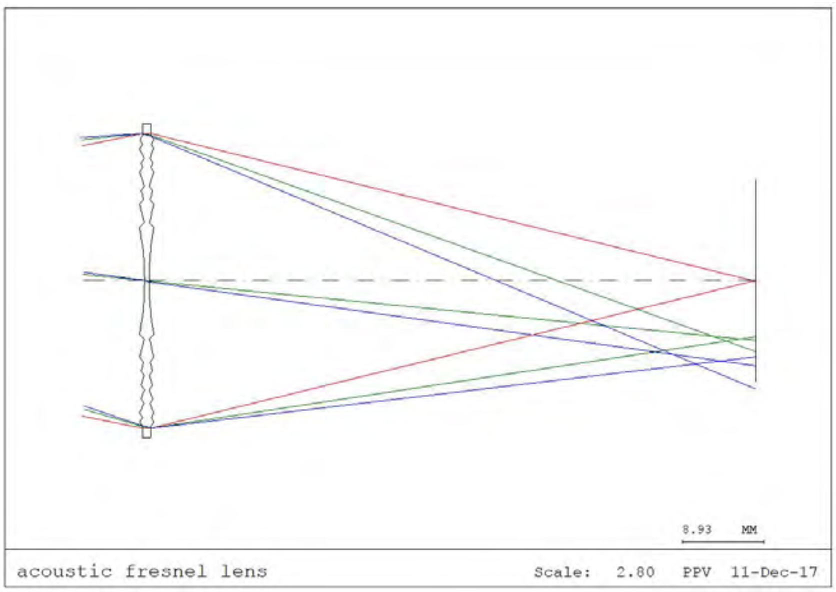


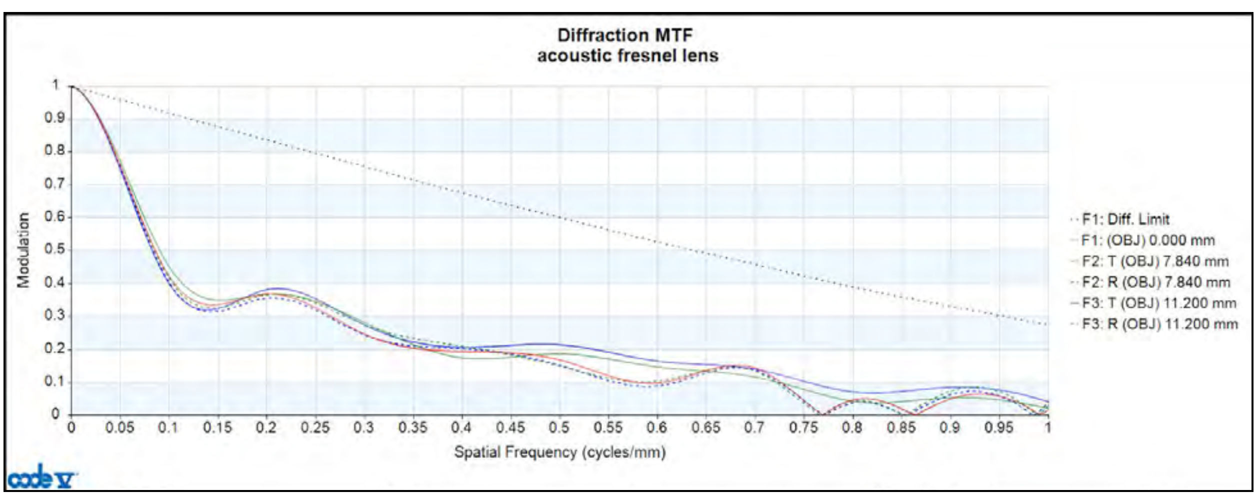


Initial Fresnel Design

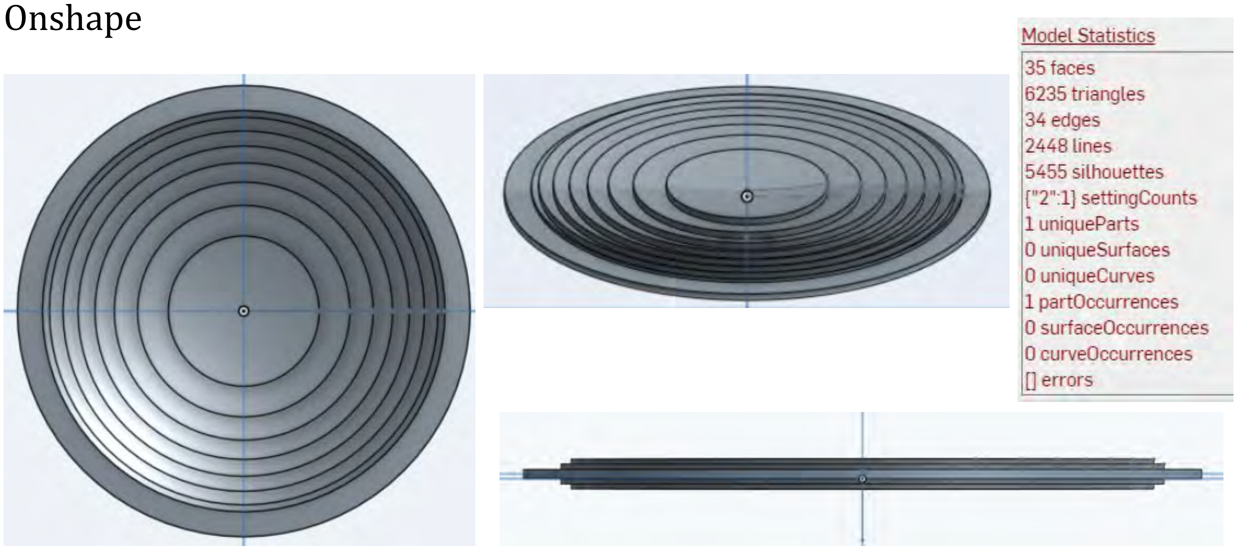
As the sample Fresnel design (included in Appendix I) was more of a test of how to make a Fresnel lens rather than the optimal design, we went back to Code V and updated the design varying the zone sag (the step height of each Fresnel ring) and the center thickness and image distance. The following are screen caps of Code V which show the updated parameters. The optimal zone sag (to the nearest 10 microns) was found to be 0.54 mm. The lens was then 3D modelled in Onshape and printed.

Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	80.0000		Refract	O
Stop		Fresnel Pl	-33.5000	0.5000	'pedro'	Refract	16.0000 O
2		Fresnel Pl	33.5000	79.5252 S		Refract	16.0000 O
Image		Sphere	Infinity	-13.0000 V		Refract	11.8236 O
End Of Data							

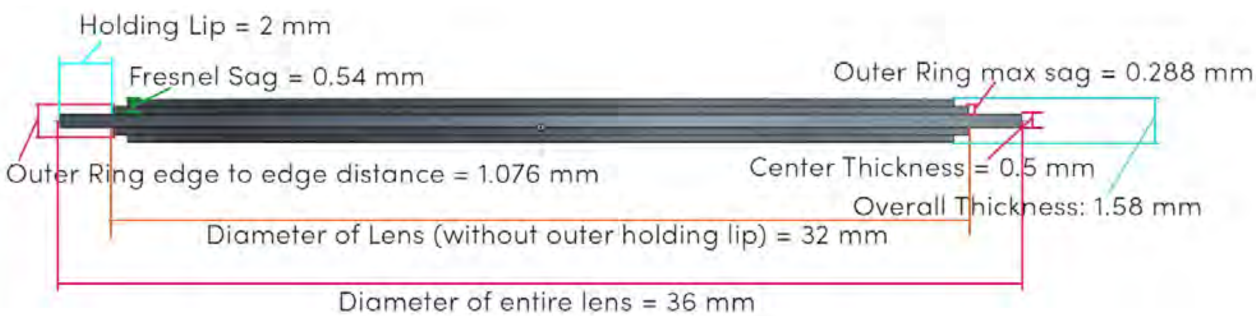


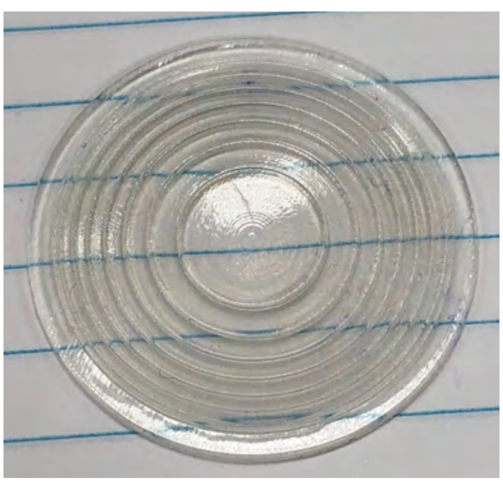


Onshape



The above is a screenshot of the design in Onshape, the CAD software recommended to us by Jim Alkins, the head of Rettner Fabrication Studio and our 3D printing advisor. For a brief explanation of how the Onshape model was made, see Appendix V. Below is a more detailed dimensional labelling of the lens.

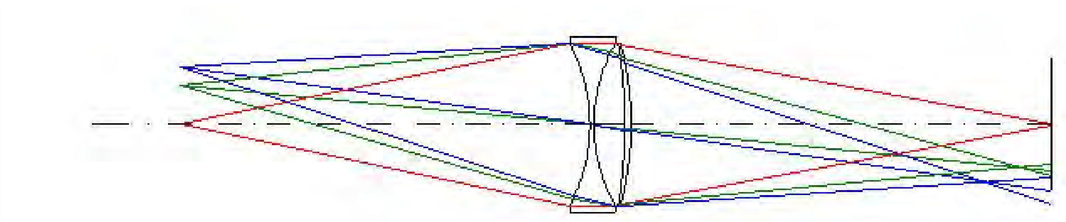


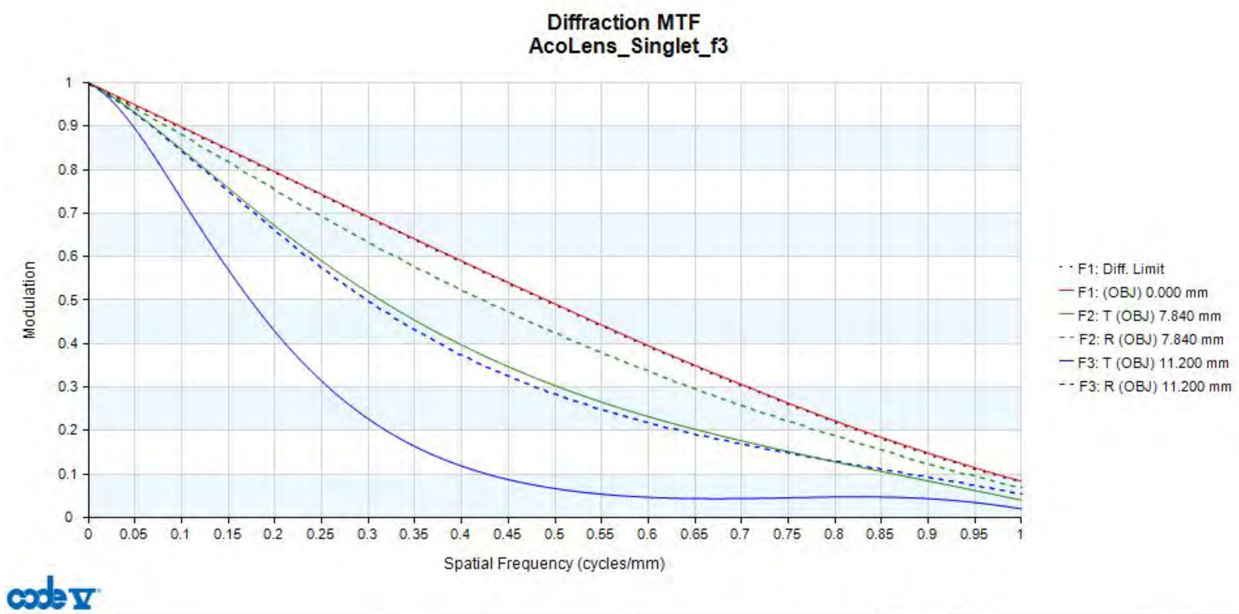


The image to the left is of the printed lens. As the material used is clear (ie it transmits light of the visible spectrum), this positive acoustic lens also acts as a negative optical lens. As the lens is quite thin, an extra copy was printed (as the material cost and time to fabricate were low) to be used as a hands on demo within class presentations of the project.

Two Lens Design

The first approach on the two lens design is not as optimal as thought. Normally, in optics area, a two lens system should work better than 1 lens system. However, after 6 hours of optimization, we cannot get out a design which is better than the original design.





The requirement says that Doctor Rao wanted the first lens that is close to the object so that it collects signals more effectively than the 2f design. However, such design is never possible in a non-veignetting condition. And when the first lens is close to the object, as aperture is the first surface, edge views will vignette very hard. In another word, few signal will go to the detector. We talked with Doctor Rao about that and he agreed that requirement is just his assumption. And he is surprised to know that no matter what to do with the two lens system. The single lens system seems to be the best solution at this point.

More simply put, the “aperture stop” in a submerged acoustic system must be a surface of the lens, as the usual obstructions like used in optics have no simple acoustic equivalent.

Improved Fresnel Lens Design

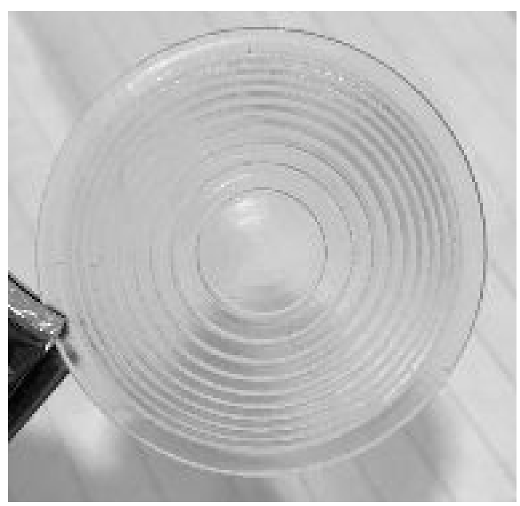
The previous iterations of the Fresnel lens were based on Code V's MTF evaluations of them, and since Code V was more of a convenient basic way of modelling the lenses and not really based on acoustic theory, we instead looked into acoustic literature and found a similar Fresnel acoustic lens attempt (which had a few differences such as materials). The formula goes as follows:

$$h = \frac{1}{Nf(1/v_l - 1/v_s)}$$

Where N is the phase number, (delay angle = 2π/N)
f is frequency
v_s is velocity in liquid
v_s is velocity in solid

In our project, we use 5 MHz frequency. V_l is 1500m/s and V_s is 2410m/s. According to the paper "*High Efficiency Fresnel Acoustic Lenses*"[5], both N = 2, 4 were put into the equation and we have a sag of 0.1986 mm for 4 phase and 0.3973 mm for 2 phase. This paper reported that the 4 phase step size was more efficient, though due to the number of rings being doubled (by halving the sag, see Appendix VI for plots of this relation), the 0.4mm zone sag was decided on for use as to not add greater dependence on 3D printer resolution.

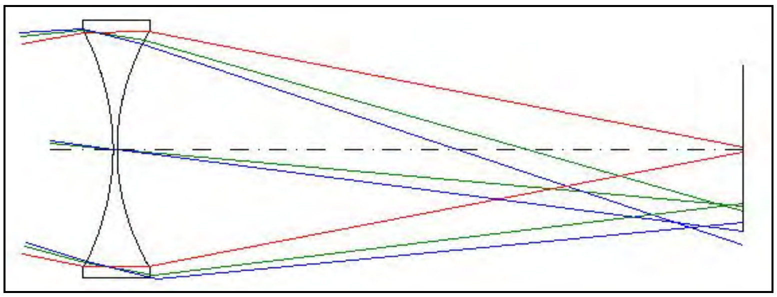
The lens was again modelled in Onshape and 3D printed by Jim in Rettner Fabrication Studio using the VeroClear material in the Objet 30 Pro printer.

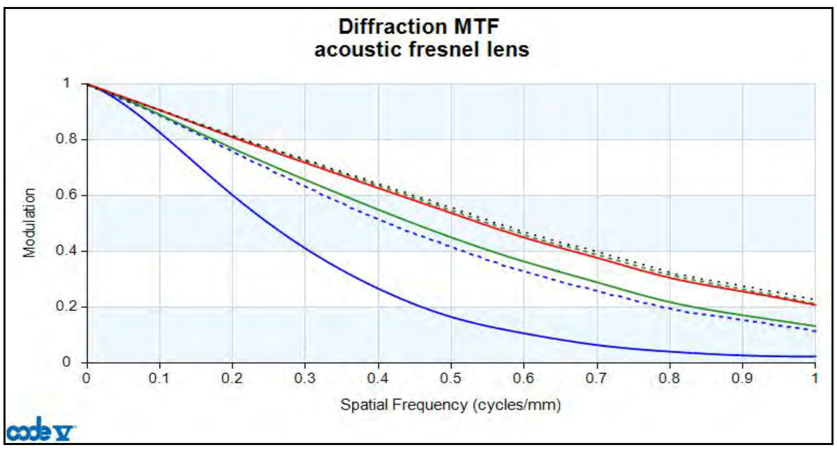


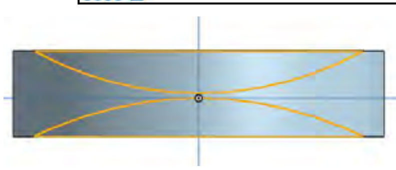
Improved Non-Fresnel Lens Design

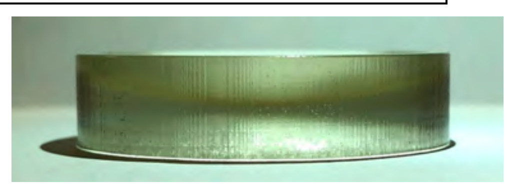
In Code V, we reduced the center thickness and added some optimized aspheric terms (which were of fairly low magnitude). The Code V MTF of this lens is roughly the same as the starting solution, but being thinner should make this lens have noticeably less attenuation. The lens has been modelled in Onshape and 3D printed.

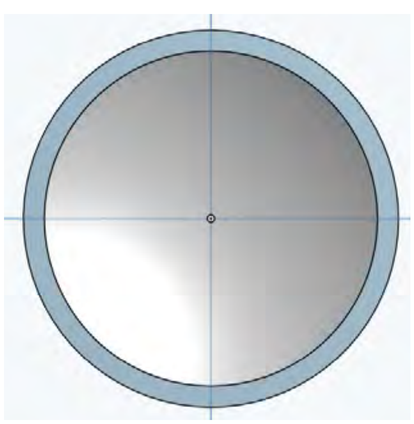
Due to its close similarities to the starting solution, our customer decided not to test it, so any improvements this lens might have had are not experimentally shown.





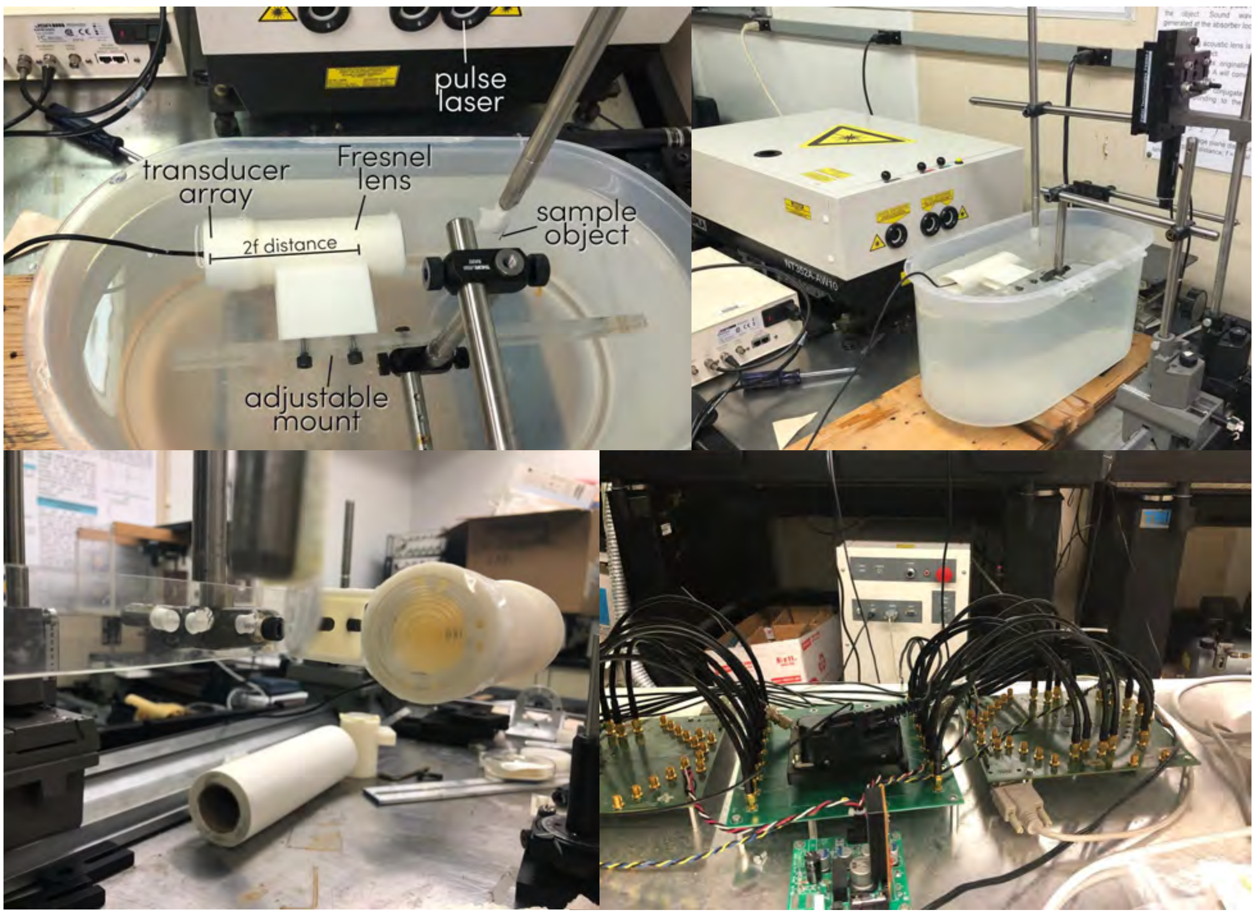






Testing Setup for Lenses

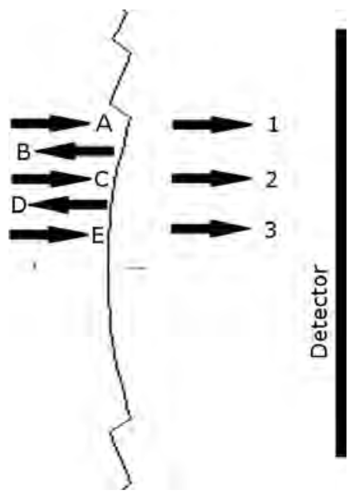
The lens being tested is attached to the end of the tube containing the transducer (at a distance of 2f of approximately 80 mm). A laser pulse is administered into the sample object (that can be varied depending on what the test is trying to evaluate), which emits an ultrasonic wave (of approximately 300 micron wavelength) which is then focused by the lens onto the transducer array which captures data used in the next section. The mount the transducer and lens are attached to can be easily adjusted between tests to find the object distance of best focus which in turn allows for additional depth of field information.

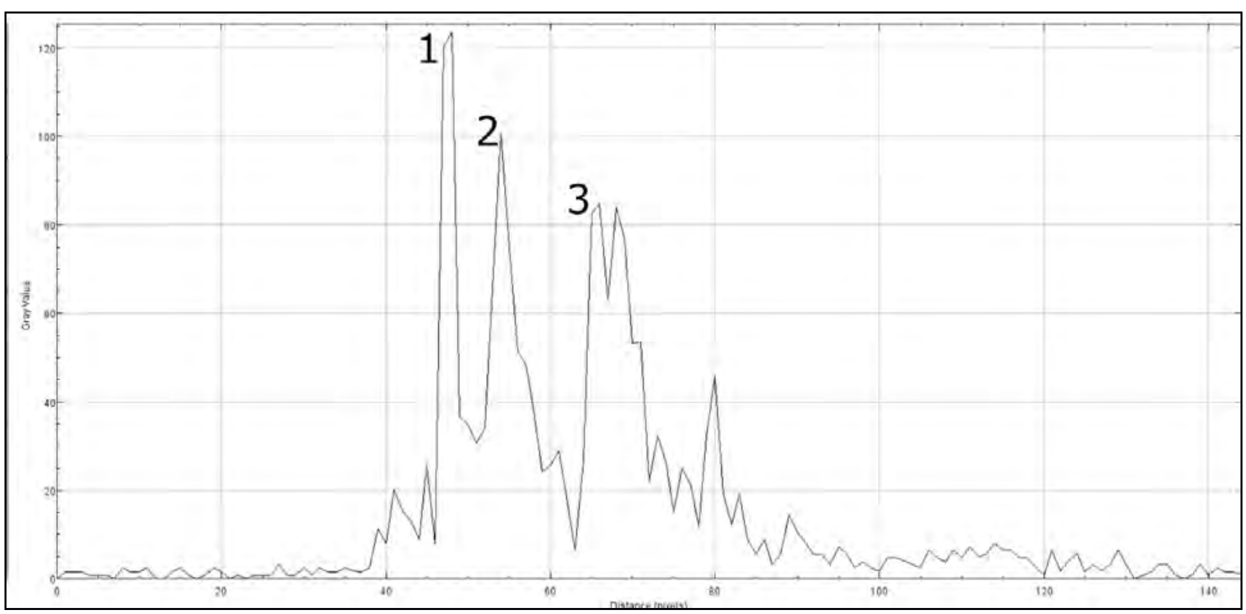


Results of Lens Tests

Results of Initial Fresnel Lens Tests

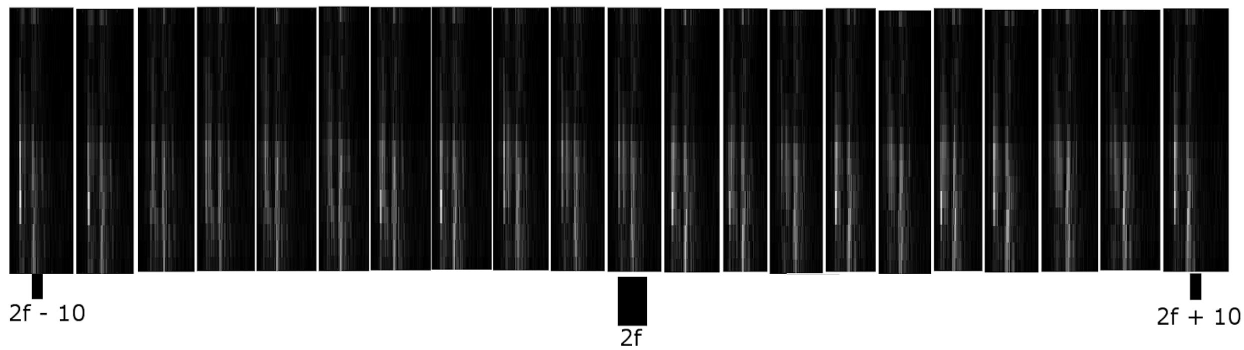
After testing the Fresnel lens with a 0.2 and 0.7 mm source, we were given quite a bit of interesting data regarding the depth of field of the Fresnel lens as well as the performance of the Fresnel lens. One notable performance issue is that the detector is receiving multiple transmission peaks for a single signal. We believe this issue arises from multiple reflections inside the Fresnel lens. This is illustrated below along with the averaged detector data using imageJ. Note that the Fresnel lens is not to scale and what is shown is solely for illustration.





The signal A transmits through the lens as signal 1 and signal B is the reflected portion of signal A. Signal B then reflects on the other side of the Fresnel lens and this is illustrated as signal C. Signal C transmits through the lens as signal 2 and this repeats multiple times through the lens. Signals 1, 2, and 3 are all then received on the detector and are visible in the above detector data (signal received per time unit).

Below is the relevant detector data for the depth of field tests on the Fresnel lens. The "object" was moved from 2f - 10 mm to 2f + 10 mm.



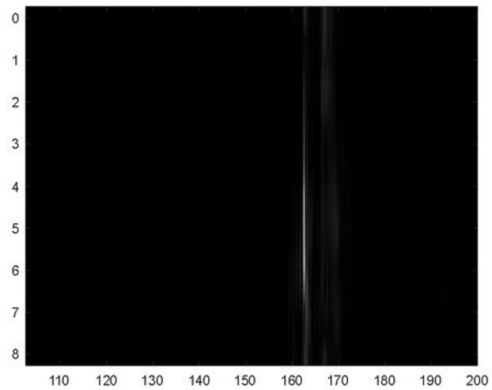
For each sub-image, the x-axis is time and the y-axis is an element of the detector array. We can again see the effects of multiple signals being received from reflections inside the lens. Below is a table relating FWHM with the edge object location.

Object Location	FWHM
2f - 10 mm	~1.45 mm
2f	~1.40 mm
2f + 10 mm	~0.90 mm

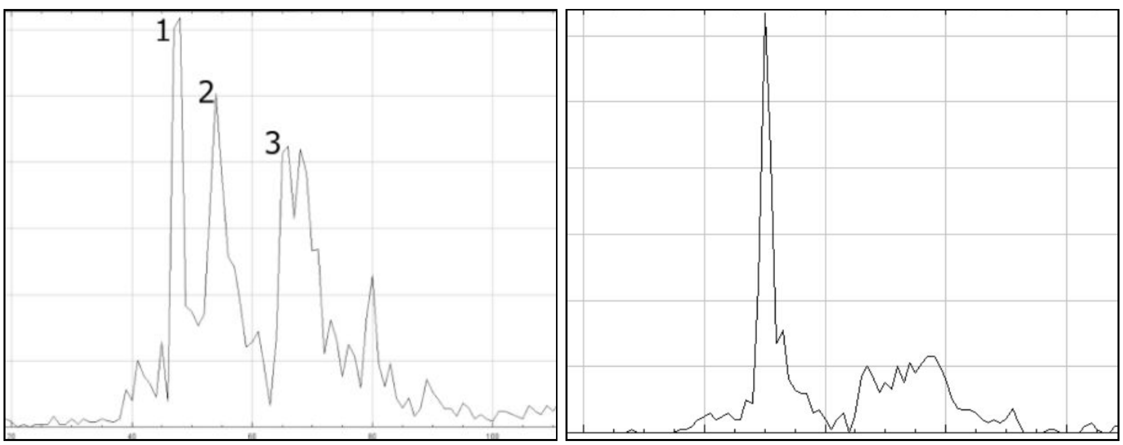
It is worth mentioning that object locations between these showed in the above table exist and their FWHM values vary in a non-linear form with object location. Appendix VII has more info as to potential solutions we originally came up with before changing the sag values.

Results of Improved Fresnel Lens Tests

After changing the zone sag to 0.4 mm in the Fresnel lens design and 3D printing it, a B-mode image was taken similar to the testing done in the initial Fresnel design test. This is shown below.



The test provided promising results when compared to the initial Fresnel design test. Below compares two zoomed A-line signals over time (where an A-line signal is like a horizontal slice of the above B-mode image).



It is clear from these plots that the signal is much cleaner in the improved Fresnel design as the existence of multiple peaks from the initial design is no longer seen in the improved design. However, a secondary signal is seen a bit after the initial peak, meaning that we are not getting the full signal at the peak. Because of this secondary signal, we are still unable to get as clean of a signal as that of the starting design.

One way to overcome the existence of this secondary signal is to utilize time gating to ignore all signal after that initial peak. Unfortunately, due to this time gating, we potentially lose vital depth information which somewhat defeats the purpose of this application. Therefore, as far as viably using this improved Fresnel lens for imaging, we must bring that secondary signal back into the peak signal (to maximize energy) or discover a way such that the secondary signal does not make it to the transducer.

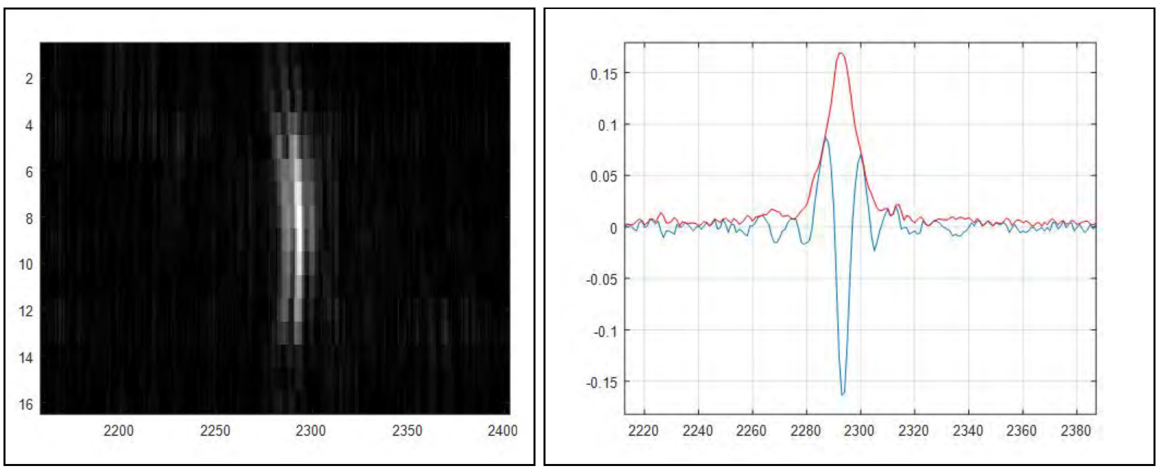
Attenuation Testing Results

In order to properly evaluate the relative attenuation of the different designs, the original biconcave lens (which was previously re-printed using the VeroClear material in order to explore whether or not the VeroClear material was what was causing the multiple peaks in the signal, see Appendix IV), and the two Fresnel lenses (with 0.54 mm and 0.4 mm zone sags) were individually tested under nearly identical circumstances, with each lens fixed at the same distance from the sample object and a transducer located just behind the lens to capture all the being transmitted.

As the purpose of the test was to *compare* the energy transmitted, the units of the measurements need only be defined relative to one another and as such are labelled as just 'arbitrary units'.

Remade Original Lens

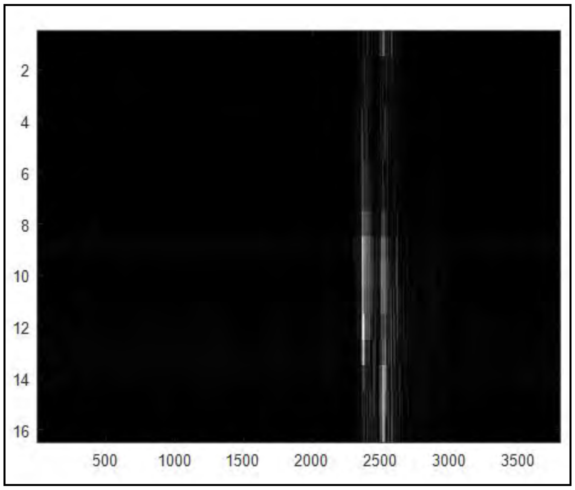
The VeroClear version of the original lens serves as the baseline for characterizing the attenuation of the system. The following are figures are the relative signal amplitudes of each pixel across the relevant data (left) and the total of all pixels at a given time (right)

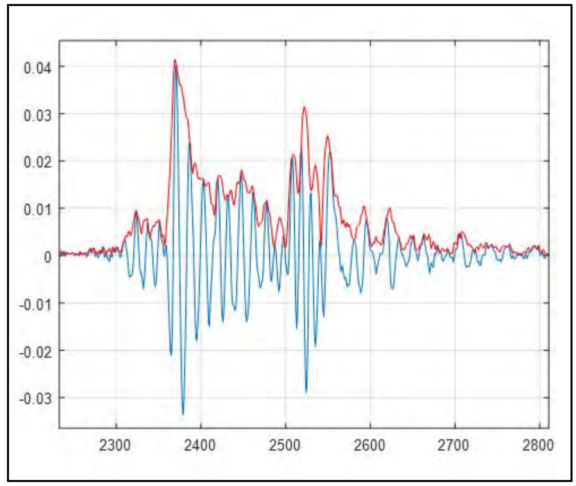


The total energy transmitted through this lens was found to be 18.6 arbitrary units.

Initial Fresnel Lens -- 0.54 mm zone sag

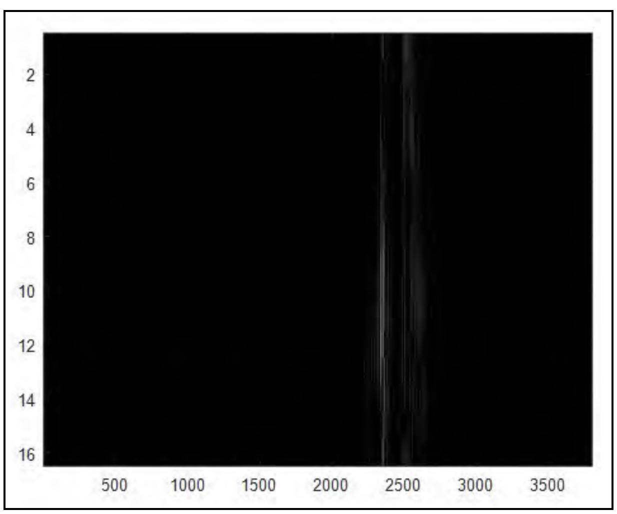
The total energy transmitted through the initial Fresnel lens was found to be significantly higher, at 106.7 arbitrary units or ~5.7x that of the starting lens. The amount of this signal which is of use is brought into question as Prof. Rao believes the slower signal and peaks to be created by shear/transverse waves which are not imagable with this system, as shear waves in plastic travel ~⅓ as fast as the usual longitudinal waves.

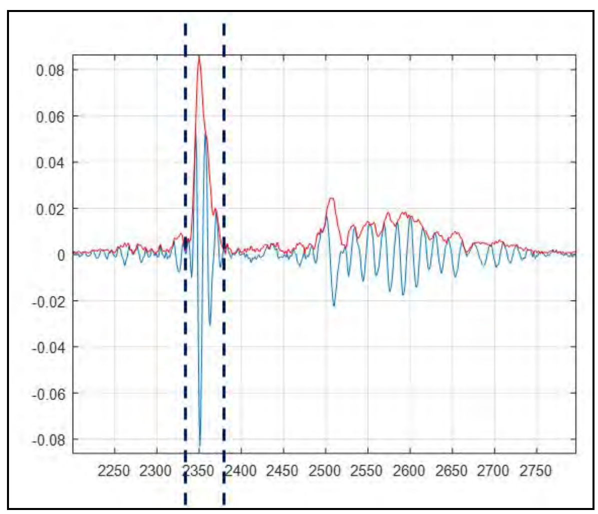




Improved Fresnel Lens -- 0.4 mm zone sag

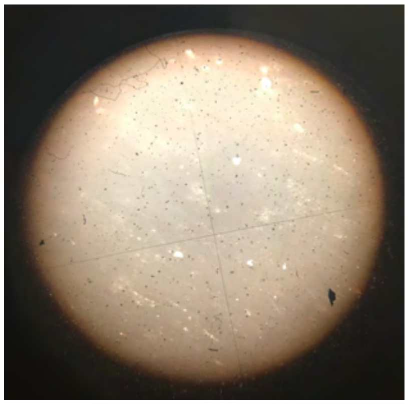
The total transmitted energy for the improved Fresnel lens is just slightly higher than that of the initial Fresnel lens, at 107.6 arbitrary units (which is again ~5.7x that of the original biconcave lens), but unlike the previous lens, the imagable, longitudinal wave peak seen by the transducer can be isolated. The two dotted black lines denote this peak and the signal between at those times was totalled to 30.0 arbitrary units, making the useful data captured by this lens to be ~1.6x that of the original biconcave lens.



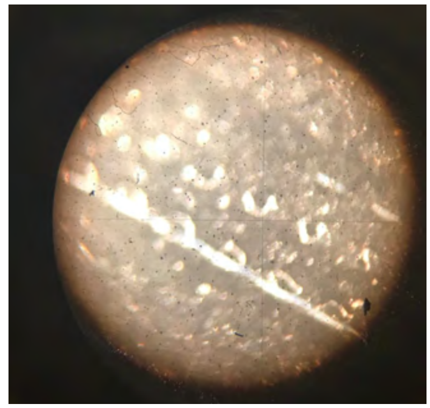


Surface Quality Observations

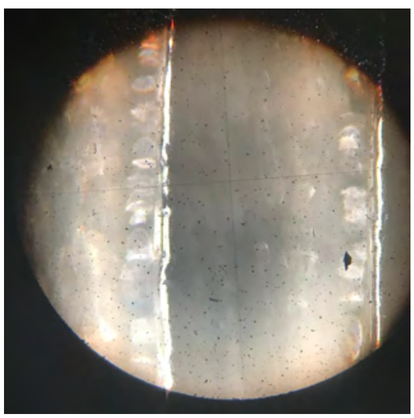
The results from the testing of the 0.4 mm zone sag Fresnel lens prompted investigation of how the surface quality (namely the roughness) might be influencing the system. The surfaces were not quantitatively measured but imaged under 100x magnification microscope with the following images being representative of our findings.



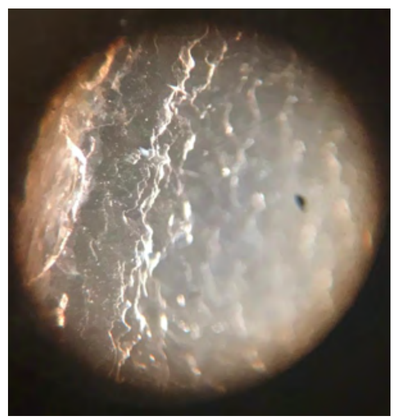
Top surface of flat sample



Bottom surface of flat sample



Top surface of Fresnel Lens (0.4 mm zone sag)



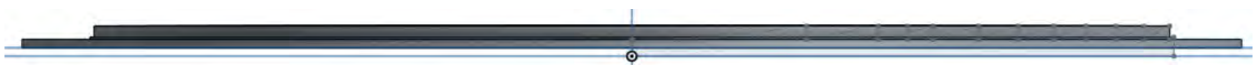
Bottom surface of Fresnel Lens (0.4 mm zone sag)

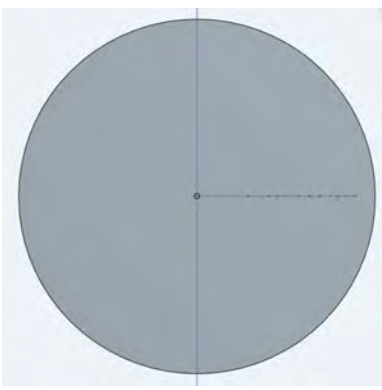
It is quite easy to see that the surfaces printed as the bottom layer in the 3D printer were considerably rougher than those faced upwards (on the order of .01 mm, an order of magnitude less than the wavelength of ultrasound in this system). This can be seen both on curved and flat surfaces, but is more patterned on the flat sample. These observations lead us to look into printing each of the powered surfaces of the Fresnel lens separately and looking into materials to use to adhere the two together (which will maximize quality of the Fresnel surfaces and possibly smooth over the patterns of the flat surfaces).

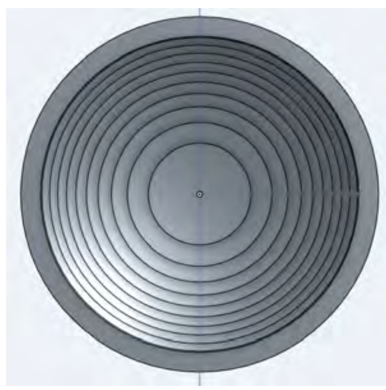
Plano-Concave Fresnel Lenses

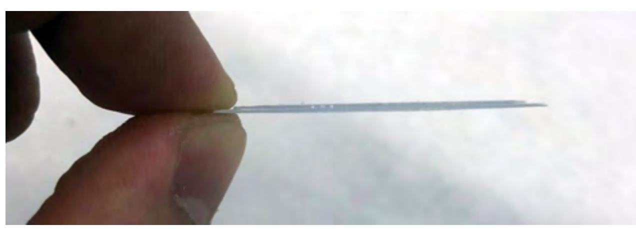
Design and Fabrication

As discussed in previous section, we decided to split the surfaces into two different pieces, and join them together. This was done fairly simply by removing half of the improved Fresnel lens (with 0.4 mm zone sag) in OnShape and then printing three copies (two for the customer for future use and one for the Hajim Design Day poster fair). The overall thickness of this design is only 0.65 mm, which appears to have printed quite well (possibly due to upping the surface tolerancing of the exported .stl from Onshape), with the only real drawback being the fragility of printing so thinly, though the plano-concave lens brought to Design Day had at least several people observe it within their hands, and there didn't appear to be any damage or flexing in the sample afterward. It is worth noting that these 'halves' are still lenses within themselves, but with a much longer focal length than the 40 mm of the original biconcave lens.









Future work on this project might involve looking into having all of the power on a single plano-concave Fresnel lens, which was considered but not attempted by our group as it roughly double the number of rings on the surface (if the zone sag was maintained) which again might bring into question the resolution capabilities of the printer, and if the zone sag was raised to reduce these numbers of rings, it would end up having around the same maximum thickness as the biconcave Fresnel lens but would lose the symmetry. Whether or not the symmetry is a benefit or a detriment was not tested but again might be worth investigating. If tests were done using the 3D printed lenses which seemed favorable, it might make sense to then attempt to fabricate it with a more traditional high resolution method such as diamond turning.

Possible Methods for Re-Combining the Plano-concave Fresnel Lenses

The following list is of no particular order but some possibilities that were brainstormed amongst the group, researched, or were suggested at Design Day* as for how to use the two separate surfaces together once more.

1. Simply clamping the outer lips together to perform testing and decide whether more complicated measures are necessary
2. Print the plano-Fresnel with a slightly thicker center thickness and do some fine sanding or polishing to smooth over the surface and again simply clamp the two halves together. Recent work has been done with investigating the polishability of 3D printed optical surfaces which suggest that softer plastics may make sanding a viable option. [6]
3. Find a type of epoxy with a similar acoustic impedance to that of the lenses spread it evenly then adhere the two lenses together. The epoxy could potentially fill in the rougher parts of the flat surfaces while also serving as an adhesive.*
4. Investigate other ultrasonically transmissive materials which do not permit the shear waves that are speculated to have been created by structure of the Fresnel lens as well as the material of it and layer the lens surfaces around a disk of this material so as to reduce the unwanted signal seen in the 'tail' of the measured data from previous experiments, thus returning some of the timegated depth information.

Conclusion

The primary goal of this project was to reduce the signal attenuation that was a consequence of using a biconcave plastic lens to focus the ultrasound signal. The Fresnel lens has been shown to have a considerably less attenuation than by the initial spherical biconcave lens solution we were provided with at the beginning of this project. With this lower attenuation value came an artifact in the form of a broad secondary signal occurring ~200 μs after the initial peak. While it is possible to time gate this secondary signal, important depth information is lost in doing so. Also, since algorithm on time gating will cut away some of the signal, the time cost to perform one experiment will increase. Still, the primary goal for this project has been achieved, while the existence of the secondary signal disrupts the clean signal from the biconcave lens.

For future projects, the improved Fresnel lens design could be used as a starting point with a primary focus of reducing the secondary signal seen in the results section. Additionally, further materials can be explored in conjunction with the equation to develop the improved Fresnel design to potentially improve the signal further. It may also be worth investing in printing our final design within the full casing for it to allow for 2D imaging and to see how influential the delayed peaks in signal might be in actual diagnostic tests.

Timeline

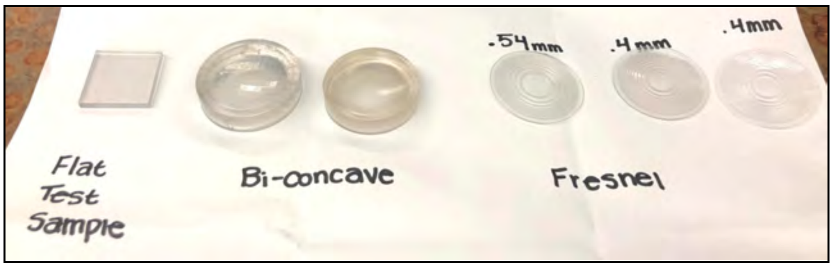
The design of the current Fresnel lens (detailed in different sections above) was completed by the end of the first semester, with modelling in CAD for it happening over break.

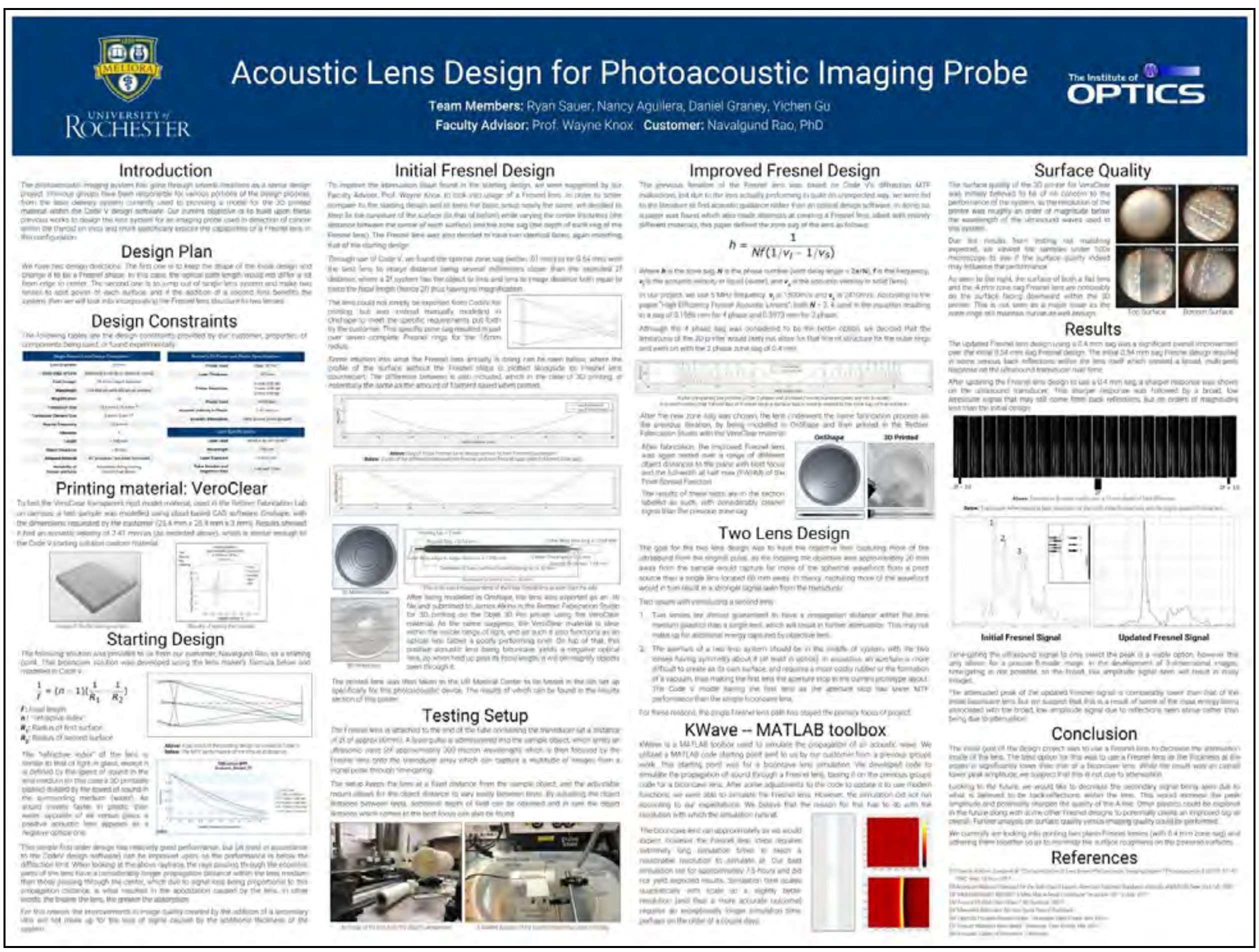
January	Week 1	Completed the Onshape (CAD) model of Fresnel lens. Submitted file for printing to Rettner Fabrication Studio.
	Week 2	Delivered Fresnel lens for Bhargava to prepare for testing Modelled and printed VeroClear sample slab.
	Week 3	Tested VeroClear sample slab to find acoustic properties. Continued updating code for K-Wave.
	Week 4	Simulated Fresnel lens using K-Wave. Tested Fresnel lens using 0.7 mm object sample.
February	Week 1	Performed Depth of Field analyses in Code V. Began design of two lens system.
	Week 2	Tested Fresnel lens using 0.2 mm object sample.
	Week 3	Received Fresnel lens performance results. Began interpretation of performance data.
	Week 4	Developed potential solutions regarding internal lens reflections. Printed original lens with VeroClear material for testing. *Midterm Design Review* (February 28)
March	Week 1	Researched and calculated sag for improved Fresnel Lens.
	Week 2	**(Spring Break)** Wrote MATLAB code for Onshape. Modelled Improved Fresnel Lens in Onshape.
	Week 3	3D printed Improved Fresnel Lens. Gave 90 second pitch at Industrial Associates meeting.
	Week 4	Designed and modelled new non-Fresnel lens (aspheric).
April	Week 1	Printed aspheric non-Fresnel lens.
	Week 2	Tested the Improved Fresnel lens.
	Week 3	Examined Surface Quality under microscope. *Final Design Document Review* (February 28)
	Week 4	Performed final attenuation tests on original and Fresnel lenses. Created and printed poster for Hajim School Design Day.
May	**Hajim School Design Day (May 4) -- Final DDD submitted**	

Hajim School Design Day

For senior design day, the group created the poster seen below summarizing the major points of the project (up until Monday 4/30) additional results obtained after printing the poster as well as some gifs/videos of the microscope surface quality were presented in a slideshow on a laptop on the side.

All of the different lenses and samples printed (aside from the sample lens in Appendix I) were displayed and passersby could get their hands on them and more easily understand the thickness reduction brought on by using Fresnel surfaces.



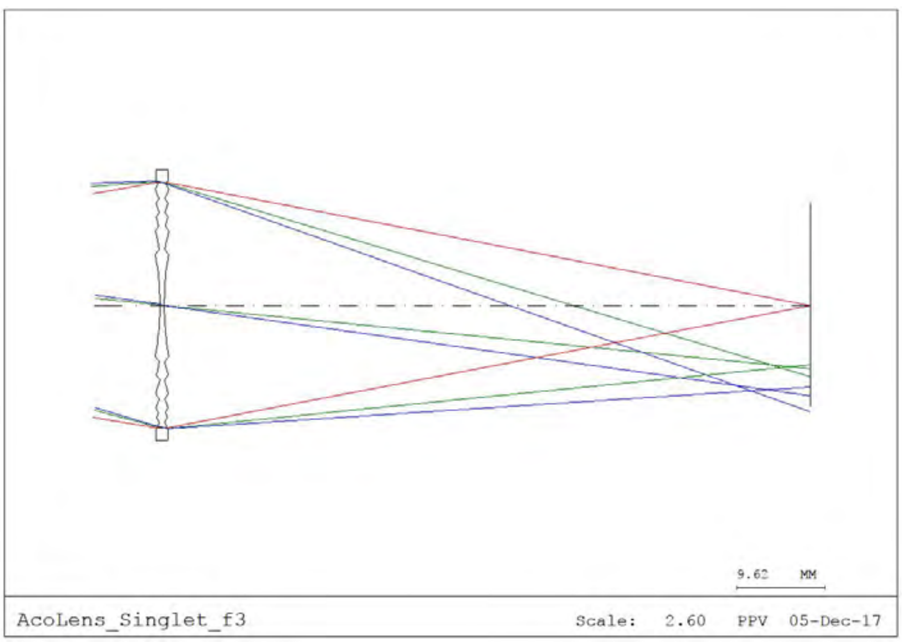


Appendix I: Sample Fresnel Design

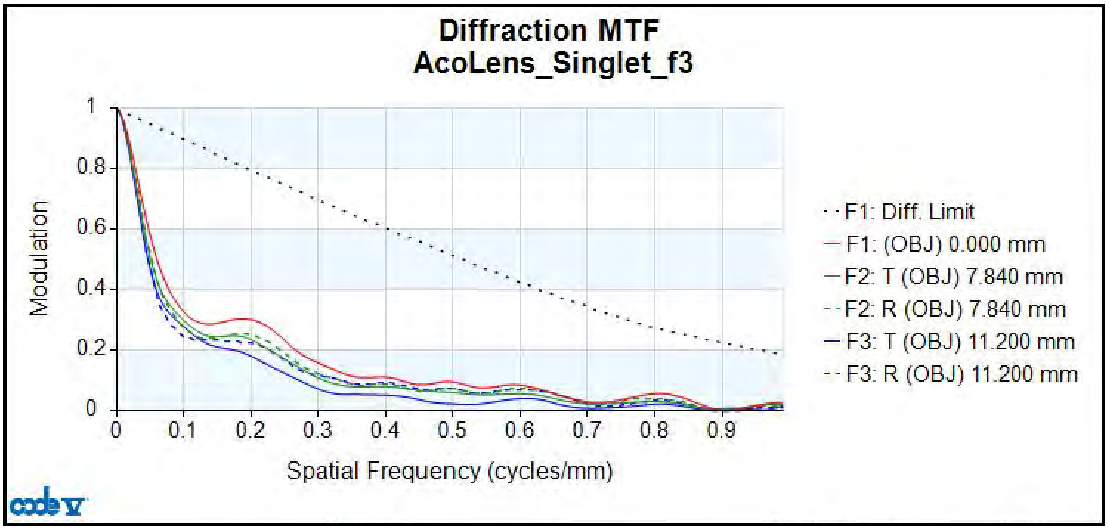
The following lens was used in demonstration for the final Product Requirement Document presentation and served as a good way to familiarize the team with the 3D printing fabrication process. The exact process used in creating these lenses will not be used moving forward, as we were suggested a better alternative method from James Alkins, but shall be included here in the appendix for sake of completeness.

Similar to the starting design, the following are screenshots of the lens within Code V. The zone sag (depth of each Fresnel ring from base thickness) was 0.5 mm.

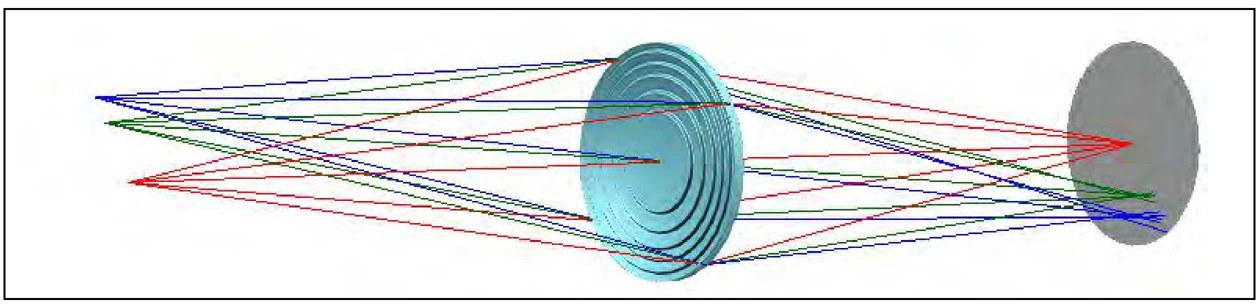
Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	80.0000		Refract	O
1		Fresnel Pl	-33.5000 V	0.5000	'pedro'	Refract	13.6744 O
Stop		Fresnel Pl	33.5000 V	79.5252 S		Refract	13.6744 O
Image		Sphere	Infinity	-8.9000 V		Refract	11.6690 O
End Of Data							



It is worth noting the Fresnel surfaces shown in the above 2D diagram of the lens is not what is actually used in ray tracing but just the softwares way of modelling it to lower computational power needed when showing the lens drawing.



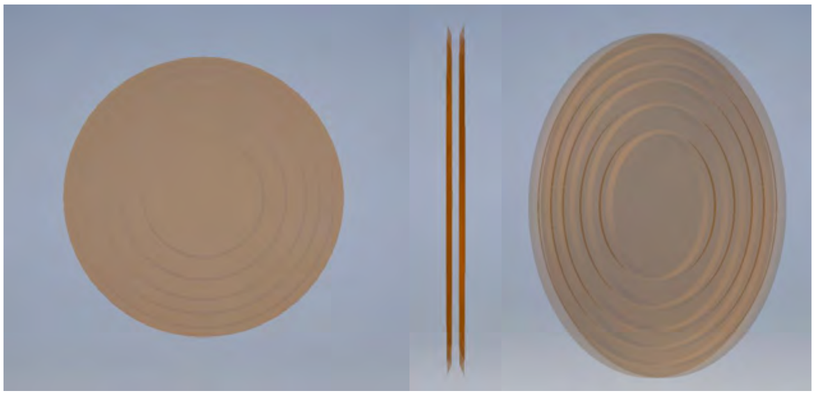
Although this may not reflect the actual performance of an acoustic lens, it is both likely and reasonable that this lens will have considerably lower performance than the starting design as the only parameters changed in the design were image location, center thickness and zone sag. The positive changes of using a Fresnel lens, to decrease signal lost as the acoustic waves propagate through the lens, are not reflected in the MTF.

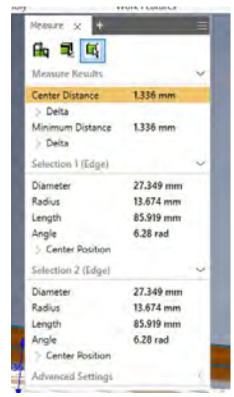


The above is a 3D rendering seen in Code V, this has a more accurate Fresnel surface and is much more similar to that seen when exported to CAD than the 2D counterpart.

Autodesk Inventor

A common alternative to SolidWorks, the CAD software suggested by Prof. Rao, is Autodesk Inventor, which has nearly all of the same functionalities, but also has free student licenses. We opened the .igs file exported from Code V into Autodesk Inventor and then removed all surfaces and rays from the file which weren't the main two Fresnel surfaces as seen below then exported the file as a .stl file, which is the suggested file type for 3D printing and can be imported into Blender.

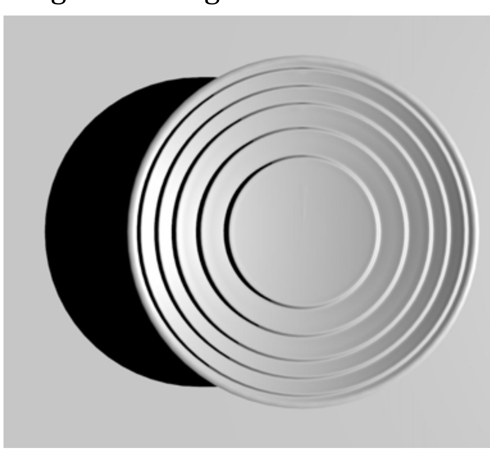


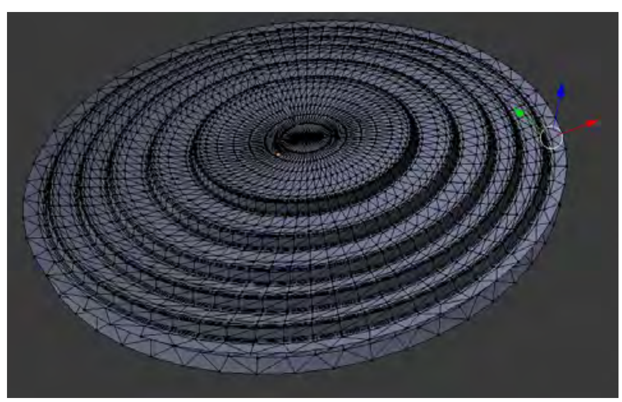


From this file we could also get the dimensional readings which are seen on the right.

Blender

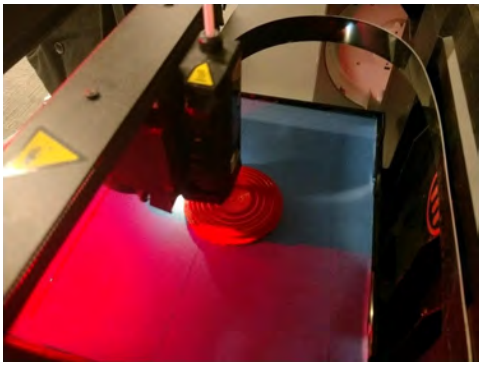
As the two Fresnel surfaces aren't a solid object, we then used Blender to fill in the outer edges to make it so. This process is not ideal and is the main step we will not be using moving forward, but does serve the purpose well enough to get the design printed. The image on the left below is a nice rendering of the lens made purely for aesthetics and the image on the right is the wireframe of the lens seen in Blender.



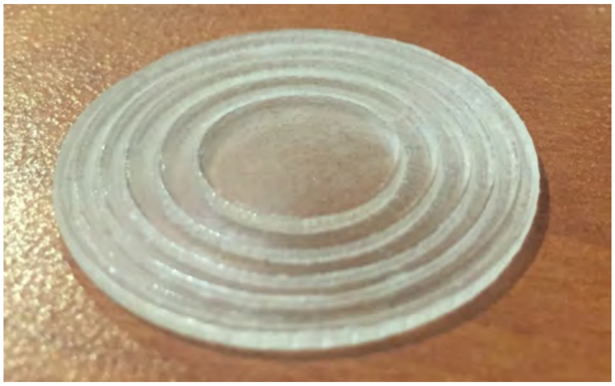


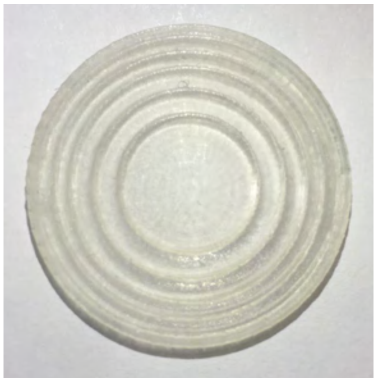
3D Printing Tests

To ensure we could have a 3D printed lens in hand come the presentation, we used the low resolution Makerbot Replicator[7] in the Rettner Media Lab, a 3D printer available for all students to use at cost of materials. The resolution being a fairly considerable issue, we decided to print it at 2.5x the design parameters, from a 27.4 mm diameter to roughly 65 mm diameter. A few images of it are shown below.



It was at this point we met with James Alkins for the first time, in which he pointed out a better alternative software (Onshape, which is used in future CAD models detailed in the body of the document). He also allowed us to use the high resolution 3D printer, the Objet 30 Pro, in the Rettner Fabrication studio. The pictures below are printed at the original scale and even so are much smoother than those above.



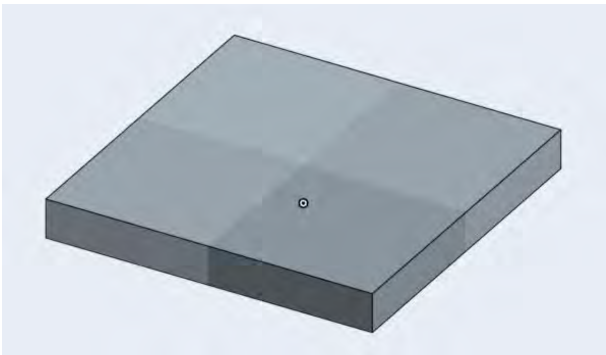


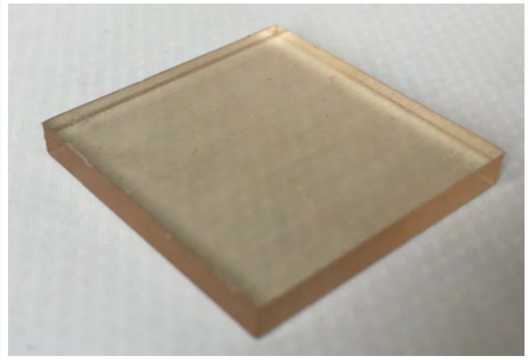
The lens was printed with the VeroClear transparent rigid model material[8], and under suggestion of Prof. Knox, we have recommended Prof. Rao to look into using this higher resolution printer as an alternative to that he has been using for past years, provided the acoustic properties are functional enough to be worth considering. A sample was made to test the acoustic properties and moving forward this material and printer were those of primary use for this project.

Note: The above lens was not tested as it does not match the correct diameter specifications given by the customer, and the surface itself (created by the default Code V to CAD exporting feature) did not actually have proper curvature and zone sag, seen by the 1st and second rings being the same width rather than eccentrically becoming narrower.

Appendix II: VeroClear Material Test Sample

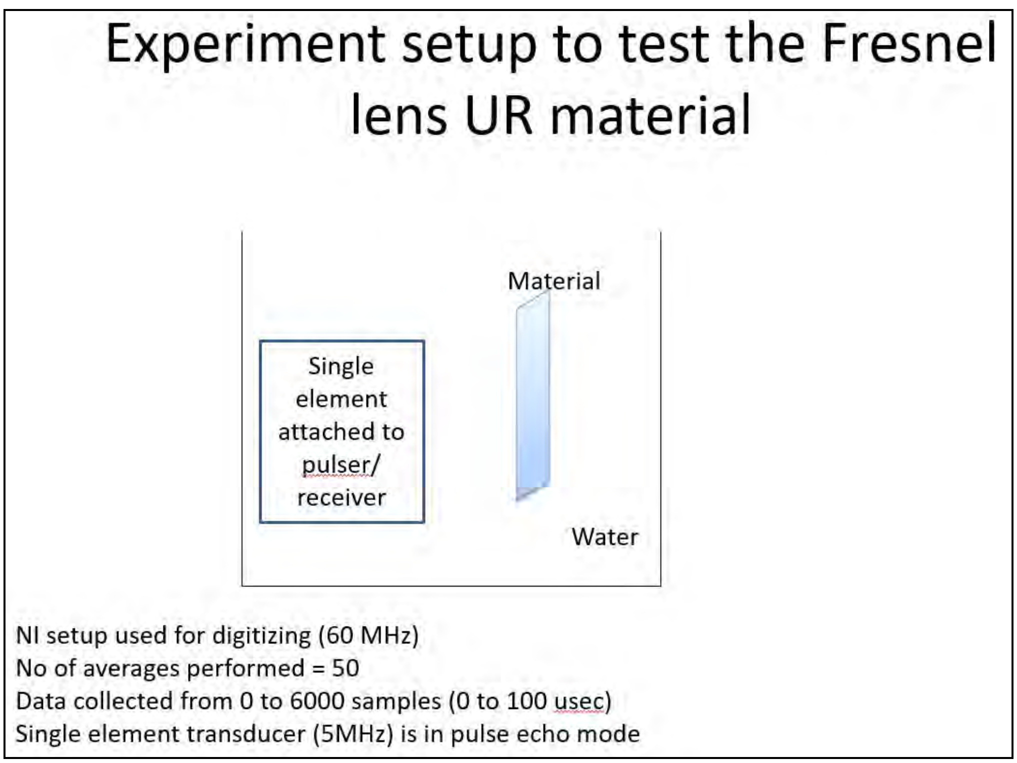
To test the VeroClear transparent rigid model material[8], used in the Rettner Fabrication Lab on campus, a test basic was modelled using Onshape with the dimensions requested by the customer (1 in x 1 in x 3 mm).



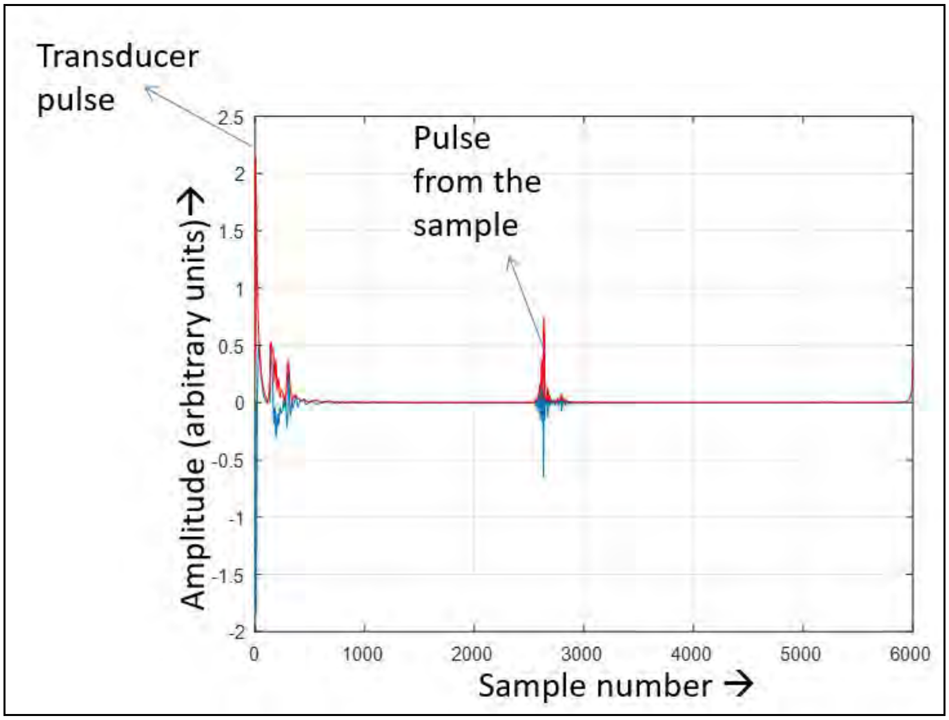


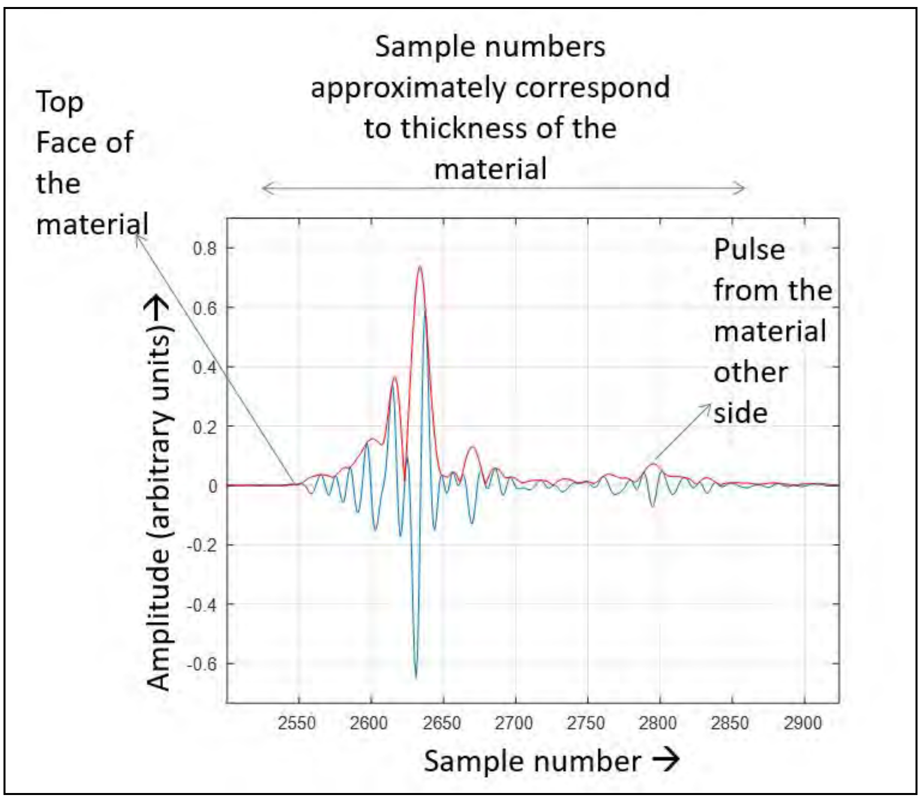
We gave the sample to Bhargava for testing, in which he concluded it has an acoustic velocity of 2.41 mm/μs (as recorded above), which is similar enough to the previous plastic material used (which had an acoustic velocity 2.43 mm/μs) for the Code V model handed down from a previous senior design project to still be a functional approximation.

The following three images are information and other data pertaining to the tests done on the material by Bhargava, given to us in the form of PowerPoint slides.



The below tests were done with a line signal and a 5 MHz transducer

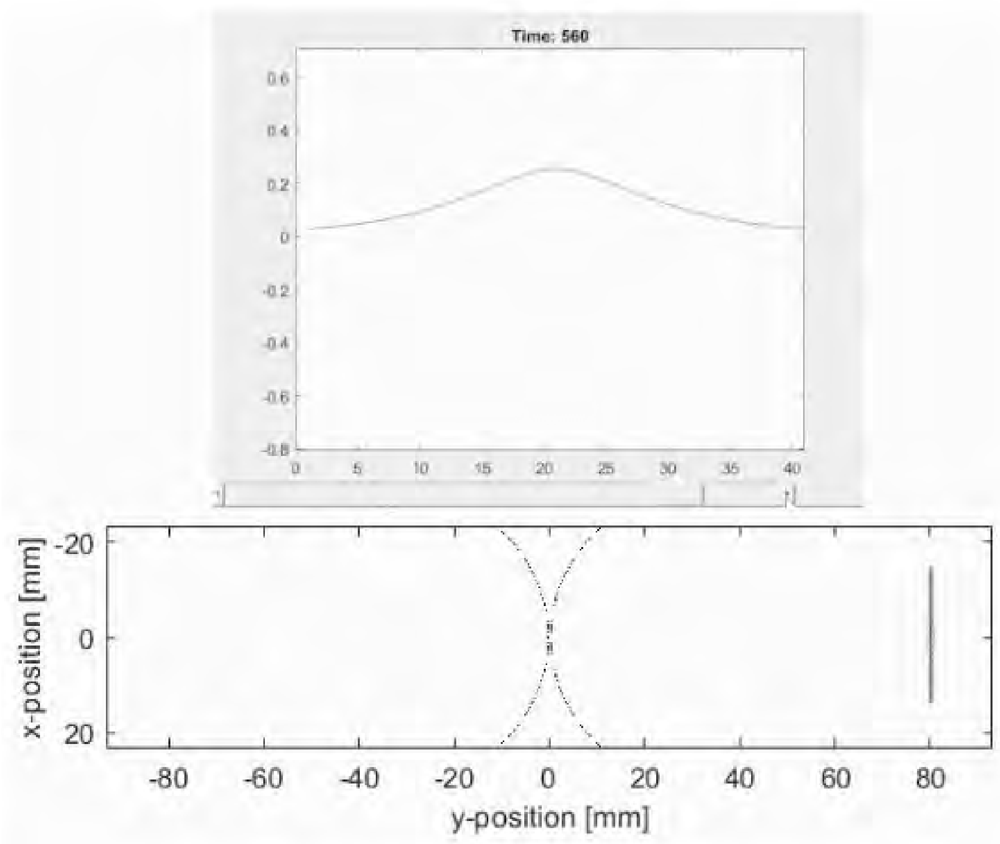




Appendix III: K-Wave

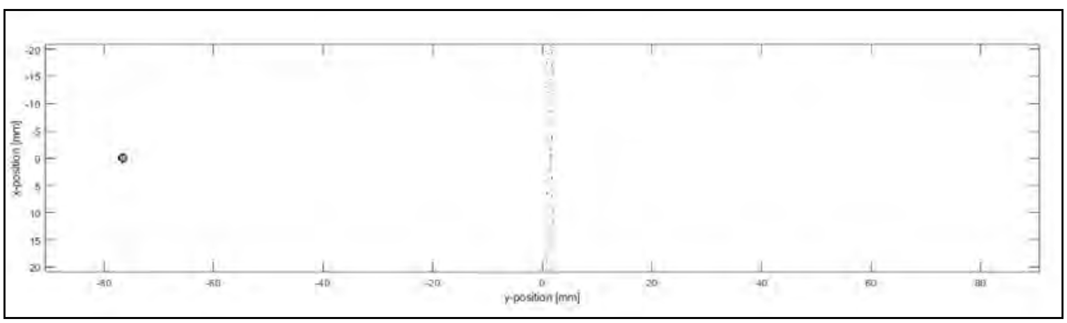
As mentioned previously in this document, the MTF found using Code V is not necessarily reliable due to differences in acoustics and optics. K-Wave is a MATLAB toolbox used to perform two-dimensional acoustic propagation simulations. We've updated the K-Wave file provided to us by Prof. Rao to work with the most up to date version of the K-Wave toolbox, as it had quite a few errors due to out-of-date syntax which needed to be fixed. We've also added the ability to scroll through the 2D PSF of the image plane at any given time in which the simulation is run.

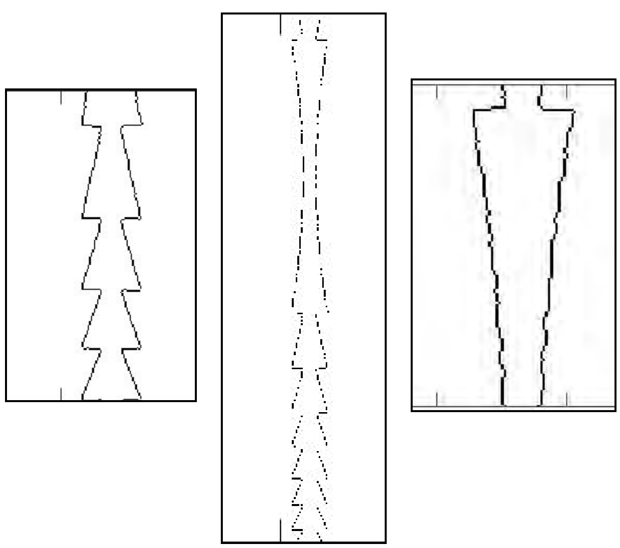
The following is a still of the video rendered from K-Wave, which shows sound emitting from an object slightly larger than a point source propagating through the lens and onto the 1D transducer, and the PSF corresponding to the time of the video still (just as the wave first makes contact with the detector).

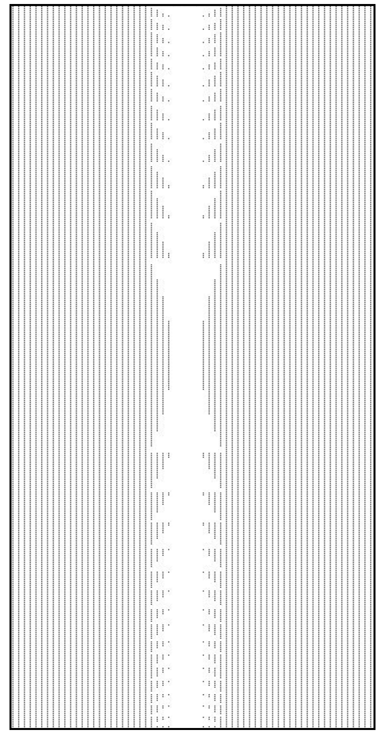


Fresnel Lens in K-Wave

After deciding on the zone sag and center thickness of the lens, we wrote the code to create the Fresnel lens within Code V. The finer structure of the lens resulted in the simulator needing to run at a higher resolution (or a lower scale as the code of the toolbox sees it). The toolbox is written such that having a considerably lower scale (ie each point in the grid represents a smaller step in reality) will result in the simulation taking much longer to render (<1 hour for the original lens, but >7 hours for the Fresnel lens) and the wave propagating through the system in the video, which fades as the strength of the wave decays, fades to white by the time it passes the lens, making it a white wave on a white background which is invisible. The actual video itself renders at a fixed 560 x 420 frame size, so when the computational grid is roughly 1000 x 4000 grid points, there are some sampling issues when zoomed in, which is what we had previously thought was caused by the code defining the Fresnel lens, but is just a scaling issue in the rendered video which does not seem to affect the PSF being simulated. Images below show this roughness due to scaling seen in the video rendered (for the 0.54 mm zone sag), while the next page has the Fresnel lens as used in the simulation grid as well as the results of the 0.4 mm zone sag simulation.



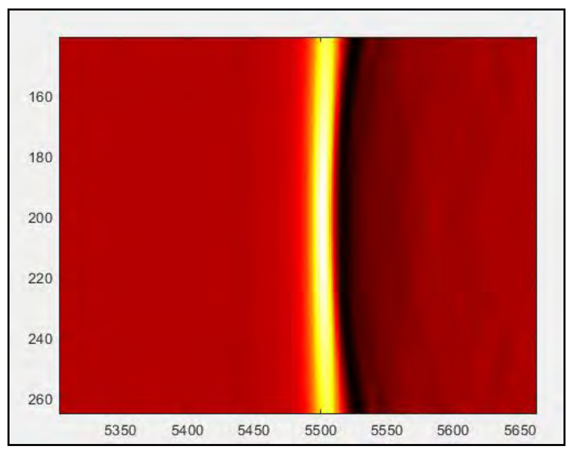


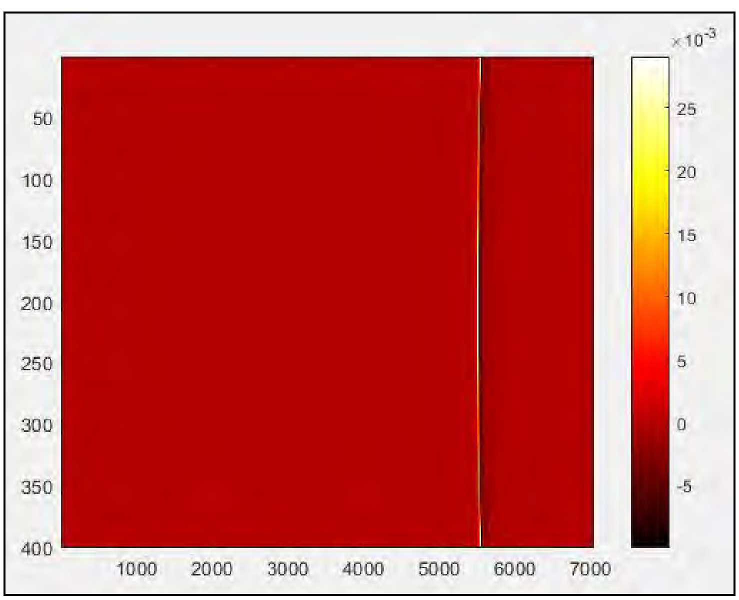


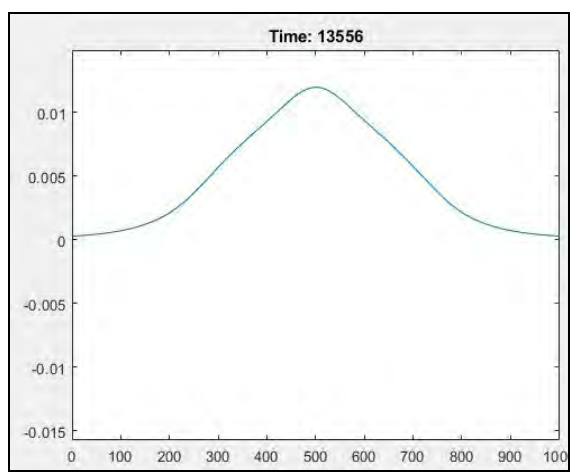
The bottom images show the PSF at different time intervals, with the each vertical line in the heat map being the PSF of a given sample number, as stated at the bottom. The PSF of the peak signal (seen in the lower right) is not quite the gaussian-like curve one might expect, and there is no tail in the signal like as seen in the experimental results.

In the video rendered for this, the wavefront did not bend as predicted through the lens, rather it seemed to bend at a much lower power than the lens itself is. Many of the different parameters within the toolbox were updated to see what might cause this and more simulations were run, all giving roughly this same result.

Code for the function used to define the Fresnel lens can be found on the next page.







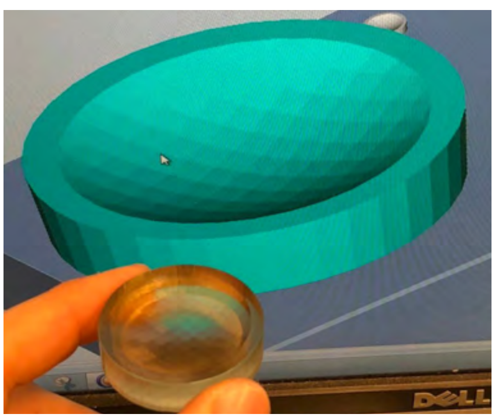
```
function [medium] = MakeFresnelAcoustLens2D(kgrid,R,D,T1,BackgrndMedium,LensMedium,scale)

%% input
% kgrid  input grid
% BackgrndMedium  background medium property
% LensMedium lens medium property
% R radius of the lens
% D diameter of the lens
% T1 thickness of the lens at the center
% t2 thickness of the lens at the lip
%% Output
% Output medium (lens + background)
dx = kgrid.dx;
dy = kgrid.dy;

%% Other code

zs = .4e-3; % zone sag
radius = D/2; % semi-aperture of lens
curv = R ; % radius of surface (assuming spherical)
dis = 80e-3 ; % distance to first surface of lens from obj
centhi = T1; %central thickness of lens

xpix = kgrid.Nx; %number of points in x
ypix = kgrid.Ny; %number of points in y

x = kgrid.x;

yf = -sqrt(curv^2 - x.^2) + curv; %defines single spherical surf
fres = mod(yf,zs); %makes fresnel surface
upperb= fres +centhi/2; % defines upper bound (surface nearest object)
lowerb= -1*mod(yf,zs)-centhi/2; %defines lower surface assuming mirr or of upper

gridt = zeros(ypix,xpix);
%% define each point in grid as being part of lens or not being part of lens
for i=1:xpix
    for j=1:ypix
        jy = dis - j*dy+dy;
        if jy < upperb(i) && jy > lowerb(i)
            gridt(j,i)=1;
        end
    end
end
transp = gridt.'; %array in 0s for water and 1s for plastic/lens
switcht = 1 - transp; %inverse (1<=>0) of above for kwave

BackgrndMedium.sound_speed = BackgrndMedium.sound_speed .* switcht;
BackgrndMedium.density = BackgrndMedium.density .* switcht;
BackgrndMedium.alpha_coeff = BackgrndMedium.alpha_coeff .* switcht;

medium.sound_speed = BackgrndMedium.sound_speed  + transp.*LensMedium.sound_speed;
medium.density = BackgrndMedium.density + transp.*LensMedium.density;
medium.alpha_coeff = BackgrndMedium.alpha_coeff + transp.* LensMedium.alpha_coeff;

end
```

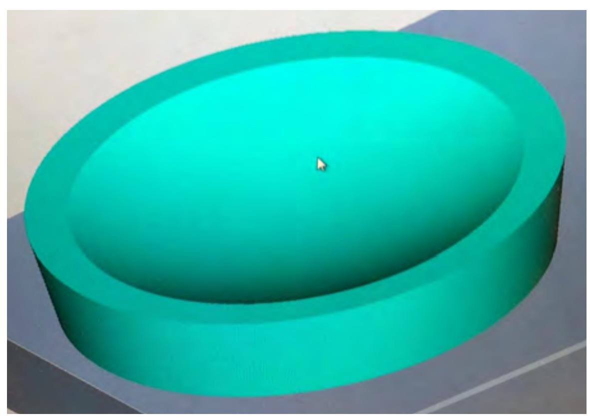
Appendix IV: Remaking Original Lens

After the Fresnel lens tests had some unexpected results, Prof. Rao suggested we print the original biconcave lens with the VeroClear material to use as a reference. So with a provided Solidworks file, we converted the design into .stl (the only file-type used in Rettner Fabrication Studio for 3D printing) and printed the original lens design as seen

below.

The 'pixelation' of the surface was an unexpected result from exporting using the default surface tolerances, and with the help of Gilead Biggie, a Mechanical Engineering student working in the fabrication studio at the time, we were able to re-tolerance some angular resolution parameters and resolved the issue as shown below.



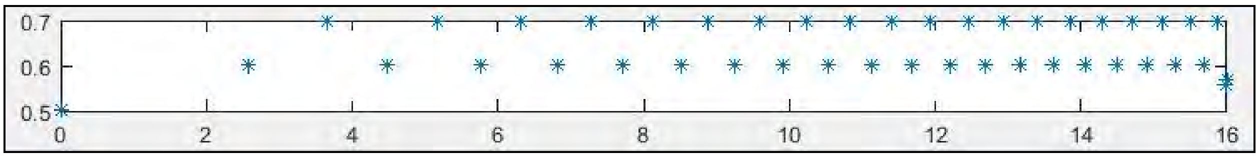


The lens took several hours to print, so Jim suggested we bring it to the customer anyway to see if it needed re-printing. Ultimately, it was decided that the 'pixelated' lens would be accurate enough for attenuation testing, so the smoothed version was not printed.

Appendix V: MATLAB code for Onshape

In order to properly create a Fresnel lens in Onshape each ring of the lens must have three points defined to create a spherical arc which when stitched together create half of the profile of a surface of the lens. The following code was written to automate this solving process and gives all of the points necessary to put into the CAD software to create the surface.

This plot shows the values used for these arcs (with the x value for the top of one ring being the same as that of the bottom of the next ring).

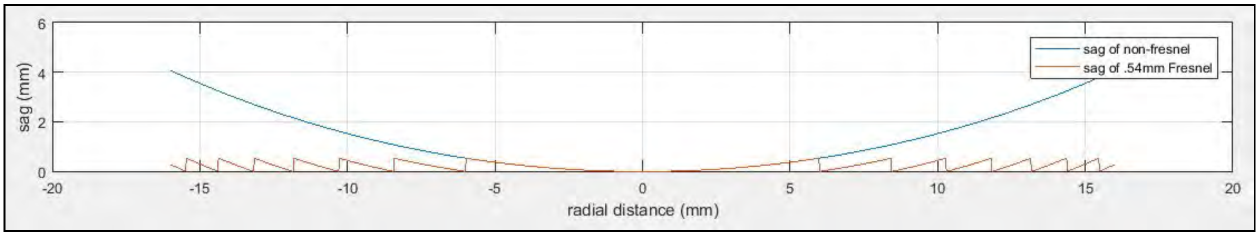


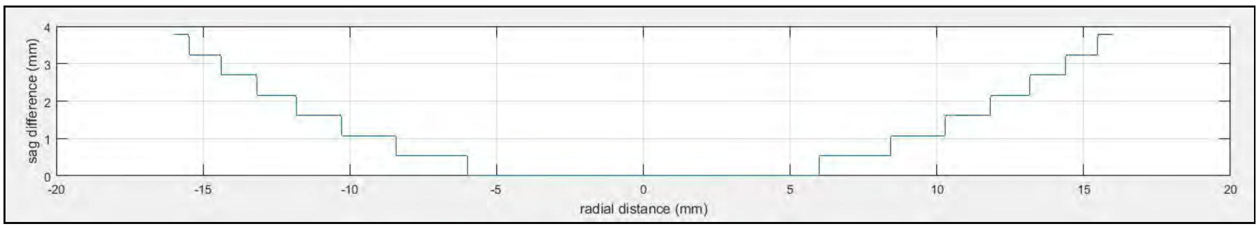

```
% matlab code to write onshape code
clear
clc
%DEFINE STUFF UP HERE

syms x % makes x a variable which can be solved symbollicaly
zs = .2; % zonesag according to code v
radius = 16; %radius in millimeter
curv = 33.5; %curvature of surface (provided it is spherical, else update code
zsh = zs*.5; % half of zone sag making midpoint for arc

yf = -sqrt( curv^2 - radius^2 ) + curv; %y at the edge of non-fresnel equiv.
% the above equation is for the profile of the lens if
r = yf / zs; %number of rings on lens unrounded
rings = floor(r); %number of rings not including outer partial ring
z = .5; %distance above z plane in onshape

i=0; %start with x=0
counts = 0; % dummy variable to keep track of loop
size = 2*rings+1;

Xs = ones(size,1);%predefining the space for x;
Ys = ones(size,1);

while i < yf

% SOLVING FOR A GIVEN SAG
eqn = -sqrt(curv^2 - x^2 )+ curv == i;
solx = solve(eqn, x);
solv = abs(solx(1)); %since fxn is rotationally symmetric and 0 has
%only one solution, this takes first abs val of first solution
%which is the x given a certain y
Xs(counts+1)=solv;
evenodd = mod(counts,2);

if counts > 0 && evenodd == 1
    y = zsh + z; %the half step height plus distance from z plane
elseif counts > 0
    y = zs + z; %the full step height plus distance from z plane
else
    y = z; %just the distance from the plane
```

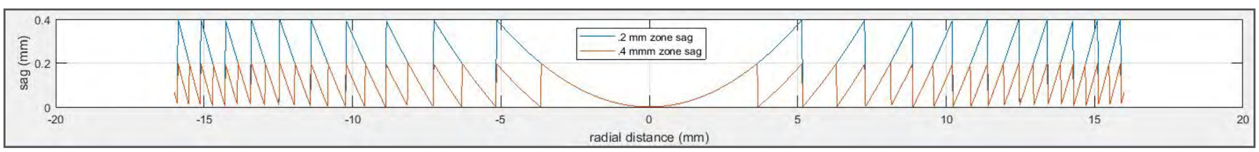
```
end

Ys(counts+1) = y;

i = i + zsh;
counts = counts + 1; %tracks number of times this loop occurs
end
%tests oddity of counts to see if the arbitary midpoint definition
% is larger than zonesag of final ring
evenodd = mod(counts,2);
size1= size+1;
size2 = size+2;
if evenodd == 0
yedge = mod(yf,zs)+z;
Xs1 = ones(size2,1);
Xs1 = ones(size2,1);
for i = 1:size1
Xs1(i)=Xs(i);
Ys1(i)=Ys(i);
end
Xs1(size2) = radius;
Ys1(size2)=mod(yf,zs)+z;
for j = 1:size2
formatSpec = 'X is %8f and Y is %8f \n';
fprintf(formatSpec,Xs1(j),Ys1(j));
end
end
if evenodd == 1
Xs2 = ones(size2,1);
for i = 1:size
Xs2(i)=Xs(i);
Ys2(i)=Ys(i);
end
yff = yf-.01;
syms x
eqn1 = curv - sqrt(curv^2 - x^2 ) == yff;
solxx = solve(eqn1, x);
solvx = abs(solxx(1));
Xs2(size1) = solvx;
Ys2(size1) = mod((yf-.01),zs)+z;
Xs2(size2) = radius;
Ys2(size2)=mod(yf,zs)+z;
for j = 1:size2
formatSpec = 'X is %8f and Y is %8f \n';
fprintf(formatSpec,Xs2(j),Ys2(j));
end
end
if evenodd == 0
plot(Xs1, Ys1, 'o')
else
plot(Xs2,Ys2,'.')
end
```

Appendix VI: MATLAB Plots Comparing Sags

The following figures were made for the poster fair to show the difference between the surface profiles of a normal (non-Fresnel) biconcave lens and a Fresnel lens. The first figure has these profiles, the second is the difference between the two sags, and the third figure compares the 2 and 4 pi phase zone sags (which were a few thousands of a mm from being exactly .4 mm and .2 mm zone sag respectively). The third plot also shows the linearity between zone sag and the number of rings of the Fresnel lens.








```
%sample for poster
scale = 1;
radius = 16*scale;
x = linspace(-1*radius,radius,1000);
curv = 33.5*scale;
zs1 = .54*scale;
zs2 = .4*scale;
zs3 = .2*scale;
y = -sqrt(curv^2 - x.^2) + curv;
y1 = mod(y,zs1);
y2 = mod(y,zs2);
y3 = mod(y,zs3);
ydif1 = y - y1;
ymax = -sqrt(curv^2 - radius^2) + curv;
ratio = ymax / (2*radius);
plot(x,yf,x,y1)
grid on
pbaspect([1 ratio 1])
xlabel('radial distance (mm)')
ylabel('sag (mm)')
legend('sag of non-fresnel','sag of .54mm Fresnel')
figure
plot(x,ydif1)
grid on
pbaspect([1 ratio 1])
(code was modified for the third figure but is largely contained in the above)
```

Appendix VII: Coatings

One possible way to correct these multiple reflections in the *optical* domain would be to apply an anti-reflection coating to the lens. These anti-reflection coatings use a specific combination of materials and thicknesses to minimize lens reflections. While, for the most part, these coatings are used to minimize reflections on the outside surfaces (i.e. light reflecting in air on a lens surface), this also minimizes reflections on the inside of the lens. In the *acoustic* domain, however, a similar solution arises in the form of a "matching layer" which uses similar equations as those used to create anti-reflection coatings. Instead of using "index of refraction", we consider the "acoustic impedance" of the materials to create a theoretical matching layer. Below are the equations used to decide the acoustic impedance and thickness of the matching layer.

In general, the intensity transmission coefficient for a "3-layer" system (lens plastic, some matching layer, and water, respectively) is as follows:

$$T_I = \frac{4}{2 + (\frac{z_3}{z_1} + \frac{z_1}{z_3})cos^2(k_2L) + (\frac{z_2^2}{z_1z_3} + \frac{z_1z_3}{z_2^2})sin^2(k_2L)}$$

Where z_n is the acoustic impedance for the n-th layer, k_2 is the wavenumber for the second layer and L is the thickness of the second layer. If we consider getting rid of the cosine term, we get the following:

$$k_2L = \frac{(2n-1)\pi}{2}$$

And thus if we solve for L, we can get the optimal thickness to eliminate the cosine term,

$$L = \frac{(2n-1)\lambda}{4}$$

So thus,

$$sin^2(k_2L) = 1 \quad \text{and} \quad cos^2(k_2L) = 0$$

And simplifying the above intensity transmission coefficient, we get,

$$T_I = \frac{4z_1z_3}{(z_2 + z_3\frac{z_1}{z_2})^2}$$

And finally we can set $T_I = 1$ and solve for z_2 to get,

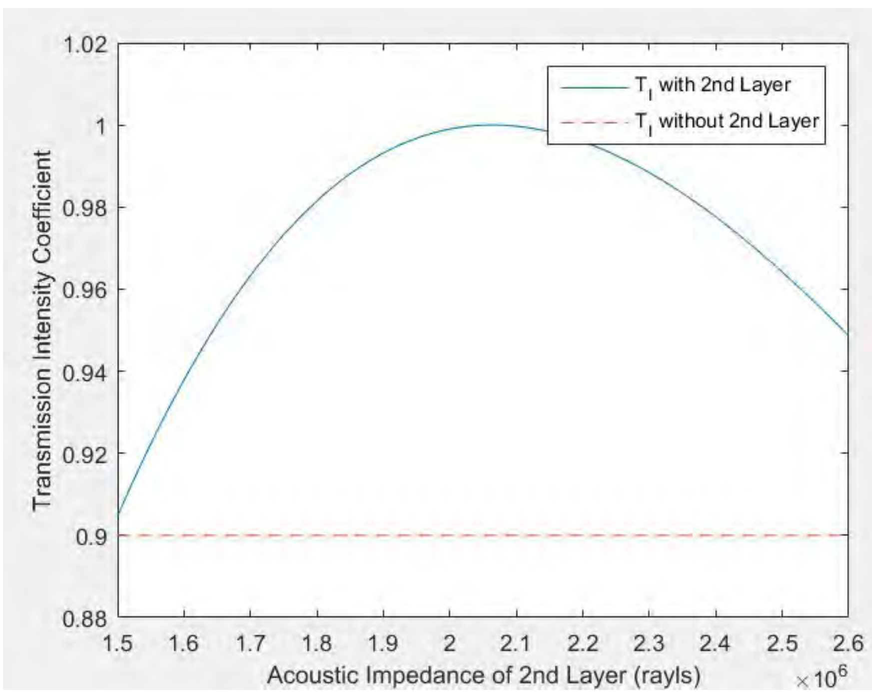
$$z_2 = \sqrt{z_1z_3}$$

Which is the optimal acoustic impedance for perfect transmission assuming the matching layer thickness with an odd number of quarter wavelength.

Putting all this information together, we find the following to be the best possible solution:

Matching Layer Properties	
Optimal Acoustic Impedance	2.064 MRayls
Optimal Thickness	Depends on Speed of Sound in Material

Because it is unrealistic to expect to find a material with exactly this acoustic impedance, it is worth observing the effects of using different acoustic impedance materials that are within a range of this optimal one. Below is a plot of the transmission intensity coefficient vs acoustic impedance of the second layer; this gives an idea as to what acoustic impedances we can consider to increase the transmission intensity.



After a bit of research, it seems that the material that comes closest to this acoustic impedance is **Polyurethane, RP-6403**[9], a rubber material with the following acoustic properties.

Polyurethane, RP-6403 Acoustic Properties	
Acoustic Impedance	2.05 MRayls
Speed of Sound	1870 m/s
Quarter Wave Thickness	95.5 μm

There are methods to mold rubber into a precise shape, so given that our team has yet to spend a significant amount of the team budget, we may be able to create such an "anti-reflection coating" in the acoustic regime. That being said, molding rubber into something so thin may not be a viable option, so other methods may need to be explored.

References

1. "MEASUREMENT REPORT: 3 MHz Matrix Array Transducer" *Imasonic.* RIT. 3 July. 2017.
2. Francis, Kalloor Joseph et al. "Characterization of Lens Based Photoacoustic Imaging System." *Photoacoustics* 8 (2017): 37–47. *PMC*. Web. 18 Nov. 2017.
3. "Accura 25 (SLA) Data Sheet." *3D Systems*. 2017.
4. "Objet 30 Pro Specification Sheet." *Stratasys*. Eden Prairie, MN. 2015.
5. Hadimioglu, B, et al. "High-efficiency Fresnel acoustic lenses." *Xerox Palo Alto Research Center.* 1993.
6. Willis, Karl, et al. "Printed optics: 3D printing of embedded optical elements for interactive devices." *Proceedings of the 25th annual ACM symposium on User interface software and technology*. ACM, 2012.
7. "MakerBot Replicator 5th Gen Quick Specs" *RedStack.*
8. "PolyJet Materials Data Sheet." *Stratasys*. Eden Prairie, MN. 2017.
9. "Acoustic Tables of Reference." *Ondacorp*. 2016.