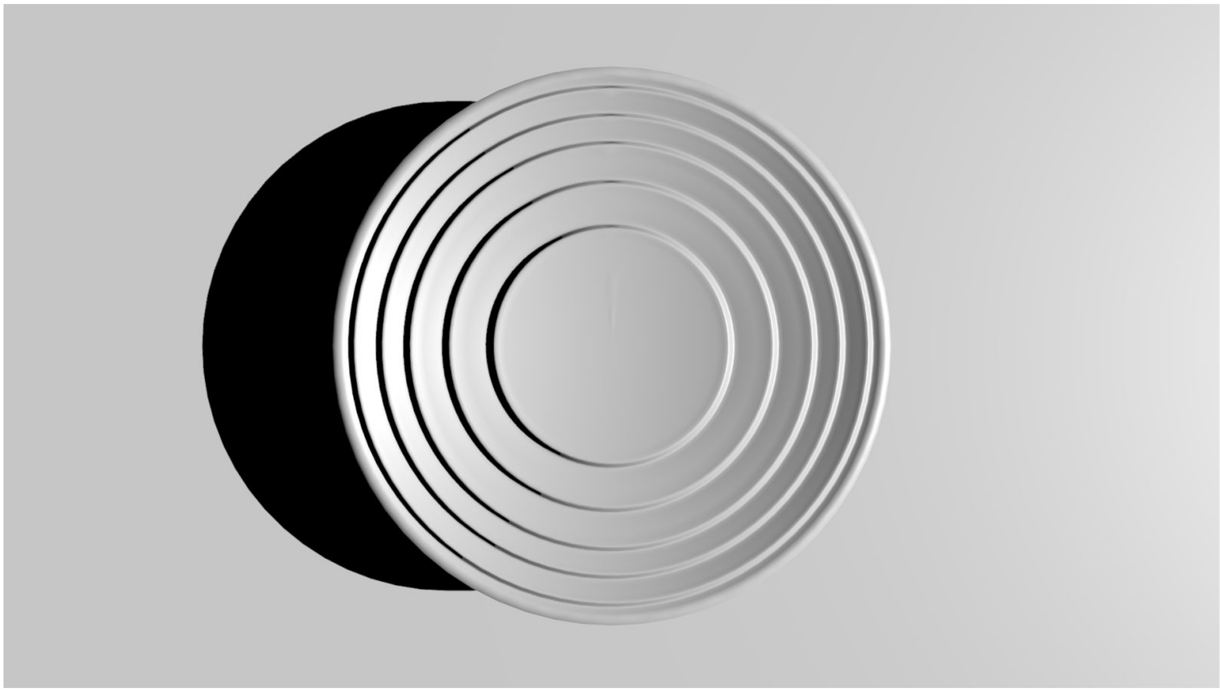
Acoustic Lens Design
Product Requirements Document
URMC / Navalgund Rao

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
L	12-15-2017

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Revision History

Rev	Description	Date
A	Initial PRD	10-30-2017
B	Specifications tables created	11-7-2017
C	Specification tables updated, starting solution added, formatting corrections	11-10-2017
D	Added Advisors and Improved Regulatory Issues	11-12-2017
E	Table of Contents, Responsibilities, & Design Considerations	11-18-2017
F	Basic System Diagram and Works Cited	11-26-2017
G	Updated Resources and Responsibilities, Added K-Wave and Initial Fresnel Design segments	12-7-2017
H	Updated Design Constraints, Changed Design Considerations, Added More Pictures and Citations	12-9-2017
I	Major Reformatting, Onshape Info, More Descriptions for Pictures of Previous Revision, added Timeline	12-12-2017
J	Updated Design Constraints again, Completed Timeline, Updated Vision, Added Design Statement	12-13-2017
K	Added Customer Approval	12-14-2017
L	Updated Customer Approval, Added Appendix V, Formatted the Document, Updated References	12-15-2017

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Team Member Responsibilities

Ryan Sauer	Primary Code V designer, scheduling meetings, graphic designer
Nancy Aguilera	Primary contact with customers and advisors, 3D printing
Daniel Graney	Primary K-Wave simulation programmer, primary scribe
Yichen Gu	Aiding in Code V design, 3D modelling, and CAD (in Onshape)

Note: the responsibilities listed above are the members specific focuses, but we will likely all have input and aid in each part of the design process.

Vision

To design, fabricate, and test acoustic lenses for use in an in-vivo thyroid photoacoustic imaging probe, focusing on decreasing signal loss found in acoustic systems.

Design Statement

The Acoustic Lens Design project is a senior design driven imaging system. As such its design inputs were derived from our interactions with our project customer, Dr. Navalgund Rao, and our faculty advisor, Professor Wayne Knox.

Environment

The lens(es) will be surrounded by water when in the final imaging system. They will be submerged in a water bath when testing performance.

The temperature and relative humidity will be the standard used in a hospital setting, roughly 63 to 78 degrees Fahrenheit and 30-60% relative humidity.

Regulatory Issues

There will be use of 790 to 800 nm pulsed laser with 5-10 ns pulses at 10 Hz repetition pulse rate[1]. The laser never exceeds ~13 mJ/cm^2 which is lower than the ANSI limit of 40 mJ/cm^2 at these wavelengths.[2] We will not be responsible for designing any of the system components which follow strict regulation.

Fitness for Use

Properties of the imaging system:
The system should have a relative large depth of field. The system uses a C-scan method which detects dimensional images. When applied to patients, because images from different layers travel different time through the system, the software is able to capture images by microseconds. Then the software will combine and process these images to form a dimensional image which shows the precise position of the cancer.

It is desirable that:

- The cost of the lens apparatus prototype is less than $1000 for all components
- Optimize “depth of field” vs. “resolution”; provide the PSF info at different depths
- We can model the 2-dimensional wave propagation in an open-source MATLAB toolbox “K-Wave.”

If there is time and/or team resources available:

- Explore and compare “Fresnel lens” technology in the current 2F geometry
- Consider using a second lens
- Use both a second and a Fresnel lens

Resources

The following individuals will serve as advisors for our team:

Dr. Wayne Knox - Faculty Advisor
Dr. Navalgund Rao - Customer and general system help
Bhargava Chinni - image processing and other software help
James Alkins - 3D modelling/printing advisor

The following tools will be used in designing and fabricating the device:

Code V: lens design software

K-Wave: A MATLAB toolbox used in acoustic wave propagation simulation to find a theoretical point spread function.

3D Modelling / CAD software: SolidWorks or 3D Builder (suggested by Prof. Rao), Autodesk Inventor and Blender (self-decided), Onshape (recommended by James Alkin)

3D Printers: Objet 30 Pro (in Rettner) and ProX 800 (printed off-campus)

Responsibilities

We are responsible for:

- Designing a fresnel lens in current 2F geometry through use of Code V
- Simulating the design in K-Wave to compare to non-Fresnel equivalent (the Point Spread Function)
- Modelling of the lens in CAD to be 3D printed
- Observe the tests and receive and compare data from them (i.e. the PSF)

<u>Time Permitting</u>

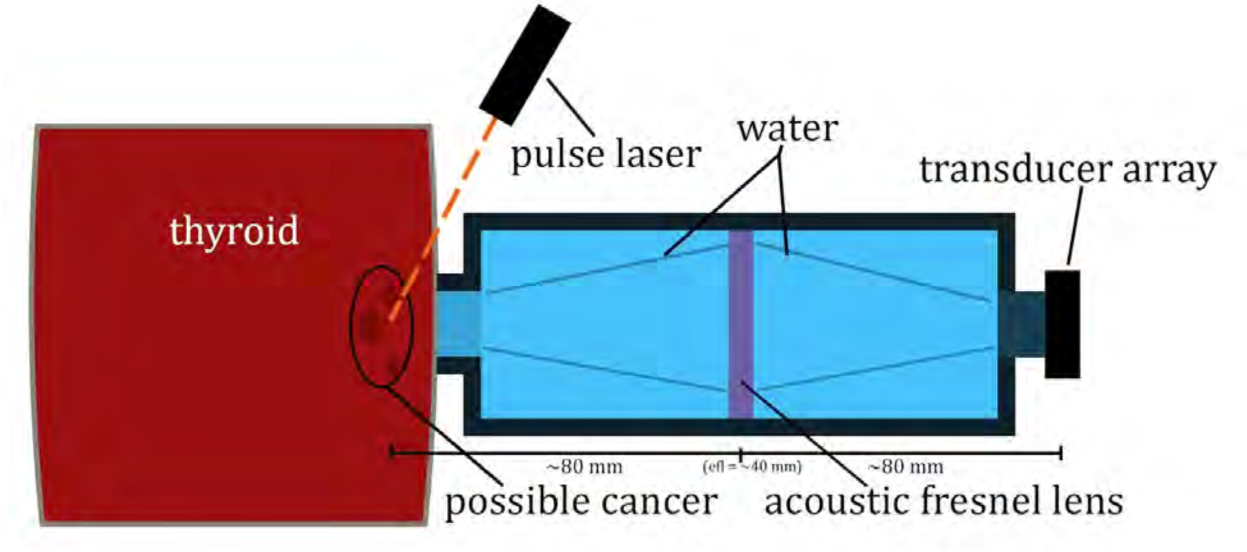
- Designing a two (non-Fresnel) lens system based on current system with additional lens closer to object, and again modelling it in both K-Wave and CAD for simulation and fabrication.
- Designing a system with two lenses and use of fresnel surface which again would be modelled in K-Wave and CAD.

We are not responsible for:

- Designing the casing of system, the laser system for administering the pulses to create ultrasonic waves, or any of the electrical components of the system.
- Designing any part of the system which might require approval by ANSI or other medical standards boards, although a familiarity of these standards is expected.
- Performing any actual medical tests involved with the system our designs will be used in.
- Performing any image analysis with the images created by our design aside from for comparison with initial design.
- Being able to run the machine on our own, although we should have a basic understanding of the process.

System Diagram

The below diagram is a simplified version of the device we will be designing for, with the fresnel lens in place. The possible two lens system will have different measurements but have the same rough layout.



Design Constraints

The following tables show the design constraints for the project.

Single Fresnel Lens 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 [3]
Transducer Element Size	2 mm x 2 mm [3]
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[5]
Wavelength	790 nm
Laser Exposure	13 mJ / cm^2
Pulse Duration and Repetition Rate	5 ns and 10 Hz

Two Lens System	
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 [3]
Transducer Element Size	2 mm x 2 mm [3]
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

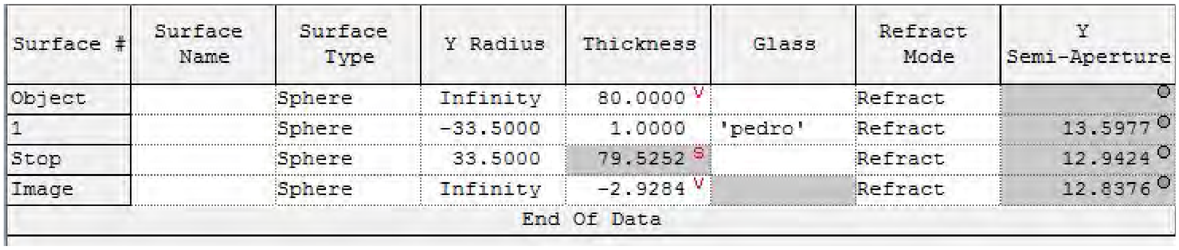
3D Printer and Plastic Specifications	
Printer Used	ProX 800 [5]
3D Printer Resolution	0.25 - 0.38 mm
Plastic Used	Accura 25 (SLA)[4]
Acoustic Velocity in Plastic	2.43 mm/µs

Timeline

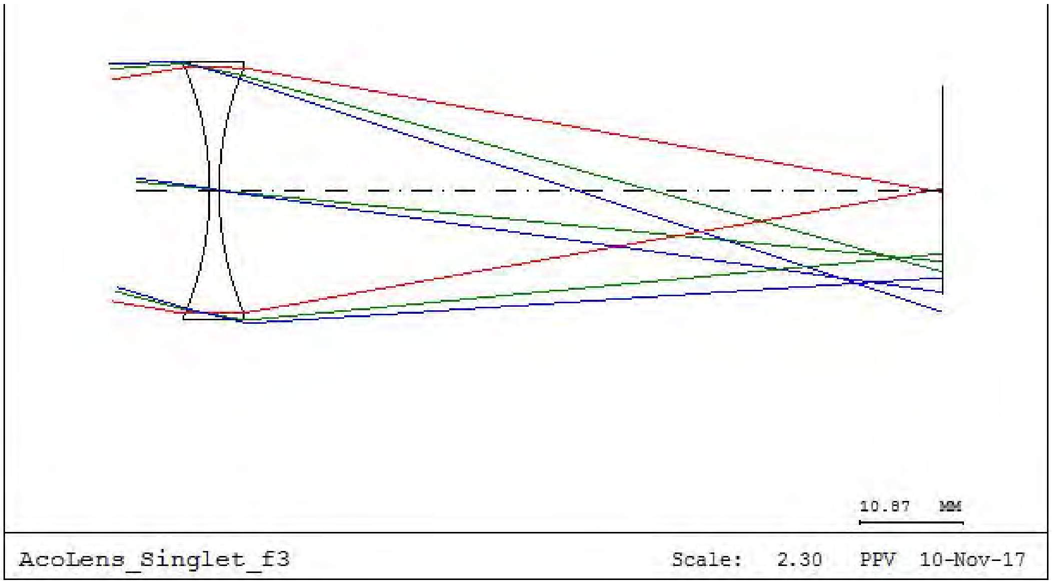
October	Assigned to Team Acoustic, First met with Prof. Rao and Bhargava, Established roles in team
November	Assigned faculty advisor, developed the product requirement document, began k-wave simulations, designed initial Fresnel lens.
December	Created 3D model of initial Fresnel lens and printed in Rettner, gave final PRD presentation, further modified design of Fresnel Lens (see appendix)
January	Submit Fresnel lens for printing and test it, depending on results we will either move onto two lens system or re-design Fresnel lens.
February	Finish with Fresnel lens designs and testing. Design a two lens system and submit for printing.
March	Finish with two lens system designs, printing, and testing.
April	Incorporate fresnel surfaces in two lens system in designing, then print and test.

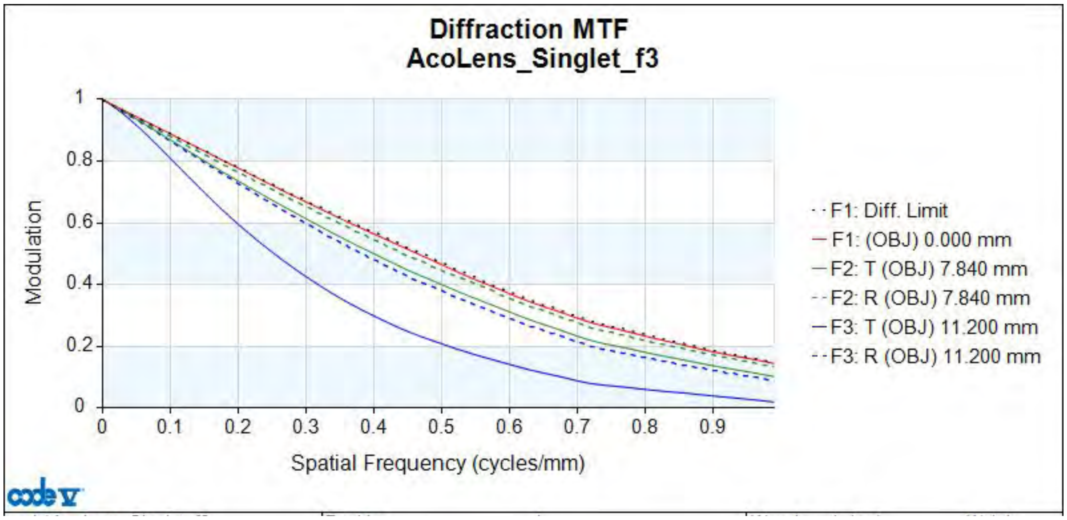
Appendix I: Starting Solution

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 simply as a reference.



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



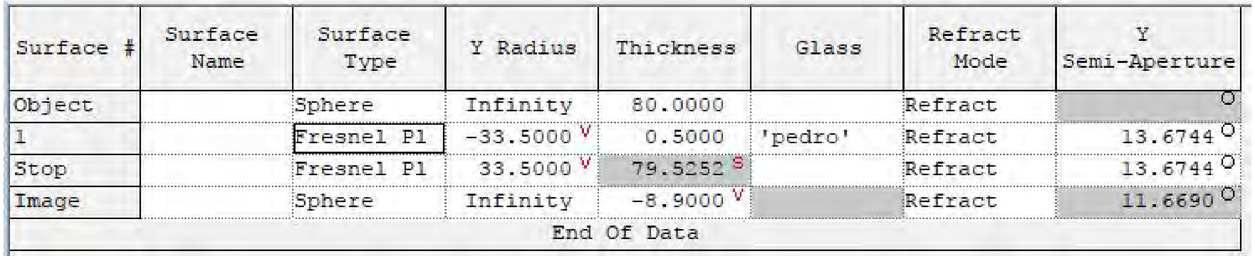


Appendix II: Initial Fresnel Design

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 will be shown here nonetheless.

Code V

Like the previous section of the appendix, 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	○
1		Fresnel Pl	-33.5000 V	0.5000	'pedro'	Refract	13.6744 ○
Stop		Fresnel Pl	33.5000 V	79.5252 S		Refract	13.6744 ○
Image		Sphere	Infinity	-8.9000 V		Refract	11.6690 ○
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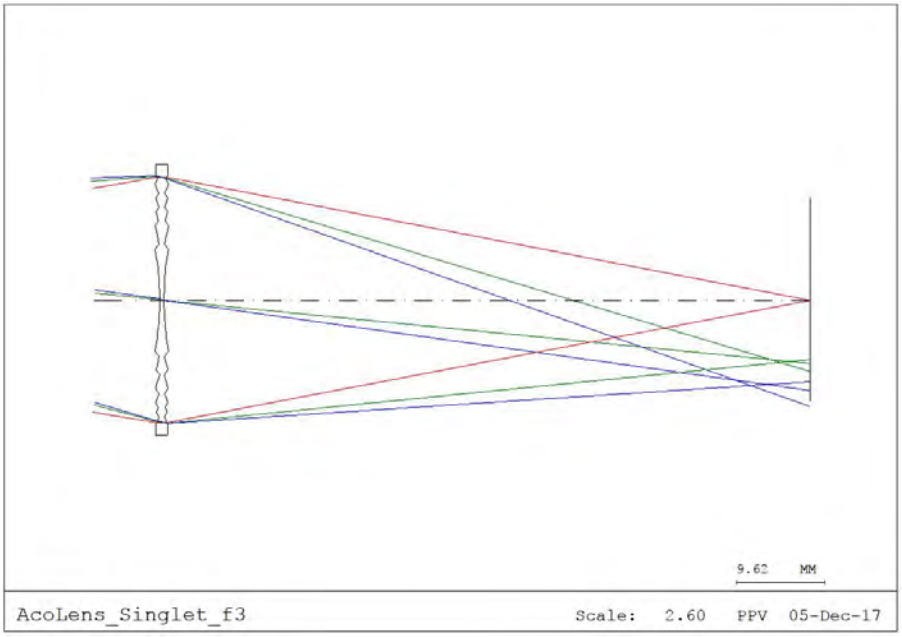
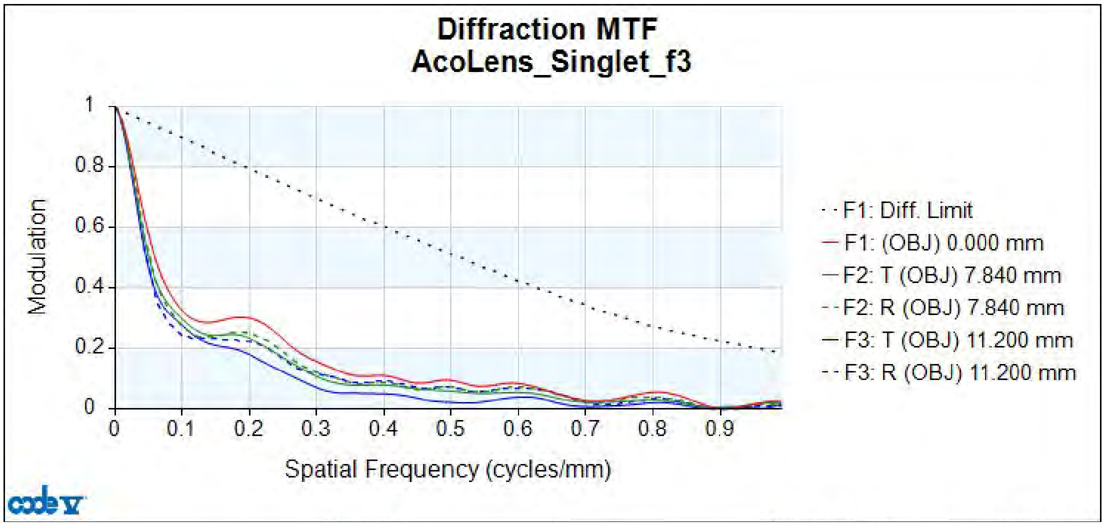
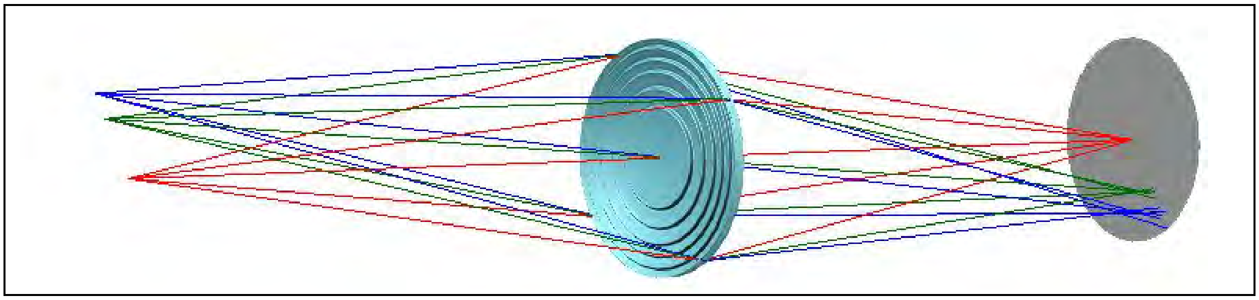


It is worth noting the surface shown in the above 2D diagram of the lens is not what is actually used in ray tracing but just the softwares way of modelling it to lower computational power needed when showing the lens drawing.



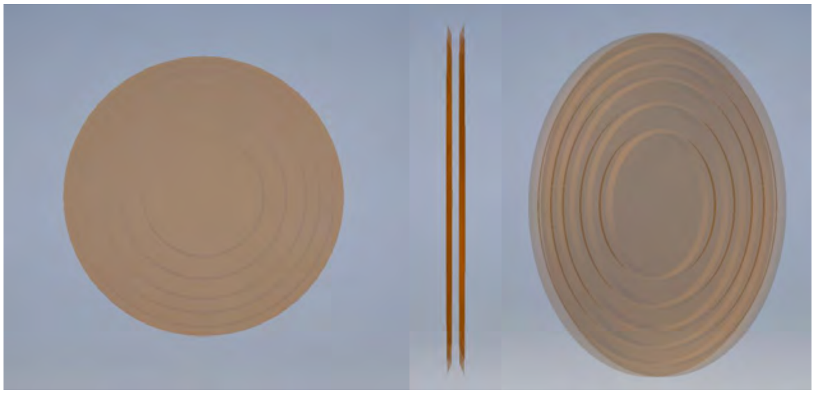
Although this may not reflect the actual performance of an acoustic lens, it is both likely and reasonable that this lens will have considerably lower performance than the starting design as the only parameters changed in the design were image location, center thickness and zone sag. The positive changes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

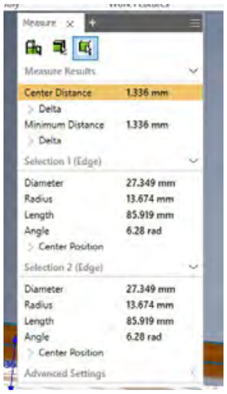


The above is a 3D rendering seen in Code V, this has a more accurate Fresnel surface and is much more similar to that seen when exported to CAD than the 2D counterpart.

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.



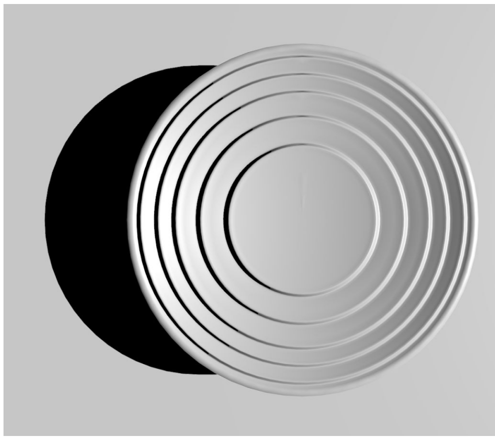


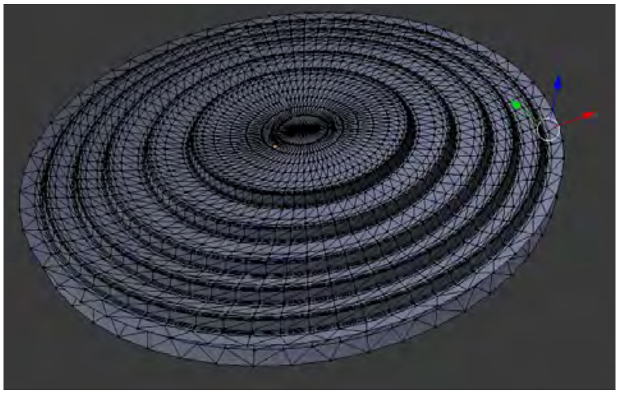
Measure Results
Center Distance 1.336 mm
Delta
Minimum Distance 1.336 mm
Delta
Selection 1 (Edge)
Diameter 27.349 mm
Radius 13.674 mm
Length 85.919 mm
Angle 6.28 rad
Center Position
Selection 2 (Edge)
Diameter 27.349 mm
Radius 13.674 mm
Length 85.919 mm
Angle 6.28 rad
Center Position

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

Blender

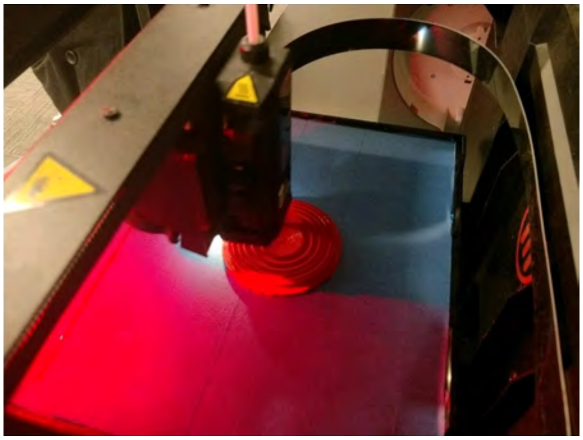
As the two Fresnel surfaces aren't a solid object, we then used Blender to fill in the outer edges to make it so. This process is not ideal and is the main step we will not be using moving forward, but does serve the purpose well enough to get the design printed. The image on the left below is a nice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



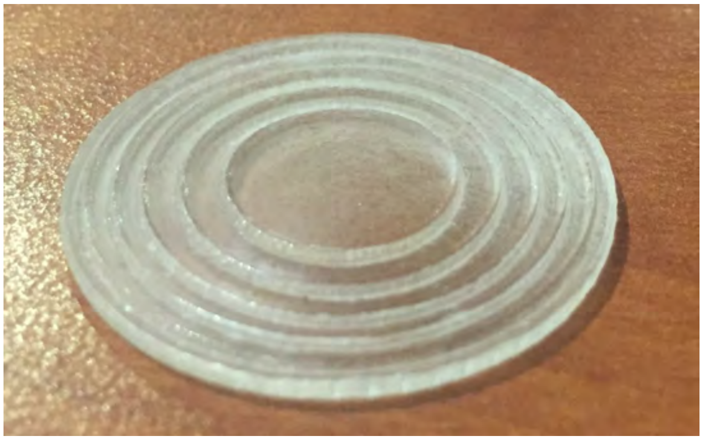


3D Printing

To ensure we could have a 3D printed lens in hand come the presentation, we used the low resolution Makerbot Replicator[5] 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.

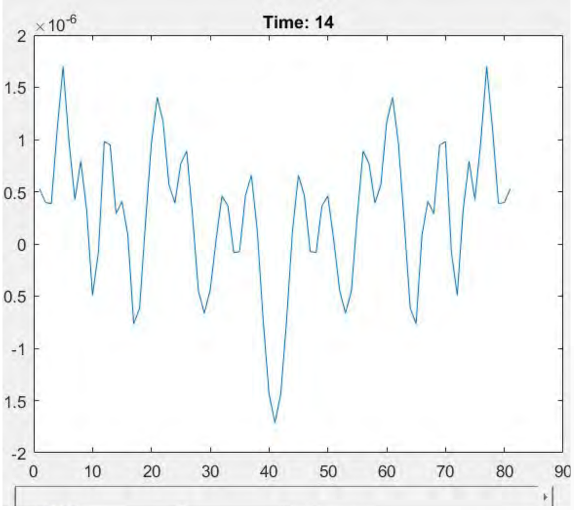
It was at this point we met with James Alkins for the first time, in which he pointed out a better alternative software (Onshape, listed in the resources earlier in this document). He also allowed us to use the high resolution (roughly 28 μm layer thickness [6]) 3D printer, the Objet 30 Pro, in the Rettner Fabrication studio. The pictures below are printed at the original scale and even so are much smoother than those above.

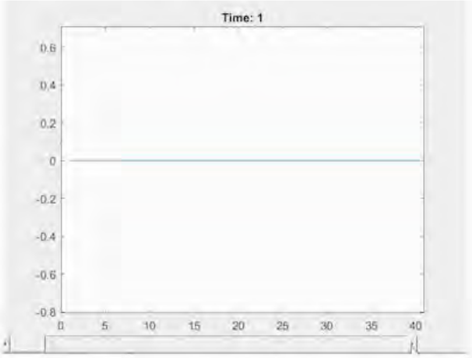


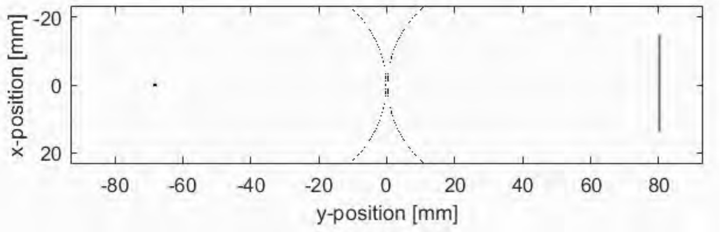

The lens was printed with the VeroClear transparent rigid model material[7], and under suggestion of Prof. Knox, we have recommended Prof. Rao to look into using this higher resolution printer as an alternative to that he has been using for past years, provided the acoustic properties are functional enough to be worth considering.

Appendix III: K-Wave

As mentioned above, the MTF found using Code V is not reliable due to the acoustic to optical differences, so to have some idea of the actual lens performance, the K-Wave toolbox for MatLab is utilized to give the readings of a transducer for an acoustic lens with a point source. 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. It is currently only working with normal spherical lenses but we hope to add fresnel capabilities in the near future (and have come up with a method which we haven't had the time to implement as of submitting this). 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 readings exported from running the simulation are seen below.

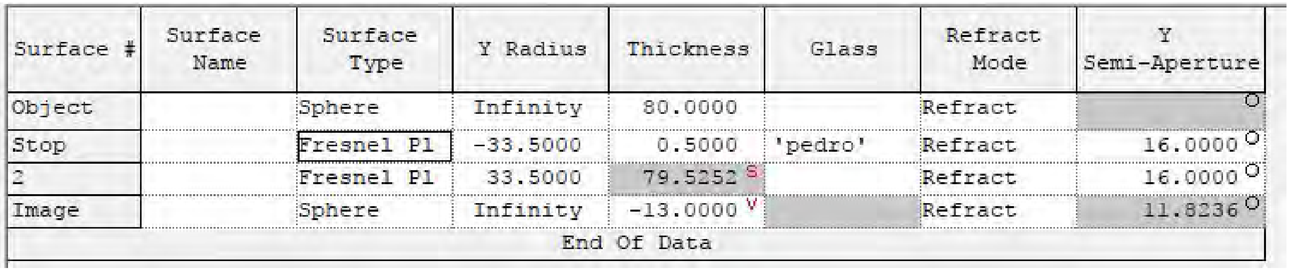




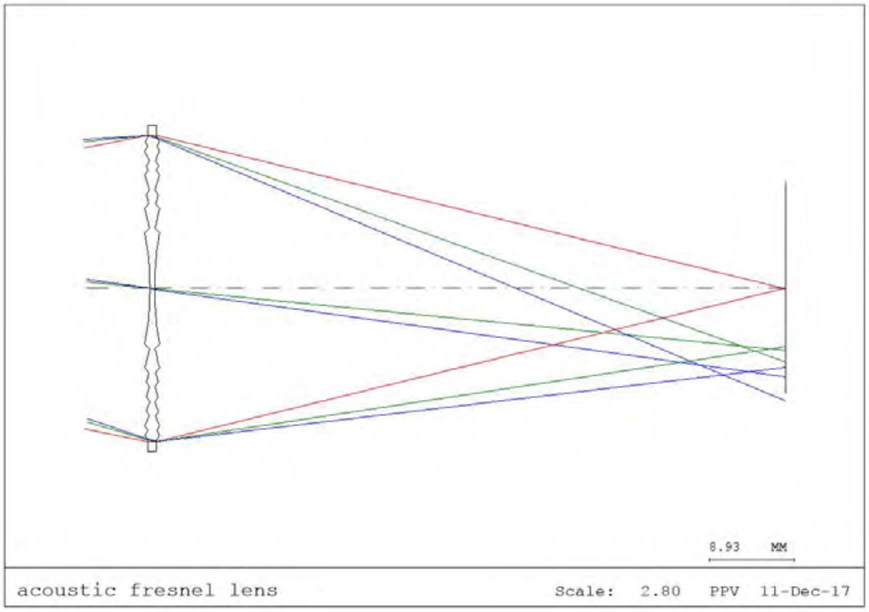


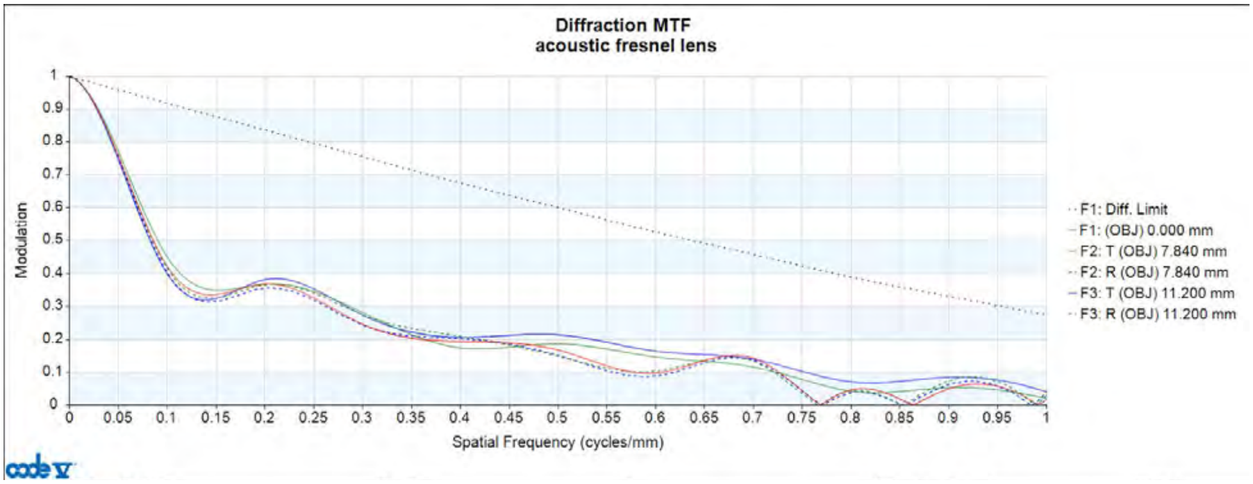
Appendix IV: Updated Fresnel Design

Considering the above design doesn't have the proper diameter required for the system, and the MTF could use some improving, we have gone back to the Code V design and modified it to adjust such, raising the semi-aperture to 16 mm and adjusting the zone sag to 0.54 mm (and again adjusting the image plane to best focus). The results are below.

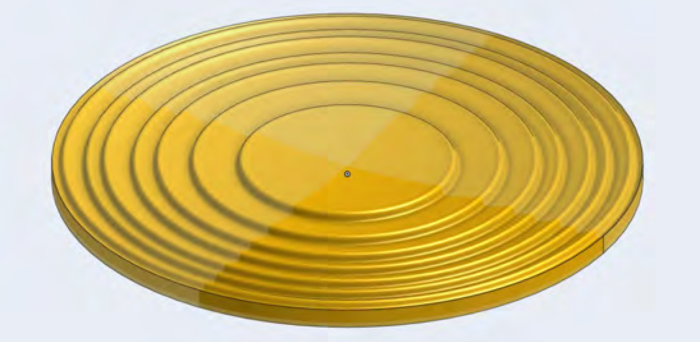


Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	80.0000		Refract	O
Stop		Fresnel Pl	-33.5000	0.5000	'pedro'	Refract	16.0000 O
2		Fresnel Pl	33.5000	79.5252 S		Refract	16.0000 O
Image		Sphere	Infinity	-13.0000 V		Refract	11.8236 O
End Of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





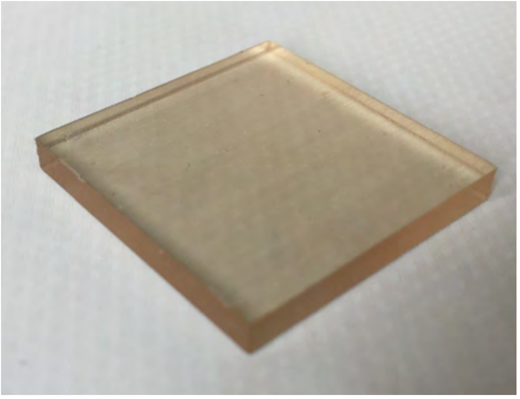
Onshape



By suggestion of James Alkins (who was recommended by Prof. Muir of Mechanical Engineering), we will be using the online cloud-based CAD program known as Onshape for modelling for 3D printing. The above was created using an "export to CAD" feature built into Code V which was then opened and modified in Onshape, but there is noteworthy concerns with this model, mainly in the fact that each successive ring should have a lower difference in radius than the previous, yet the fifth step of the above lens is noticeably wider than the fourth, so instead of just exporting the Code V file to CAD then just converting it to an .stl (the file type used in 3D printing), we may need to define the surface manually in Onshape given the parameters shown in Code V. Considering none of us have yet familiarized ourselves with the software, it is hard to judge how long this process might take. It follows that the initial fresnel lens design we had printed to familiarize ourselves with the process may also have irregularities in step size or curvature that were less visually apparent. This is where the design stands as of writing the document but we hope to have this design finalized and submitted for printing soon enough to have it ready for testing come the Spring Semester.

Appendix V : VeroClear Test Sample

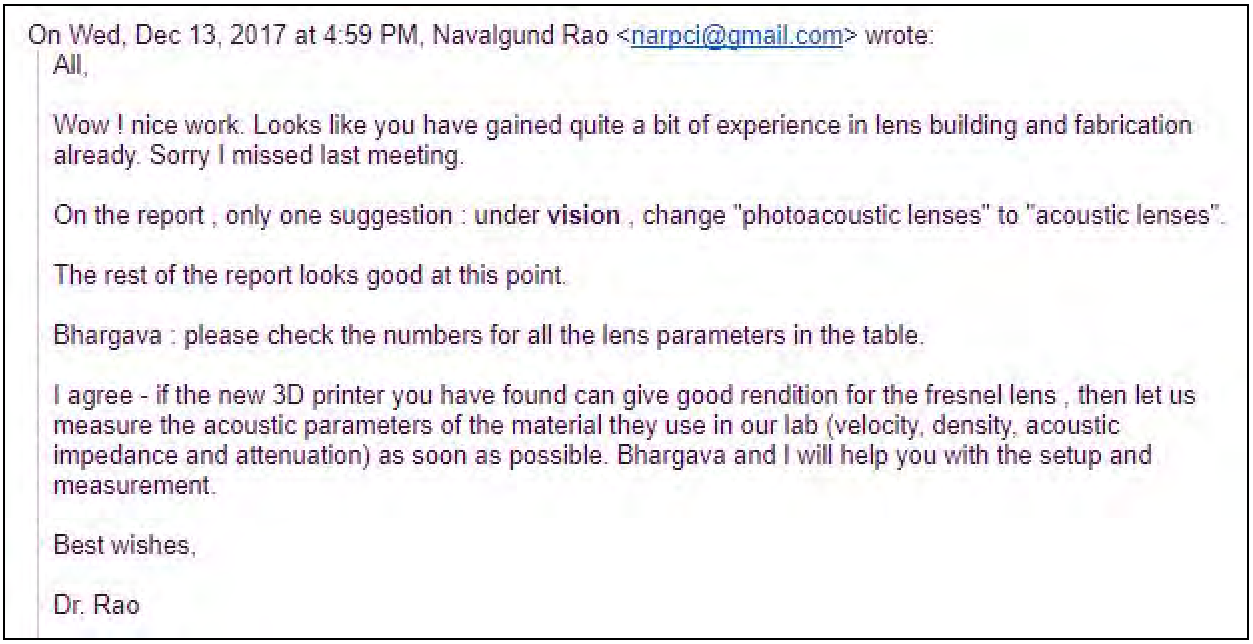
To test the VeroClear transparent rigid model material[7], used in the Rettner Fabrication Lab on campus, a test sample was modelled using Onshape with the dimensions requested by the customer (1 in x 1 in x 3 mm). We have given the sample to Bhargava for testing, and he will measure its acoustic properties and update us with the viability of the material when moving forward with our project.



References

1. Francis, Kalloor Joseph et al. "Characterization of Lens Based Photoacoustic Imaging System." *Photoacoustics* 8 (2017): 37–47. *PMC*. Web. 18 Nov. 2017.
2. American National Standard for the Safe Use of Lasers, American National Standards Institute. ANSIZ136, New York, NY. 2007.
3. "MEASUREMENT REPORT: 3 MHz Matrix Array Transducer" *Imasonic.* RIT. 3 July. 2017.
4. "Accura 25 (SLA) Data Sheet." *3D Systems*. 2017.
5. "MakerBot Replicator 5th Gen Quick Specs" *RedStack.*
6. "Objet 30 Pro Specification Sheet." *Stratasys*. Eden Prairie, MN. 2015.
7. "PolyJet Materials Data Sheet." *Stratasys*. Eden Prairie, MN. 2017.

Email Approval by Customer



On Wed, Dec 13, 2017 at 4:59 PM, Navalgund Rao <narpci@gmail.com> wrote:

All,

Wow ! nice work. Looks like you have gained quite a bit of experience in lens building and fabrication already. Sorry I missed last meeting.

On the report , only one suggestion : under **vision** , change "photoacoustic lenses" to "acoustic lenses".

The rest of the report looks good at this point.

Bhargava : please check the numbers for all the lens parameters in the table.

I agree - if the new 3D printer you have found can give good rendition for the fresnel lens , then let us measure the acoustic parameters of the material they use in our lab (velocity, density, acoustic impedance and attenuation) as soon as possible. Bhargava and I will help you with the setup and measurement.

Best wishes,

Dr. Rao

The above is a screenshot of the email Professor Rao sent as a reply to our near-final PRD. We've made the change he has noted.

When we dropped off the sample described in Appendix V for testing (on 12/15/17 at around noon) with Bhargava, he gave us verbal approval of our numbers in the lens parameter tables (which Prof. Rao had requested in the above email) and also approved of the rest of the document.

Appendix V was added after given approval for the final PRD by the customers using information relayed to us by them both in person and via email and as such does not warrant sending to them for reapproval.