Lens System for Photoacoustic Imaging of Prostate

Design Description Document

OPT 310 - Acoustic Imaging Team

Document Number 002

Revision Level	Date
D	30 April 2015

Revision History

Revision	Major Changes	Date
A	Initial release	3/4/15
B	Added lens dimensions for static designs	3/24/15
C	Updated specification sheet and design constraints	4/15/15
D	Added Existing Design and Future Design sections	4/30/15

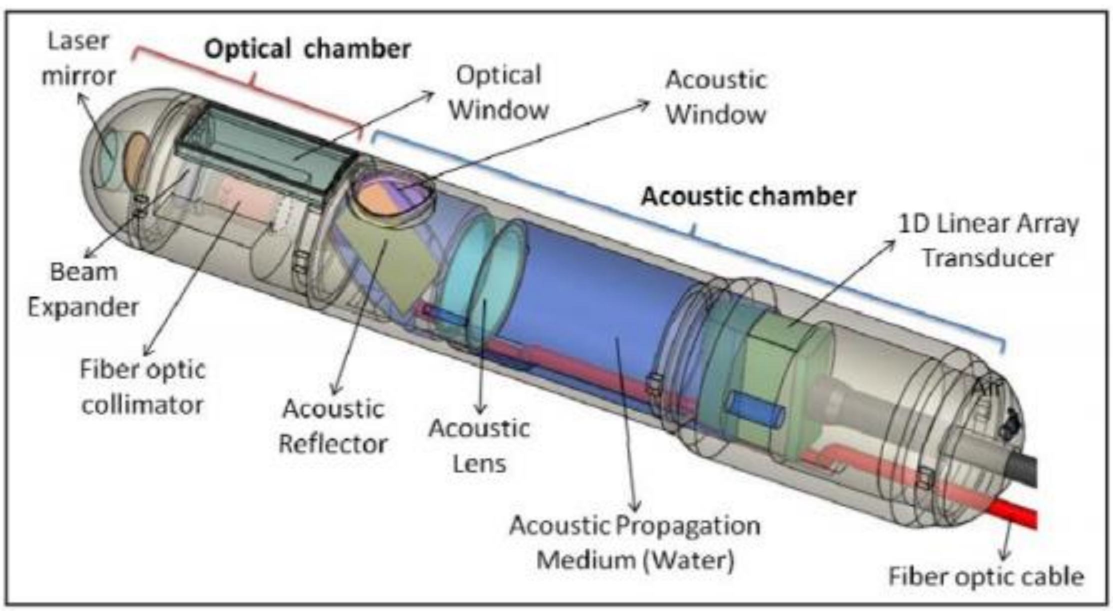
Project Description

Our customers are designing a transrectal probe for imaging prostate tissue. The probe will allow medical professionals to detect and diagnose disorders related to the prostate. The probe works on the principle of photoacoustic imaging. Illumination of the prostate tissue by high-intensity optical radiation causes ultrasonic acoustic signals to be produced. This acoustic signal can be imaged onto a detector such that a region of prostate tissue can be mapped. This produces a real-time video output as doctor is performing the procedure.

This product is currently being developed by Dr. Vikram Dogra, M.D. and Dr. Navalgund Rao, Ph.D. at the University of Rochester Medical Center. Early ex-vivo prototypes for the system exist and are being tested on tissue samples. The current lens system used for imaging the returning acoustic signal is relatively unsophisticated. The goal of the project is to deliver an improved lens system which will produce higher resolution images while satisfying the same design constraints. It is also desirable to add variable magnification functionality to the imaging system to allow the physician to zoom in on regions of interest as well as image different depths of the prostate.

Product Overview

A laser is located at the tip of the probe for generating the high-intensity optical signal. The returning acoustic signal is then collected through an acoustic window and focused onto a transducer array by an acoustic lens system.



Design Scope

This document will describe the design, manufacturing, and testing for the lens system used for imaging the induced ultrasound signal onto an acoustic sensor. This includes the acoustic reflector, acoustic lenses, and acoustic sensor. No other components of the product will be directly addressed. The mounting of these components and the mechanisms for translating them to produce variable magnification are not within the scope of this document.

Lens Design Description

After redirecting the acoustic signal with a reflector, a system of lenses will image the acoustic signal onto an acoustic sensor. The lenses will be immersed in distilled water which reduces the attenuation of the acoustic signal. All of the lenses will be made of Somos Protogen 18420 plastic which matches the acoustic impedance of water. To change the depth of the object plane, the entire lens system and sensor will be translated along the axis of the probe barrel. To change the field of view and resolution, individual elements of the lens system will be moved relative to each other. The design of the mechanisms for producing these movements is not within the scope of this document.

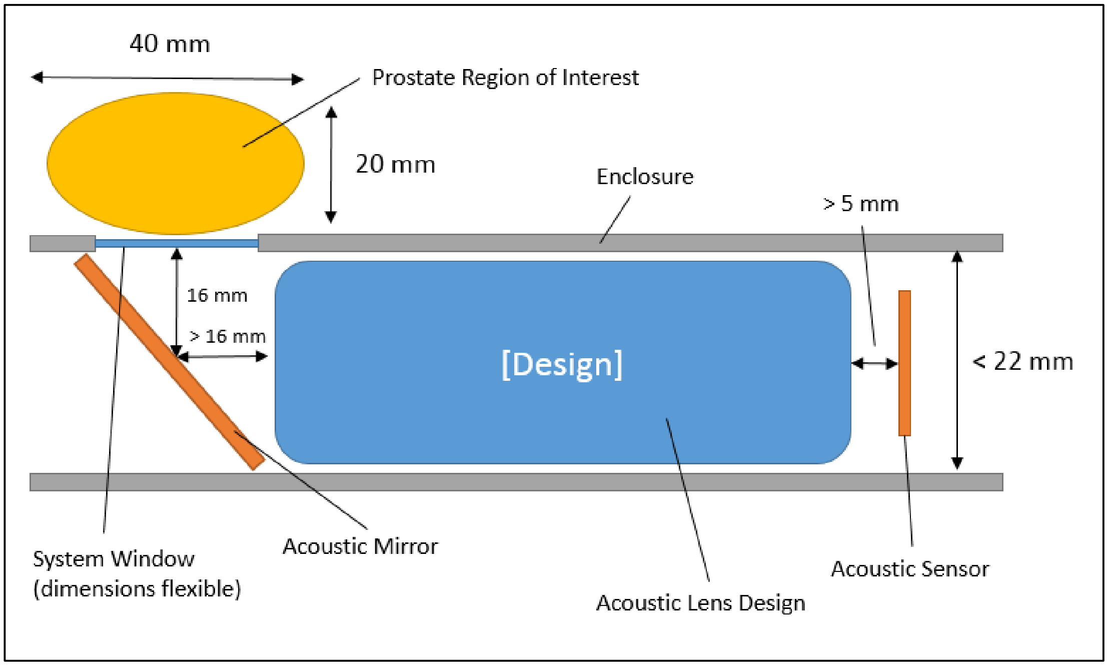
Specific Requirements

Aperture	< f/3
Field (Image)	22.4 mm object diam. (22.4 mm primary)
Wavelength	150, 300 (primary), and 450 µm
Magnification	0.5 - 4
Sensor Size	22.4 x 22.4 mm (32 x 1 pixels)
Pixel Size	0.1 x 1 mm
Nyquist	0.5 lp/mm
MTF (as-built)	0.30 ± 0.04 across field at 0.5 lp/mm
Distortion	< 4%
Telecentricity	n/a
Relative Illumination	> 90% off-axis; no vignetting
Elements	≤ 3 (pending testing)
Diameter	< 22 mm
Length	< 500 mm
Object Clearance	> 32 mm from entrance window
Image Clearance	> 5 mm
Field OPL*	< 2 mm
Airspace Material	All airspaces are water immersed

* Difference on optical path length between the on-axis and off-axis fields. See “Ultrasound Time-gating” below.

Imaging System Diagram

The following diagram outlines the major physical dimensions of the acoustic imaging system.

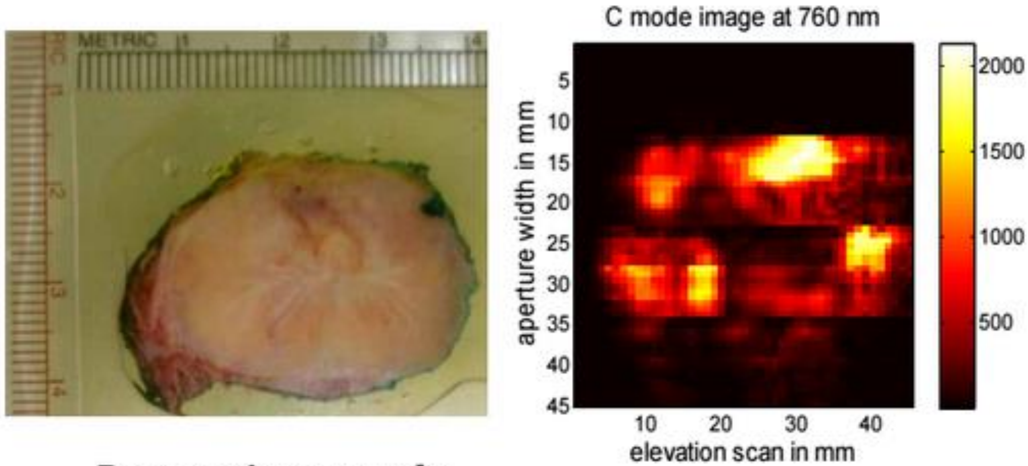


Existing Design

Existing Manufactured Design

The current design used for testing is a singlet lens. The lens is f/3 and 3D printing using Somos Protogen 18420. It has a diameter of roughly 27 mm. This system is unsophisticated and suffers from severe field curvature aberrations which limit the resolution of the image.

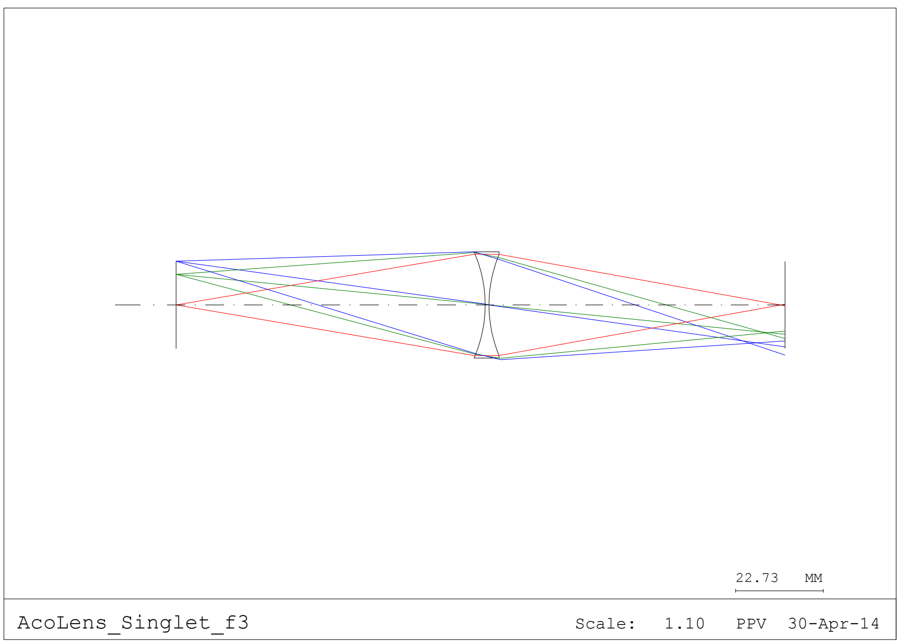
Current Images



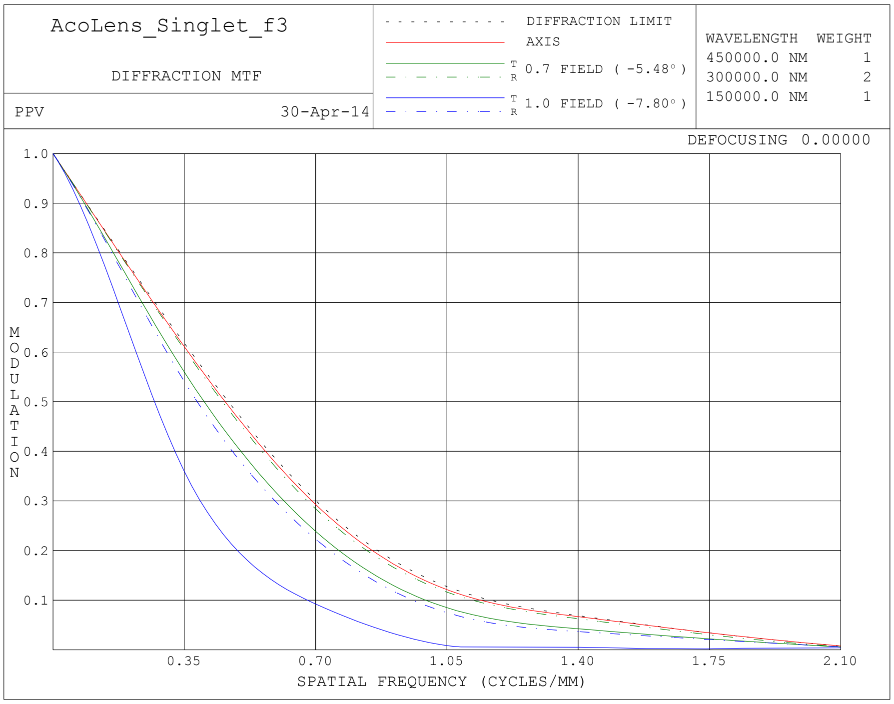
Prostate tissue sample

C-mode PA image of the prostate tissue sample

Lens View



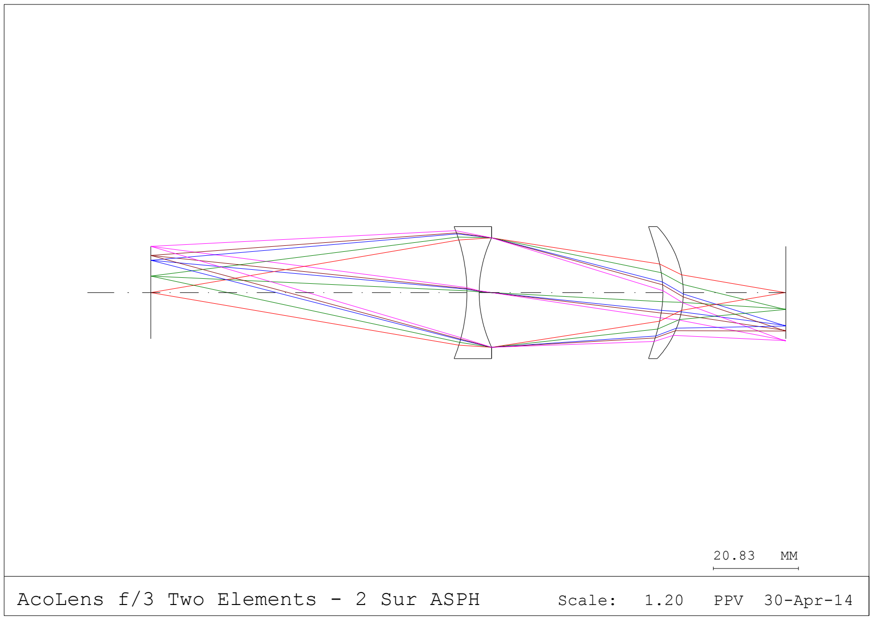
MTF



Existing Theoretical Design

In the Spring of 2014 Pedro Vallejo, an undergraduate optical engineering student at the University of Rochester, created an improved lens system design which has not yet been manufactured. The design uses two lenses with aspheric shapes on surfaces two and three. This dramatically improves the resolution of the imaging system, achieving an MTF of 0.3 at 0.7 lp/mm across all fields. However the system was designed with a relaxed diameter constraint of 32 mm. Furthermore, the MTF requirements of the system have since been reduced to 0.3 at 0.5 lp/mm so this system surpasses the usable Nyquist frequency of the detector. Because of this, the design serves as a good starting point but must be modified significantly to meet updated specifications.

View Lens



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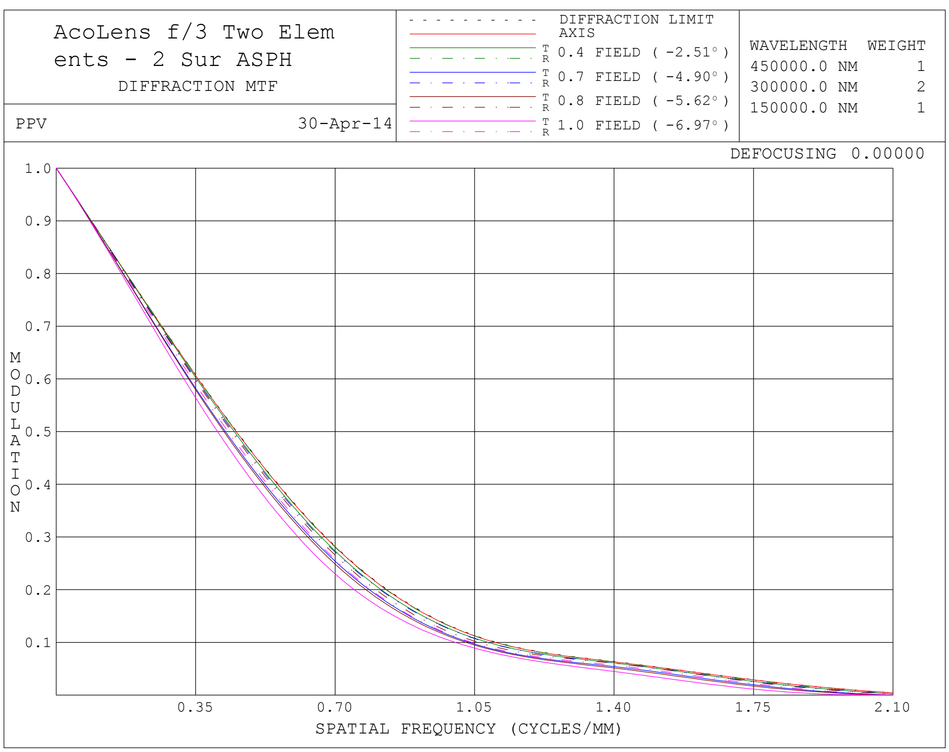


Design Considerations

3D Printing and Surface Shapes

The wavelength of the acoustic signal being imaged is on the order of several hundred microns. This is significantly longer than the wavelength of visible light. Because of this, the surface roughness of the lenses can be much greater while maintaining image quality. In addition, acoustic materials are typically made of plastic. Together, these features make 3D printing a viable manufacturing technique for the acoustic lenses. Midrange 3D printers can achieve resolutions of 30 microns which is sufficiently smooth for the acoustic signal.

Furthermore, because less precision is needed, less precise surface testing techniques can be used. A simple mechanical profilometer can be used to test both surface roughness and surface form. Unlike interferometric techniques which typically assume spherical surfaces, the accuracy of mechanical profilometer is not affected by the surface shape. Because arbitrary surface shapes can be created using 3D printing and tested using mechanical profilometry, aspheric and freeform surface can be used for the acoustic lenses.

Material Selection

Because the imaging system is immersed in water, it is important that the acoustic impedance of the selected materials matches the acoustic impedance water. Similar to electronic systems, impedance mismatching causes reflections at the interfaces which reduces the available signal. Because the available signal is already limited, it is critical that this effect be minimized.

The next important property of the material is the acoustic refractive index or the speed of sound in that material. It is important that this velocity be sufficiently different from the velocity of sound in water so that the acoustic lenses can effectively bend and focus the signal.

Ultrasound Time-gating

In imaging systems, light from the edge of the field of view travels a longer path to reach the detector than light on-axis. In optical systems, this effect is negligible because the speed of light is very fast. However, in ultrasound systems this can cause differences on the order of milliseconds and must be considered.

This is corrected using a technique called time-gating which waits for different portions of the signal to hit different parts of the detector. This limits the rate at which full frames can be captured and processed. As such, the difference in optical path length between the on-axis and off-axis fields should be minimized.

Design Variations

Curved Folding Reflector

The acoustic reflector which folds the signal will be constructed of a metal such as stainless steel or tungsten. This metal can conceivably be machined to any shape using CNC machining. As such, this surface can provide power or aberration correction to the system instead of simply folding the signal. This provides a number of advantages:

- The first focusing surface can be closer to the object making it easier to collect a larger solid angle of the signal
- Because the mirror is angled, it can have a larger diameter and still fit within the diameter constraint of the barrel, again increasing the amount of signal collected
- Fewer lenses and thus interfaces will be necessary for the same imaging performance which will reduce signal loss

There are also multiple disadvantages:

- This will break the rotational symmetry of the system which may require complex freeform surfaces to correct. Although freefrom surfaces will be possible to manufacture, it may increase the complexity and difficulty of the design.
- One simple method for changing the depth of the object plane is to shift the entire lens system and the senor along the axis of the barrel. If the folding mirror was given power, this simple technique would no longer be possible and more complex techniques would be necessary.

Probe Diameter Constraint

The strong lens diameter constraint is due to patient comfort considerations as the probe is inserted into his rectum. However this diameter consideration only applies to the portion of the probe which is inserted into the body. The average person's prostate is located around 4-5 cm into the rectum so the probe will not need to enter farther than this. As such, after 5 cm from the object plane, the 22 mm diameter constraint no longer applies and larger lenses can be used.

Static Magnification Design Discussion

Before a variable magnification lens was design, multiple static magnification systems were designed. There are several motivations for designing and manufacturing these intermediate designs:

- Explore the viability of designs at static points within the desired range. If a design cannot be found at a given magnification value, it is unlikely that a dynamic magnification system can be made over it.
- Verify the quality of the 3D printed manufacturing method.
- Verify the accuracy of optical software modeling at non-optical wavelengths.
- Determine the maximum number of lenses that can be added while maintaining an acceptable signal to noise ratio. This will be determined by adding flat plate(s) to simulate additional lenses.

1X Static Magnification Design

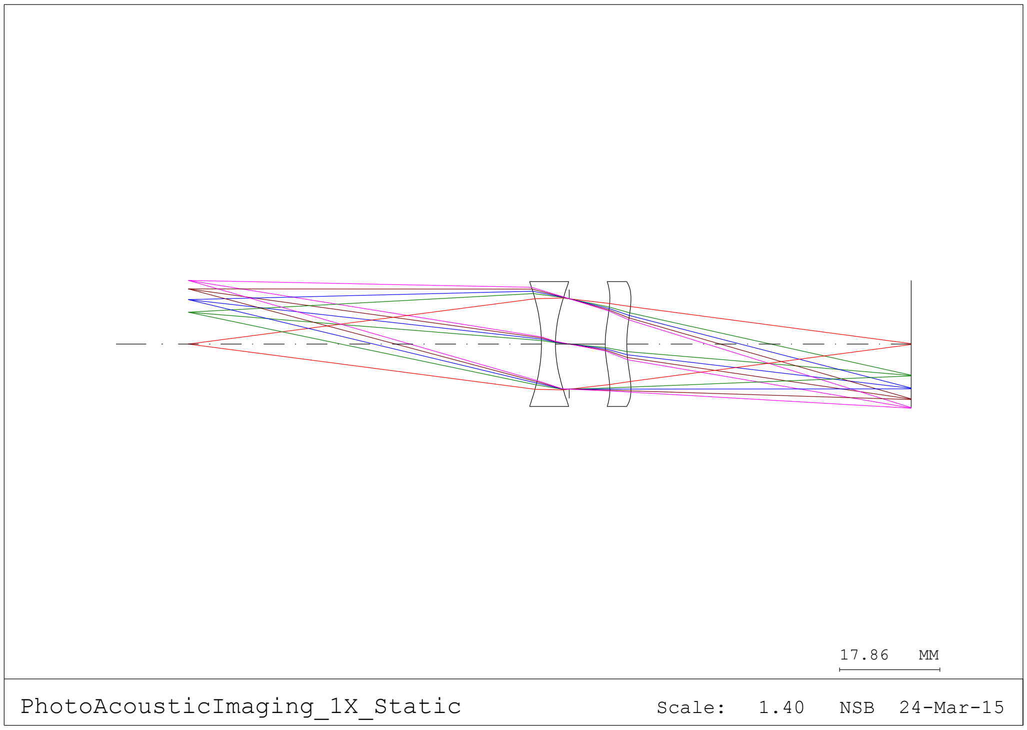
Design Description

This system uses two lenses, each with two aspheric surfaces. The primary purpose of the first lens is to provide focusing power to the system while the second lens corrects for aberrations, primarily the field curvature. The aperture stop is located just beyond the second surface of the first lens.

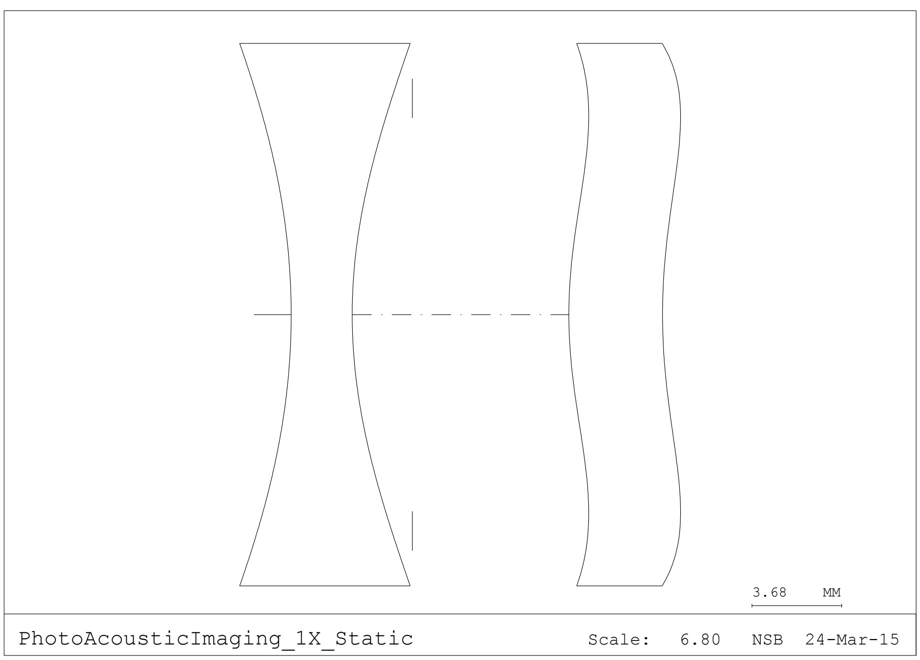
Magnification Specifications

Object diameter: 22.4 mm
Image diameter: 22.4 mm
Magnification: 1

Lens View



Lens Dimensions



Lens 1

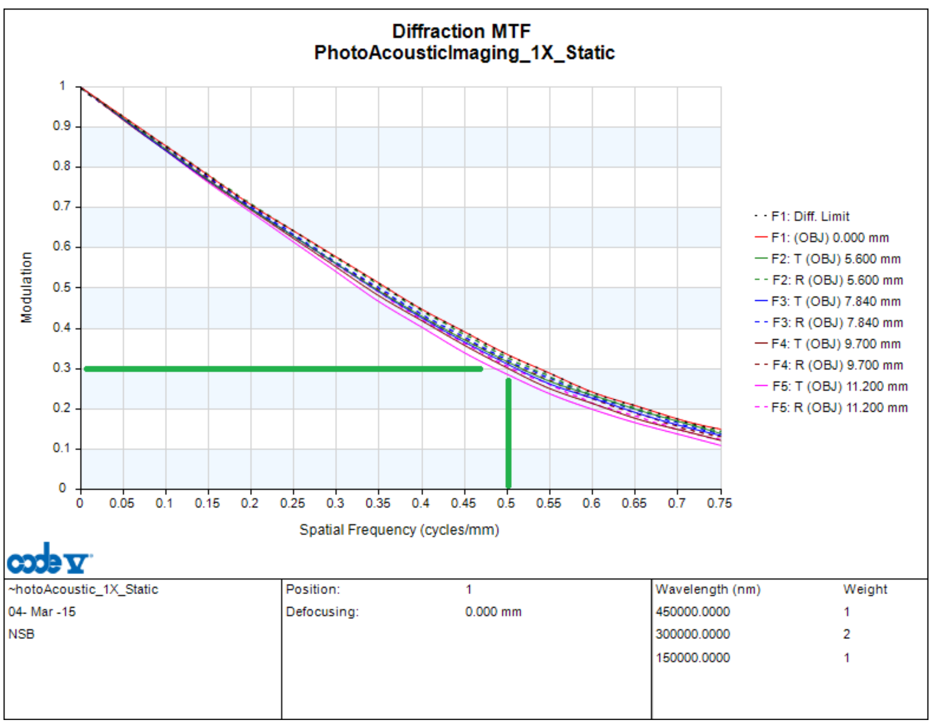
- Center Thickness: 2.5 mm
- Edge Thickness: 7.1 mm
- Diameter: 24.0 mm
- Radius 1 (Asphere*): -27.03 mm
- Radius 2 (Asphere): 21.05 mm

Lens 2

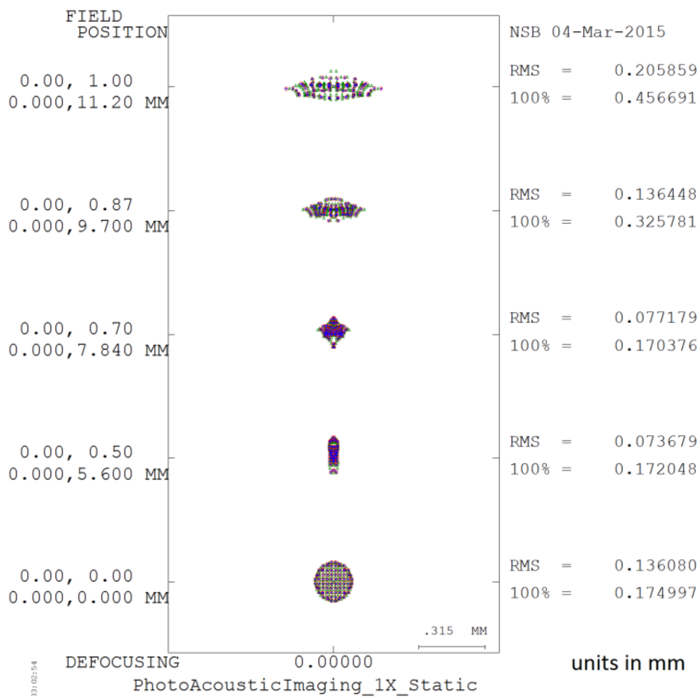
- Center Thickness: 3.84 mm
- Edge Thickness: 3.5 mm
- Diameter: 24.0 mm
- Radius 1 (Asphere): 19.05 mm
- Radius 2 (Asphere): 23.66 mm

* This radius of curvature is heavily modified by aspheric terms and represents only a rough estimate of the shape of the given surface.

MTF



Spot Diagram



Off-axis Optical Path Difference

1.829 mm difference in path length between the on-axis and off-axis ray bundles. For reference, the singlet design was 1.512 mm.

2X Static Magnification Design

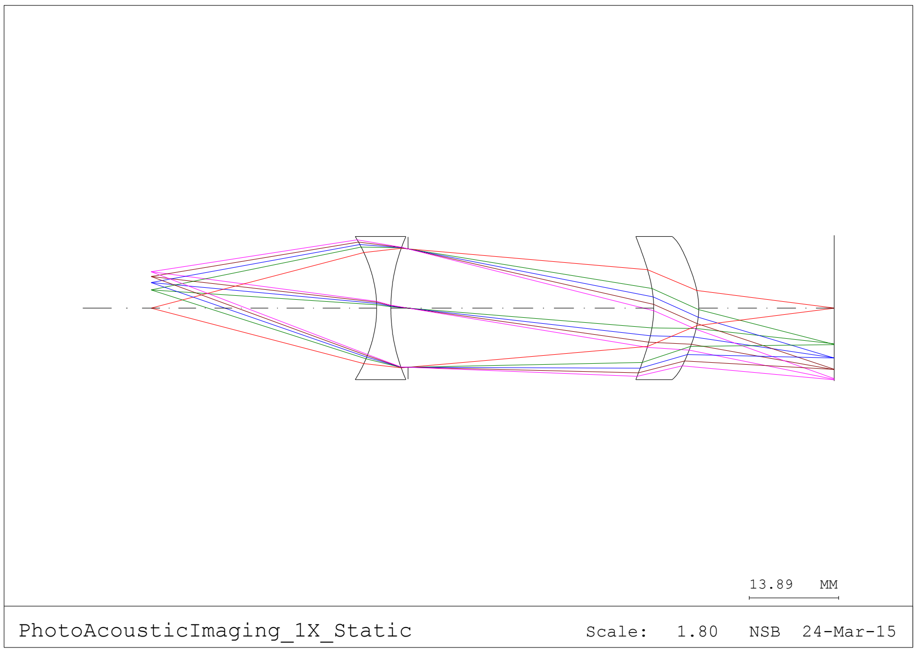
Design Description

This system uses two lenses, each with two aspheric surfaces. The primary purpose of the first lens is to provide focusing power to the system. This focusing lens is located closer to the object plane than in the 1X static magnification design as would be predicted by a first-order analysis. The second lens primarily corrects for aberrations and is located closer to the image plane where it can correct for field curvature. The aperture stop is located just beyond the second surface of the first lens.

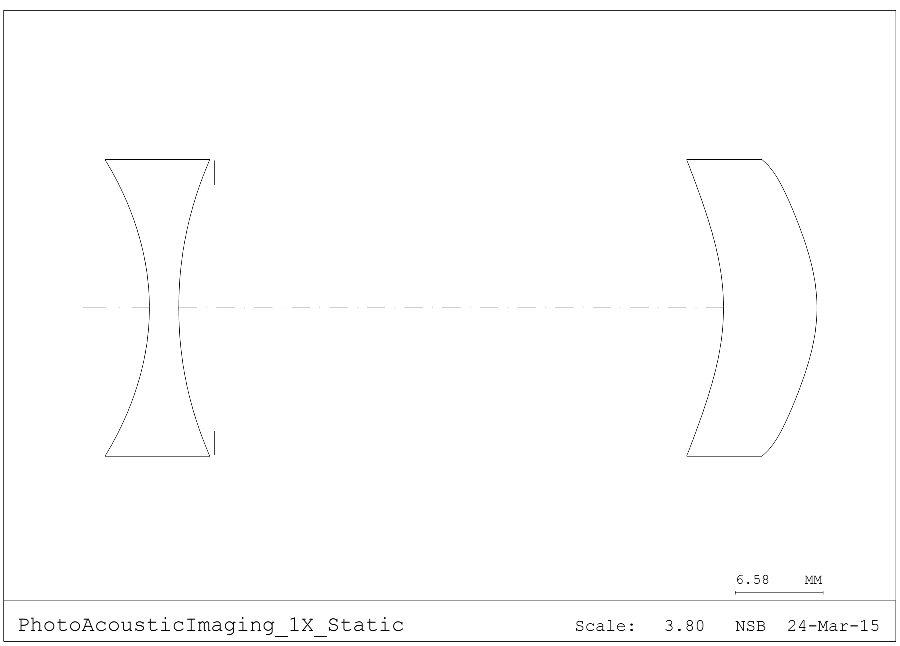
Magnification Specifications

Object diameter: 11.2 mm
Image diameter: 22.4 mm
Magnification: 1

View Lens



Lens Dimensions



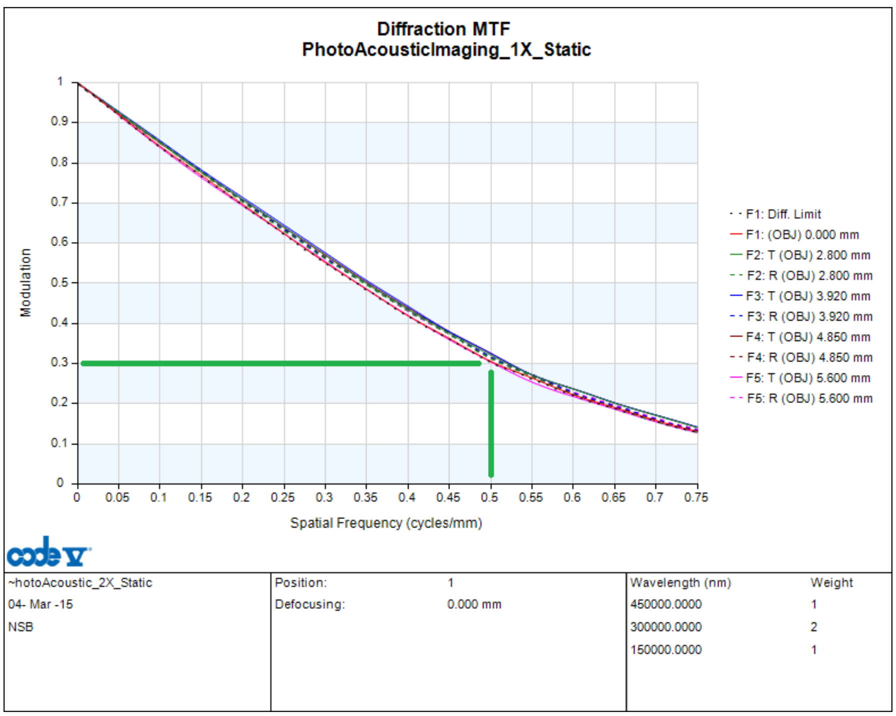
Lens 1

- Center Thickness: 2.20 mm
- Edge Thickness: 7.8 mm
- Diameter: 24.0 mm
- Radius 1 (Asphere): -18.19 mm
- Radius 2 (Asphere): 28.00 mm

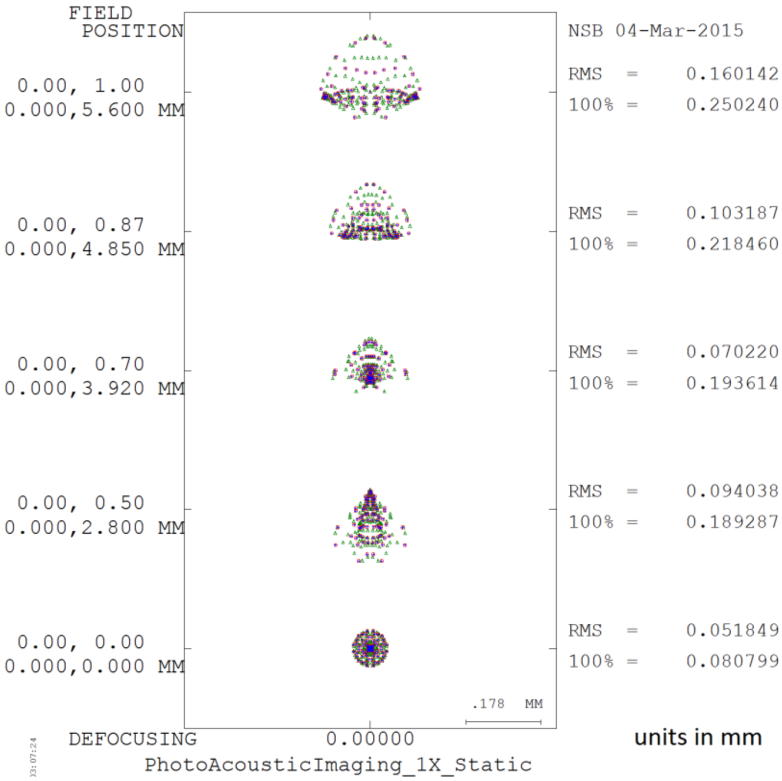
Lens 2

- Center Thickness: 7.00 mm
- Edge Thickness: 5.5 mm
- Diameter: 24.0 mm
- Radius 1 (Asphere): -16.87 mm
- Radius 2 (Asphere): -12.01 mm

MTF



Spot Diagram



Off-axis Optical Path Difference

1.511 mm difference in path length between the on-axis and off-axis ray bundles.

4X Static Magnification Design

Design Discussion

A 4X static magnification design meeting the outlined specifications could not be achieved. At this higher magnification, the primary focusing optic must be closer to the image plane as found by a first-order analysis. In order to maintain enough object clearance for the folding mirror, the entire system must be elongated. This lowers the effective focal length of the system which increases the pupil diameter required to achieve the necessary f-number. The object clearance and diameter constraints cannot be simultaneously met in the case of a 4X magnification. Because of this difficulty, it is very unlikely that a variable magnification system could be designed that incorporates a 4X magnification.

Variable Magnification Design

A secondary goal of the project is to add variable magnification functionality to the system to allow the physician to zoom in on a region of interest. Furthermore, the system should be able to change the depth of the object plane in order to view different sections of the prostate. The first can be accomplished by moving two elements in the system. These will most likely be the first lens, which provides most of the focusing power and thus magnification change, and the sensor, which will refocus the image. The second can be accomplish by translating the entire system including the sensor along the axis of the barrel. Alternatively, this the change in depth can be accomplished by moving a third element in the system. Because the static system designs have not yet been manufactured and tested, a zoom design was not completed.

Future Design

Significant work must still be done to complete the original goals of the project. First, the static magnification designs should be manufactured and tested. This will provide an improved testing system and advise the design of the variable magnification system. Next the variable magnification system should be designed, built, and tested. It is predicted that a 0.5 – 2X magnification specification should be designed.

A stray “light” analysis of the system may also be useful. Currently there are signal reflections off of various component in the barrel which reach the detector and increase noise. A detailed quantitative analysis of these non-sequential paths should reveal primary sources of noise as well as potential solutions for increasing the signal to noise ratio.