Low Cost, Lightweight Solar Concentrator
Product Requirements Document

Team Members: Mike Dupuis, Wanyue Song, Daniel Morgen, Bryan Maas

Customer: Wayne Knox, Professor of Optics Engineering at the University of Rochester

Document 00001

Revision	Date
D	Dec. 10, 2015

Authentication Block

Contents

Revision History

Rev	Description	Date	Authorization
A	First revision of PRD, for Monday presentation	10/31/2015	MD
B	Second revision of PRD, for Friday Presentation	11/14/2015	MD
C	Third revision of PRD, for Friday Presentation. Includes mechanical engineering team requirements, revised specifications, revised OPT101 specifications and build	12/2/2015	MD
D	Final revision of PRD for submission	12/10/2015	MD

Team Members

Michael Dupuis (Project Coordinate, Optical Design advisor)
Wanyue "Fifi" Song (Document Handler, Testing advisor)
Bryan Maas (Customer Liaison, Optical Design advisor)
Daniel Morgen (Scribe, Testing advisor, Safety expert)

Background

Professor Wayne Knox, our advisor, built a solar concentrator in his garage, using plywood, reflective mylar, lots of tape, and a vacuum cleaner. This concave mirror is able to burn lumber, cook burgers, and scorch asphalt in a matter of seconds. The optics senior design team this year is tasked with pushing Knox's design to the next level, increasing the total concentrated power and efficiency.

Product Vision

Archimedes used mirrors to destroy the Roman fleet in 212BC. The vision of this project is to recreate this in modern times as a University of Rochester public relations stunt. It is our intent to build a low-cost, lightweight, high efficiency solar concentrator that is superior to previous iterations of this technology. In particular, we seek to best previous technology through either improved weight or efficiency. Two design options are available—one vacuum based and one inflatable based.

Figure 1: Previous iteration of "vacuum" solar concentrator[1]

---

[1] From WHK presentation "Large Lightweight Low Cost Solar Concentrators"

Environment

As an outdoor solar concentrator based in Rochester, NY, it needs to operate in the following environment:

Temperature
0-100 degrees F – operating range

Humidity
0-100% – operating range

Wind
Should operate at wind speeds of 10mph, with a maximum membrane deflection of 5%. Deflection is defined as the standard deviation of the difference between the desired shape and actual shape of the membrane.

Regulatory Issues

This solar concentrator has the potential to create extremely high temperatures. These temperatures will be enough to burn human skin or cause property damage if there is extended exposure. Users should use extreme caution when operating.

Standards

OSHA 1910.132 "Personal Protective Equipment - General Requirements"
OSHA 1910.133 "Personal Protective Equipment - Eye and Face Protection"
OSHA 1910.138 "Personal Protective Equipment - Hand Protection"

Guidelines

Any user is to take safety precautions including but not limited to heat resistant gloves and Attenuating goggles/glasses
All use of the system and/or prototypes must be under the strict supervision of member(s) of the Solar Concentrator team and/or Professor Wayne Knox.

Fitness for use

The system will:

- Have an overall cost of less than $100 dollars
- Have a maximum weight that allows for an average adult to comfortably hold the concentrator in front of them for 5 minutes of use. We estimate this weight to be approximately 15 lbs.
- More powerful and efficient than Wayne Knox's prototype.
- Have a diameter of 4ft.

It is desirable that:

- We have less weight than Wayne Knox's prototype.
- We meet the requirements of Pedro's challenge (i.e. able to be shipped to third world countries and be easily reconstructed to function properly)

Group Responsibilities

Three groups will be collaborating on this project:

- The first is the optical design team, tasked with designing and optimizing different shapes, curvatures of the membrane, and minimizing aberrations to achieve a high power in a 2 inch diameter disc 10ft away.
- The second is the mechanical design team. They are tasked to investigate the mechanical properties of different materials, such as the effect of frame thickness, and generate virtual models. Also, they are tasked with optimizing the shape of the frames to achieve a lightweight and portable size that could potentially be folded into a tube or box for transport and assembly at a later time.
- The last team consists of three optics 101 students. They assist the two above teams in the testing procedure which includes assembling the calorimeter (see appendix B).

We Are Not Responsible For:

- Optimizing frame development
- Developing a logistical plan to implement "Pedro's Challenge"
- Coordinating a public relations stunt
- Providing emotional support to Prof. Knox when we beat his prototype
- All CAD & FEA

Process Flowchart

The following flowchart illustrates the approach used in designing, building, testing, and revising our project prototypes.
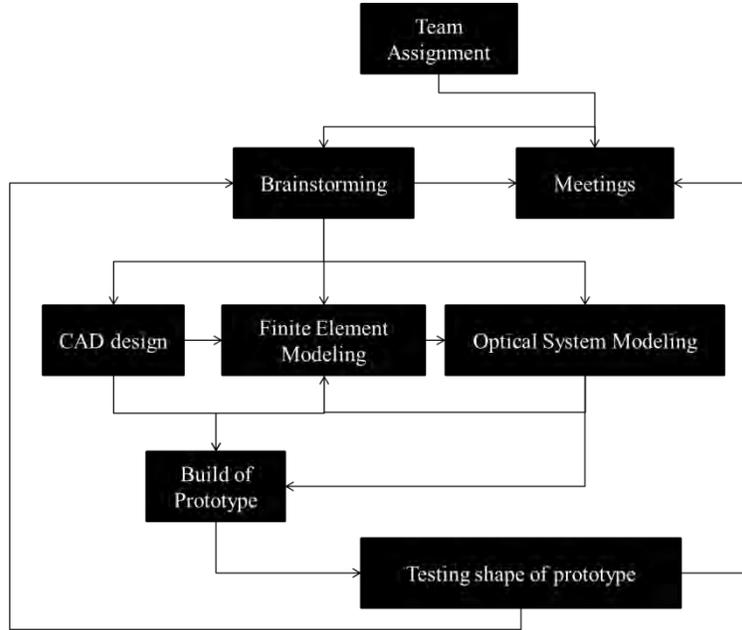

Figure 2: Flowchart of team decision-making and action.

Specifications

Mechanical Specifications	
Mirror Diameter	4ft
Weight	15lbs
Pressure Stability	Maintain shape for 10 minutes
Pressure Differential	0.1 psi

Optical Specifications	
Total Power enclosed in 2in diameter circle	Better than Wayne Knox
Spot size	2 inches diameter
Wavelength	VIS-IR (sunlight)

Budget

Part Name	Description	Supplier	Part Number	Unit Cost	Quantity	Units	Subtotal
Oriented Strand Board	Common: 7/16 in. x 4 ft. x 8 ft.; Actual: 0.418 in. x 47.75 in. x 95.75 in.	Home Depot	386081	$10.45	2	EACH	$20.90
2 in. x 4 in. x 10 ft. lumber	Standard & Better Kiln-Dried Heat Treated Spruce-Pine-Fir Lumber	Home Depot	161659	$3.72	2	EACH	$7.44
#8 x 2-1/2 in. Wood Screws	Philips Bugle-Head Coarse Thread Sharp Point Polymer Coated Exterior Screws	Home Depot	PTN212S1	$8.47	1	PACK	$8.47
Foylon	4 1/2' X 25' Foylon Roll	Harvest Moon Hydroponics	N/A	$27.80	1	ROLL	$27.80
Reflective Mylar Film	25 ft. Mylar 2 mil Reflective Film	Home Depot	VMY130	$29.97	1	ROLL	$27.80
Packaging Tape	Scotch 1.88 in. x 22.2 yds. Heavy Duty Shipping Packaging Tape with Dispenser	Home Depot	142-DC	$2.97	1	EACH	$2.97
Gorilla glue	2 fl. oz. All-Purpose Adhesive	Home Depot	269	$4.97	1	EACH	$4.97

Table 1: Bill of materials for first vacuum prototype. Total cost is $100.35.

Intellectual Resources

The following individuals will be necessary as advisors to our team:
- Chris Muir (UR, Mechanical Engineering) for FEM and CAD help
- Wayne Knox (UR, Optical Engineering) for system help
- Julie Bentley (UR, Lens Design) for membrane shape help

The following software is necessary for design:
- LightTools (Optical raytracing)
- MeshLab (point cloud cleaning and formatting)
- MATLAB (point cloud editing for LightTools import)
- NASTRAN (finite element modeling)
- Siemens NX (CAD modeling)

00001   Rev D

Timeline

Date	Action Items (OPT and ME)	Meetings
Week of 11/1/2015	Submit BOM, Order materials	Meet as a team with Knox on Monday
Week of 11/8/2015	Develop testing/manufacturing methods, CodeV/LightTools design study	Meet as a team with Knox on Monday
Week of 11/15/2015	Build 1st prototype "Jolanda". Met with OPT 101 team to involve them in testing process	Meet as a team with Knox on Monday
Week of 11/22/2015 (Thanksgiving week)	Compare the previous team's caliper and string testing method with our depth sensor method. Refine models and design studies. Carve off a requirements document for the MechE team	Meet as a team with Knox on Monday
Week of 11/29/2015	Build 2nd prototype to compare an alternative material, foylon, and improve tensioning method to avoid wrinkles on the mirror's edge	Meet as a team with Knox on Monday
End of Fall semester	Finish final PRD, prepare for final presentation, build calorimeter with OPT101 students	Meet with Knox and ME's on Monday
December - January	Optical modeling – what is the optimal shape? Determine testing procedures for measuring shape of Mylar membrane (comparing point cloud to last years string method), evaluate concentrator prototypes, refine FEM analysis	Meet with Knox and ME's on Monday
February - March	Build 4ft diameter prototype, test Foylon and Mylar, test spray rubber, develop method for changing membrane shape with FEA	Meet with Knox and ME's on Monday
April - May	Further optimization of membrane shape, testing and analysis of Knox's prototype with calorimeter, finish final design, prepare for design day	Meet with Knox and ME's on Monday

Appendix A: Solar Concentrator Assembly Process

General Purpose

The purpose of this document is to outline a general procedure for the construction of solar concentrators. Though this process will evolve as we continue our work, this document will serve as a baseline for future builds.

Components and Required Materials

- Frame
    - Plywood
- Reflective Surface
    - Mylar or Foylon
- Gap Insulation
    - Weather Stripping
- Miscellaneous components
    - Aluminum flashing
    - Aluminum tape (mylar onto aluminum flashing)
    - Screws
    - Sharpie
- Tools
    - Jig saw
    - Drill
    - Clamps
    - Screws
    - Safety Goggles
    - Tin Snips

Step-by-Step Build

1. Create a schematic of the build process
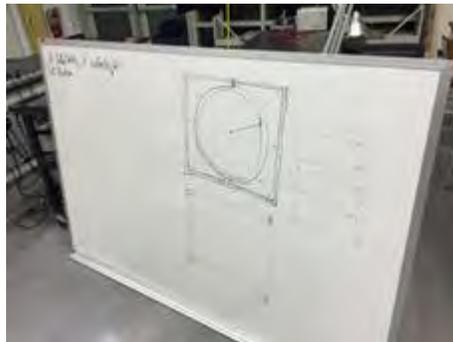
2. Measure and outline areas on plywood that will be cut to create frame. Note, two of the side pieces must be shorter than the others in order to create the overlap necessary for a box frame. The circular outline is created by first putting a screw in the center of the circle. Next a string with the desired radius of the circle is attached to the center screw on one end and a sharpie on the other. The sharpie is then turned in a circular pattern while holding the string taught. This will create the desired circular outline.

3. Cut wood with jig saw to desired specifications to create the backs and sides. Next, using a drill, make about a 1 inch diameter hole to serve as the input for our vacuum. Make sure to appropriately clamp all wood to workbench. In addition, always make sure to be wearing safety goggles.

00001   Rev D

4. Creating the wooden top, with a hole cut out of it for the mirror, is somewhat of a trickier process. A "starter hole" must be created first, in order to allow for the jig saw to navigate through the circle. From there, the circle can be cut.
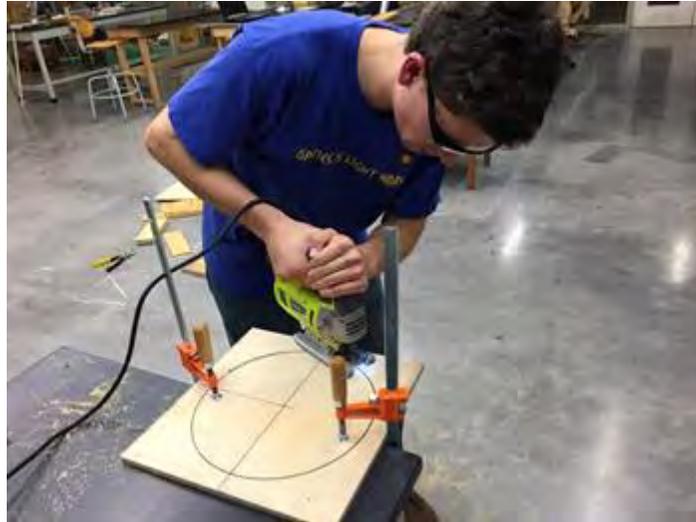

5. Weather strip all connection points between the frame components

00001   Rev D
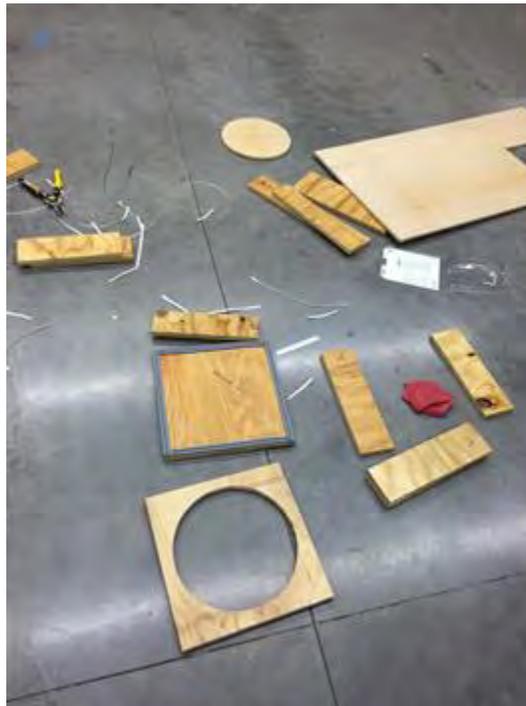
6. Assemble the frame using screws and the drill.

7. Cut out two sections of aluminum flashing into "arches" with the tin snips that go around the circle but do not exceed the dimensions of the frame. It is extremely important to not exceed the dimensions of the frame, as the flashing is extremely sharp.

00001   Rev D
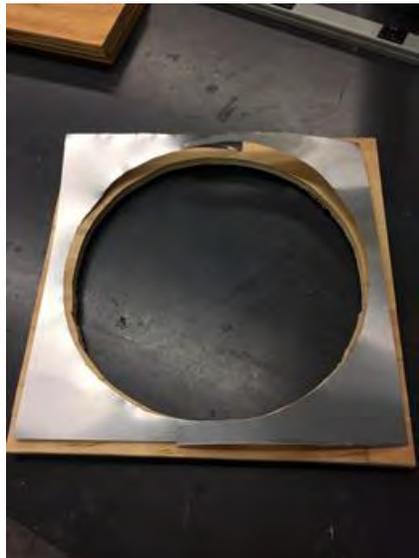
8. Assemble the frame. This includes screwing the aluminum flashing in place.

9. Cut out a circular portion of reflective membrane that approximately fits over the frame. Hold the reflective membrane portion over the cutout and snip down any extraneous material so that there is about an inch of membrane exceeding the limits of the circle. Now tension the membrane around the circle and, using aluminum tape, tape down the membrane to the flashing.

10. Test the membrane using a vacuum pressed against the 1 inch diameter hole to create a pressure differential. If it appears that there is some form of major leakage, continue to apply aluminum tape to gaps.

00001   Rev D

Appendix B: OPT 101 Project Procedures-- Calorimeter Project

Document Goal

The purpose of this document is to outline the procedures necessary for the OPT101 students to build and use a calorimeter for the "Low-cost, lightweight solar concentrator" optics senior design team.

Background: Solar Concentrator Project

Professor Wayne Knox built a solar concentrator in his garage, using plywood, reflective mylar, lots of tape, and a vacuum cleaner. This concave mirror is able to burn lumber, cook burgers, and scorch asphalt in a matter of seconds. An optics senior design team this year is tasked with pushing Knox's design to the next level, increasing the total concentrated power and efficiency.

OPT101 Task

The project for the OPT101 students is to build a calorimeter for Professor Knox's senior design team. A calorimeter is a device used to measure heat transfer, and can consist of a thermometer in a metal bucket filled with water. The purpose of this calorimeter in the senior design project is to evaluate the performance of the team's prototype in comparison to Professor Knox's prototype.

Calorimetry

The fundamental equation for calorimetry is $q = C\Delta T$. The energy imparted on the system is q, the heat capacity of the system is C, and the change in temperature is ΔT. For a simple system of a bucket filled with water, the equation can be rewritten as $q = q_c + q_w = (C_c + C_w)\Delta T$. The heat capacity of the bucket is C_c, and the heat capacity of water is $C_w = m_w s_w$. The specific heat of water, s_w, is 4.184 J $^{\circ}$C^{-1} g^{-1}. The mass of water, m_w, can be calculated from its volume and density. This means that, to calculate q, we need to measure C_c and calibrate the calorimeter. This can be done by imparting a known amount of heat to the system to a known amount of water.

Building Procedures

1. Find a thermometer.
2. Range: 0°F to 250°F
3. Precision: 5°F
4. Find a watertight metal container that is rectangular in shape. Do some research, you might be able to find this at the UR, online, or you might have to machine it!
5. Dimensions: 6" x 6" x 6"
6. Wall thickness: ⅛"
7. The container must have a watertight lid, with a hole in it for the thermometer!
8. Paint the outside surface of the container black. This is easiest done with spray paint.
9. Accurately measure the volume of water that fills the box, with the thermometer in place.
10. Attach the thermometer to the lid, and seal the hole.

Calibrate the calorimeter

1. Fill box with water. Seal lid.
2. Record initial temperature of water.
3. Impart a known amount of energy to the system, via a bunsen burner.
4. Record the final temperature of the system.
5. Divide the known energy quantity by the temperature difference, and subtract the heat capacity of the water. This value is the calibrated heat capacity of the calorimeter.

Testing Procedures

1. Fill box with water. Seal lid.
2. Record initial temperature of water.
3. Focus sunlight on black surface of box.
4. Every 5s, record the temperature of the water.
5. After 2 minutes, plot the temperature vs time.
6. The slope of the trendline is (total power / total heat capacity).
7. Solve for total power.

Breadcrumbs

For more about calorimetry:
http://www.chm.davidson.edu/vce/calorimetry/heatcapacityofcalorimeter.html
https://en.wikipedia.org/wiki/Calorimeter
For more about the solar collector:
https://drive.google.com/file/d/0B05dV5tzBTCNSWJ3TDR3NHZZd2M/view?usp=sharing
For design ideas:
https://www.google.com/webhp?sourceid=chrome-instant&ion=1&espv=2&ie=UTF-8#q=watertight+metal+box

Appendix C: Requirements for ME205 students

A team of four students from Chris Muir's ME205 class will be assisting the optics team in the Lightweight, Low Cost, Solar Concentrator project. The purpose of this document is to outline the roles of the Mechanical Engineering team.

Team Members

The mechanical engineering team will consist of:
- Sean Reid
- Jacob Blacksberg
- Michal Adar
- Henry Pablo

Background and Introduction

The solar concentrator project consists of three major design studies:

1. What is the optimal membrane shape to meet the optical specifications? (LightTools)
2. How can the membrane shape be mechanically controlled? (NASTRAN)
3. Design and manufacture of frame for tensioning Mylar sheet. (NX)
   - Is the frame design lightweight?
   - Is the frame design portable?
   - Can the design operate under vacuum OR pressure conditions?

The ME205 students are responsible for design study 2, the FEM analysis of the Mylar membrane, and design study 3, the design and manufacture of the lightweight, portable, dual-use frame for tensioning Mylar.

Responsibilities of ME205 students (Design Study 2)

- Create model of uniform thickness Mylar membrane under uniform tension and pressure, subject to a fixed translation constraint
- This model must be compared with the measured point cloud data
- Characterize how changing model parameters (Mylar thickness, boundary conditions, applied load, material properties) affects membrane shape
- Propose an optimal process for achieving a desired membrane shape (for example, spray rubber)
- Analyze the analytical solution to the uniform thickness deformed membrane, for further insight (may be nonlinear)

Responsibilities of ME205 students (Design Study 3)
The ME students are responsible for the following deliverables, in the following order:
- At least 15 different ideas for a method to tension Mylar in a lightweight, portable manner
   - Sketches are good
   - CAD and preliminary FEM is better

00001   Rev D

- A Pugh matrix objectively comparing each idea in the following categories (each category discussed in next section):
  - Total Cost
  - Total Weight
  - Failure load
  - Time taken to assemble
  - Ease of manufacture
  - Material availability
  - Uniformity of Mylar tensioning
  - Selection of optimal design and reasoning
  - FE analysis of selected frame design in NASTRAN calculating the following:
  - Total weight of structure
  - Failure load in buckling
  - Failure load in stress
  - Uniformity of Mylar tensioning (a variance of materials problem)
- Bill of materials of necessary components, with the following categories:
  - Part Name (Ex. "Black-Oxide Alloy Steel Socket Head Cap Screw")
  - Part Description (Ex. "6-32 Thread, 1/2" Length")
  - Supplier (Ex. "Mcmaster-Carr")
  - Part Number (Ex. "91251A148")
  - Unit Cost (Ex. "$8.25")
  - Units (Ex. "PACK")
  - Quantity (Ex. "2")
  - Subtotal (Ex. "$16.50")
  - Total Cost (Ex. "$204.75")
- Procedures for manufacturing/assembling components
- Custom frame for tensioning Mylar sheet meeting all specifications

Specifications of Design

The frame design must meet the following specifications.

Specification Description	Logic	Value	[units]
Total Cost	<	100	[US dollars]
Total Weight	<	15	[lbf]
Failure Load	>	50 (estimation)	[lbf]
Time of Assembly	<	30 (estimation)	[minutes/prototype]
Uniformity of Mylar tension*	>	90	[%]
Manufacturing time	<	2	[hours/prototype]
Lifetime**	>	24	[hours/tensioning]

* The uniformity metric is calculated according to the following equation:

$$U = 1 - \sigma_{stress}$$

00001   Rev D

Where U is the uniformity and σ_{stress} is the standard deviation of the membrane stress when subject to a tension-only load (no pressure differential applied).

** The lifetime is defined as the time of continuous use that the membrane can withstand, without significant shape variance, under pressure differential without being re-tensioned. "Significant shape variance" is defined as greater than 5% standard deviation of the desired membrane shape minus the actual shape.

Appendix D: Importing point cloud measurements into LightTools

Point Cloud Measurements

To characterize the shape of the vacuum-tensioned Mylar, an Asus Xtion Pro 3D scanner, which is similar in operation to an Xbox Kinect but has a higher depth resolution. The Xtion Pro outputs a rectangular intensity image, with each pixel value corresponding to a depth. The depth resolution of the Xtion Pro is specified as 100 microns, but in practical use is about a millimeter.

Procedures

The Mylar surface was positioned at 1 meter from the 3D sensor.
Six depth images were captured at various angles to the membrane. This is to ensure that all gaps in the point cloud data are filled.
The images are saved as .TXT files with comma delimeters.

Formatting Point Clouds for LightTools

The raw data from the Xtion Pro is messy, noisy, full of gaps, unitless and contained in several independent images. To convert this raw data to a format that the LightTools freeform surface interpolator can understand, a combination of actions/functions in MeshLab and Matlab must be implemented. MeshLab is a free graphical implementation of point cloud and mesh algorithms, useful for visualizing and cleaning point cloud data. It can be found here.

00001   Rev D

Procedures

1. Load .TXT files into MeshLab. Set the import settings as shown below:
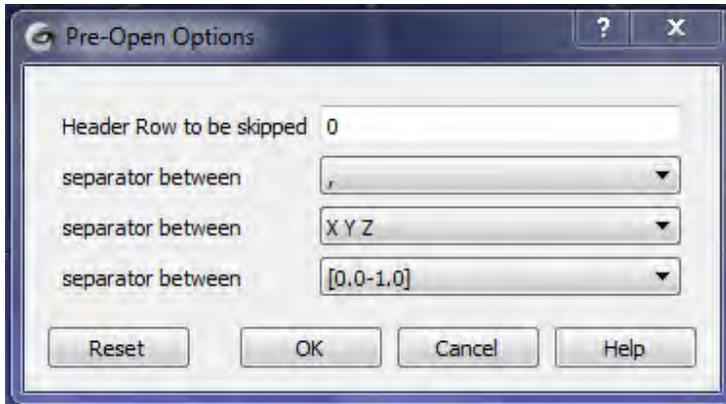
2. The raw data will look like the following image. Messy, noisy, and filled with unwanted features.

00001   Rev D
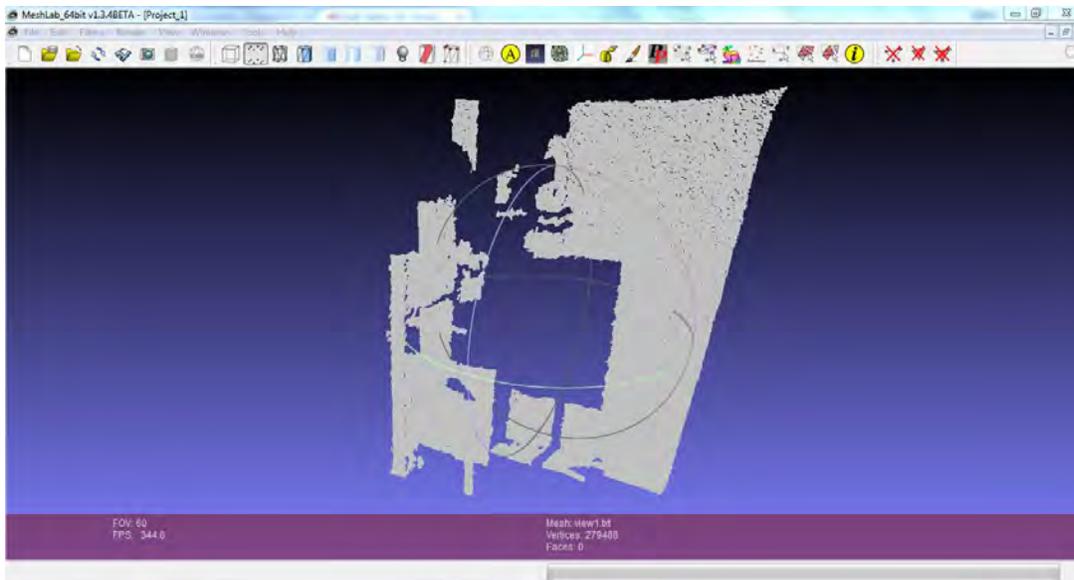
3. Select unwanted points using this button, found on the top toolbar: [button image] It may be helpful to turn the model to the side, as the mirror is probably the closest object in your cloud. The points turn red after you select them.
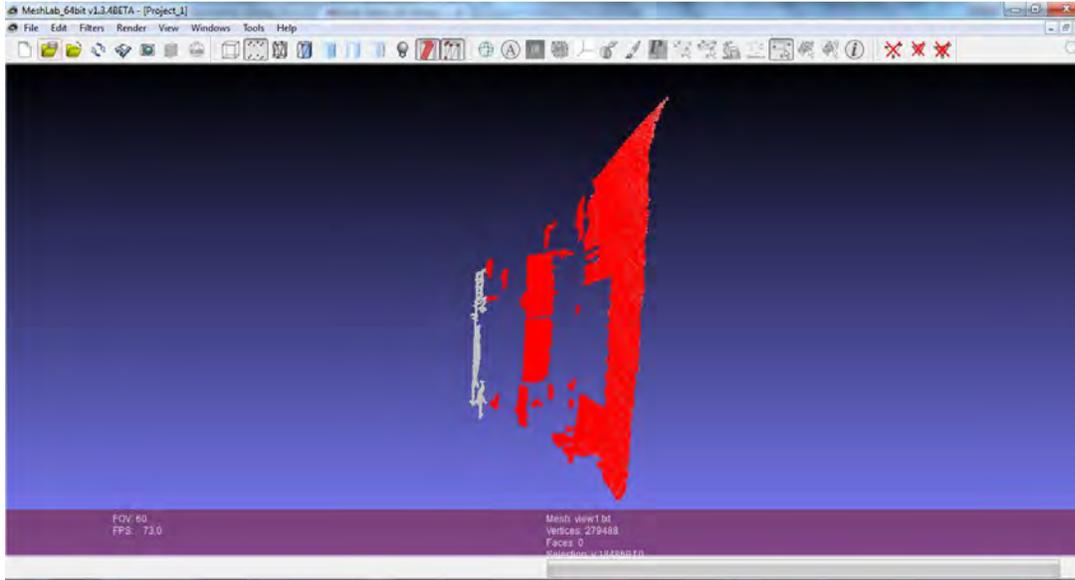

4. The fully cropped point cloud will look like this:

00001   Rev D
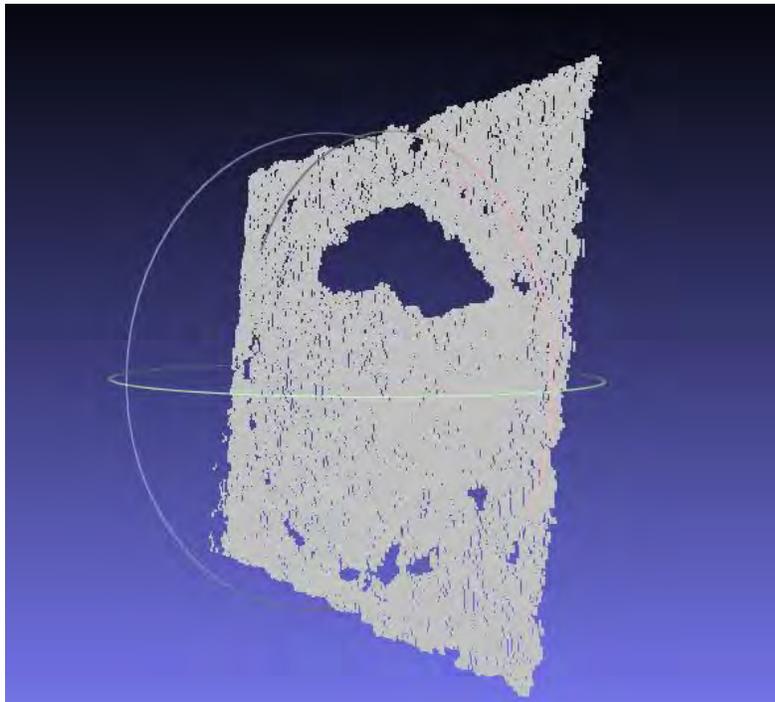
5. Once all of the individual point clouds are cropped, export them as new meshes under the file tab. Open a new project, and import these cropped meshes. You will notice that they need to be aligned.
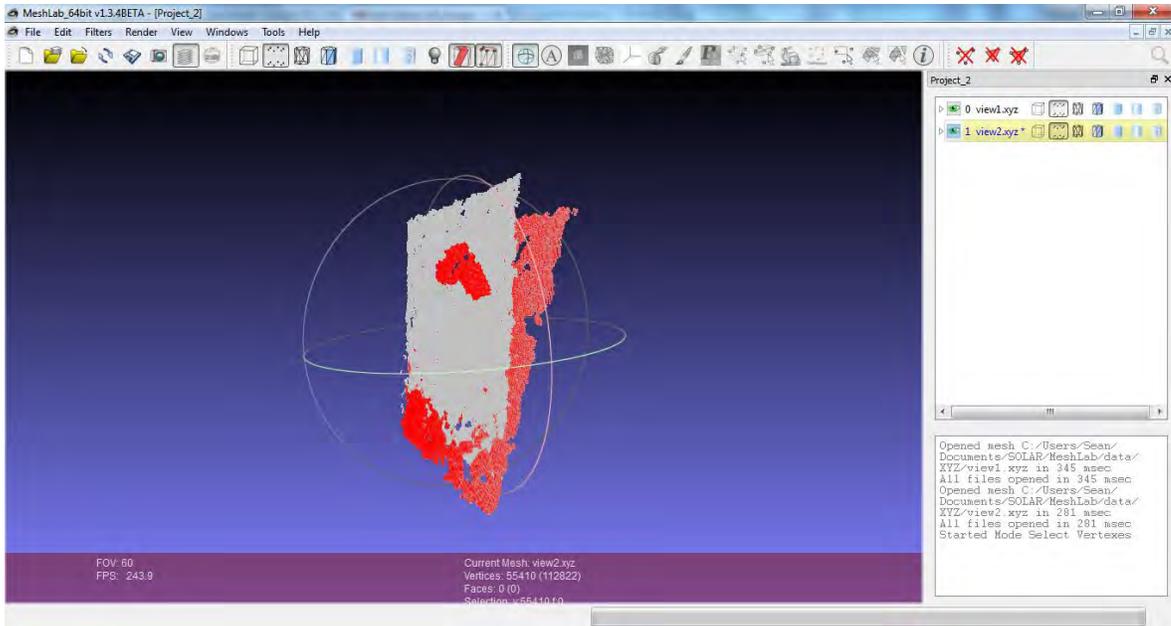

6. See? All six meshes have been imported in the following image, and they are all over the place. It is time to align them with the "align" tool:

00001   Rev D
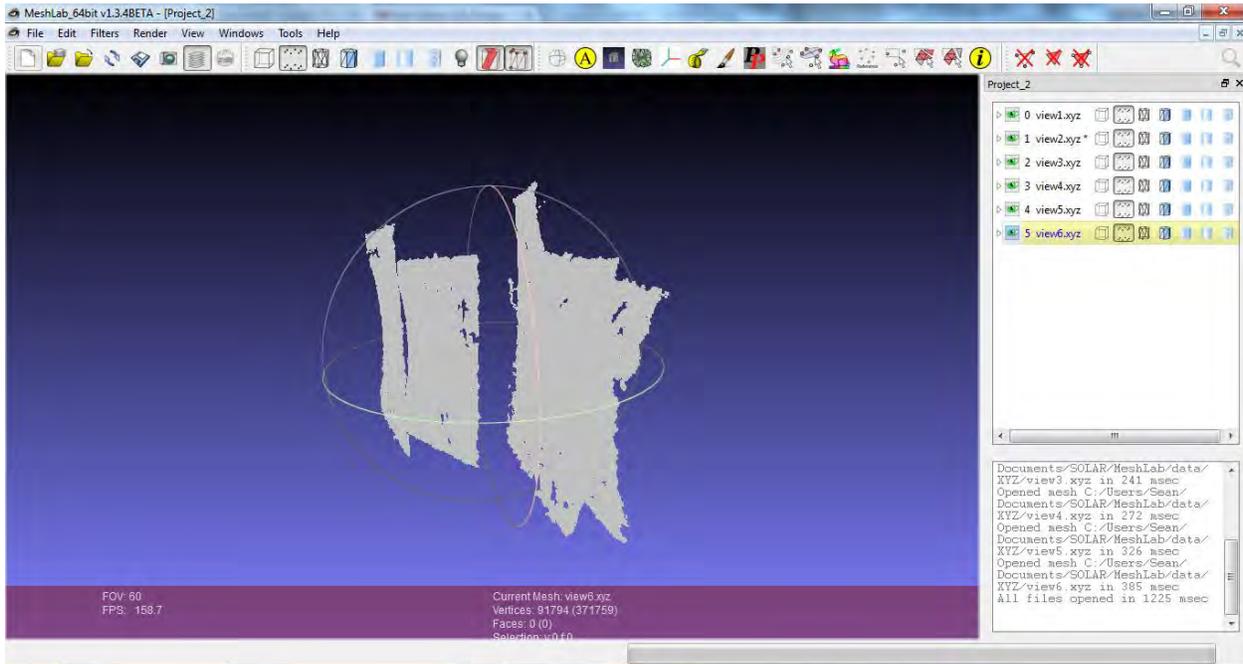
7. Glue the first point cloud. This will fix it in place so that it cannot move during alignment.
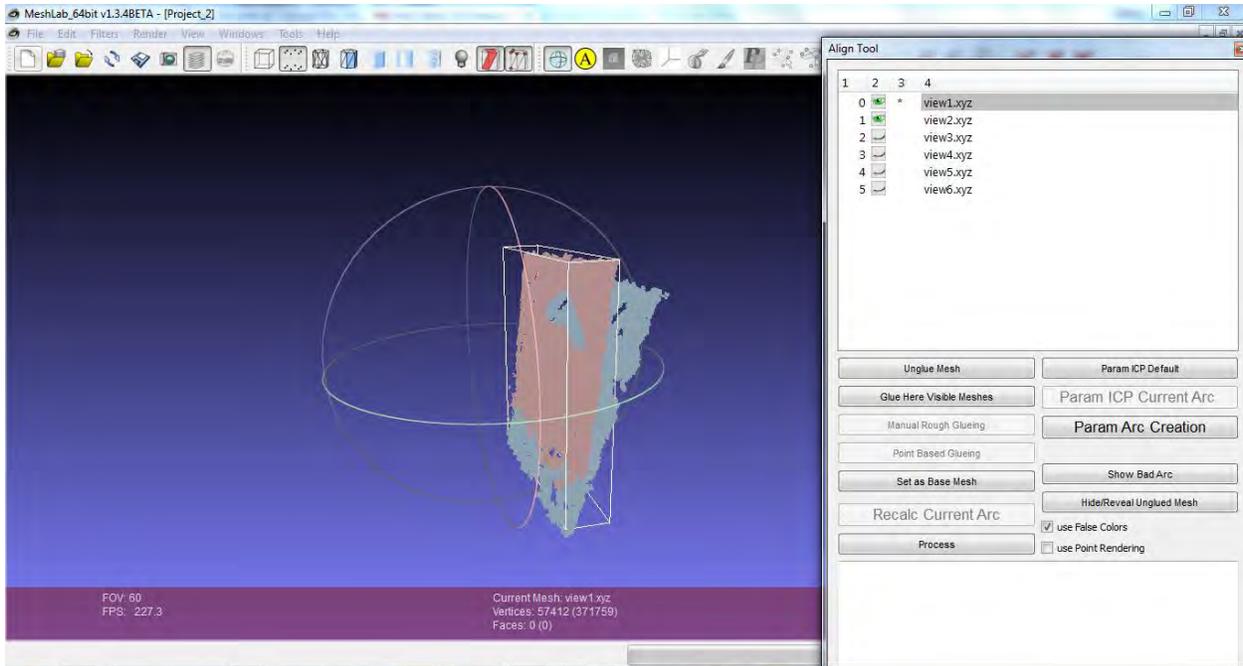

8. Select the second mesh and use the "point-based gluing" option. A window will open showing the first and second point cloud. Double click to select similar points on each cloud as shown.
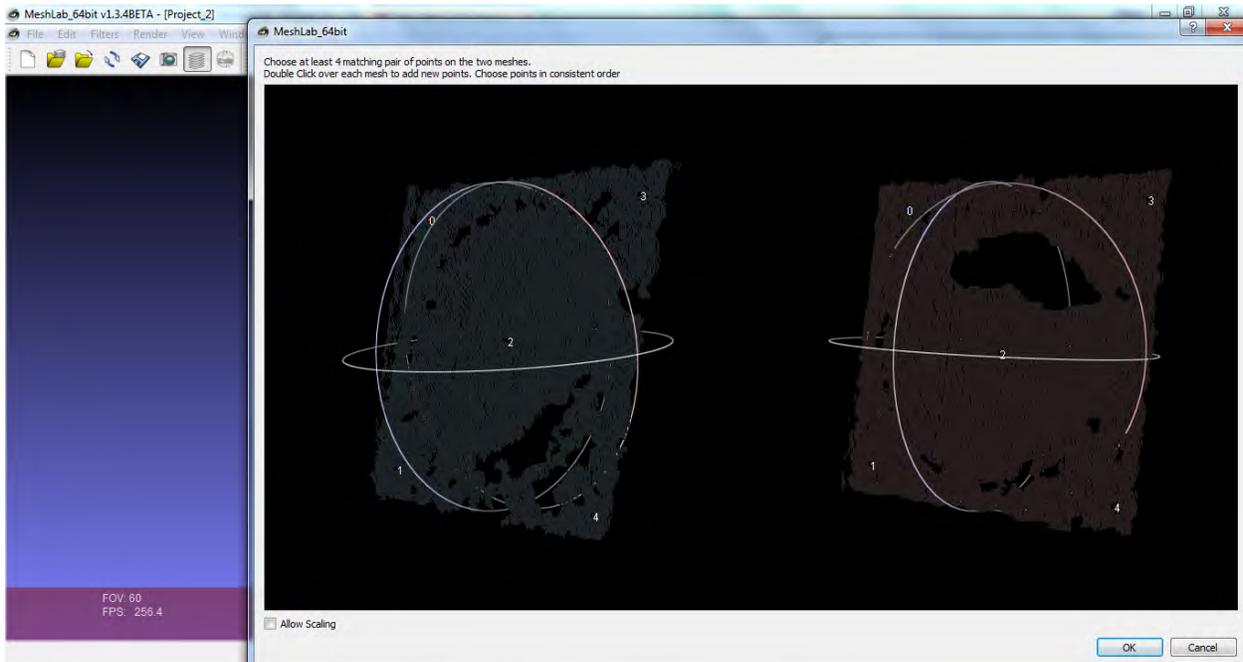
9. Press OK, and exit the align window. The overlayed meshes fill the gaps, as shown.
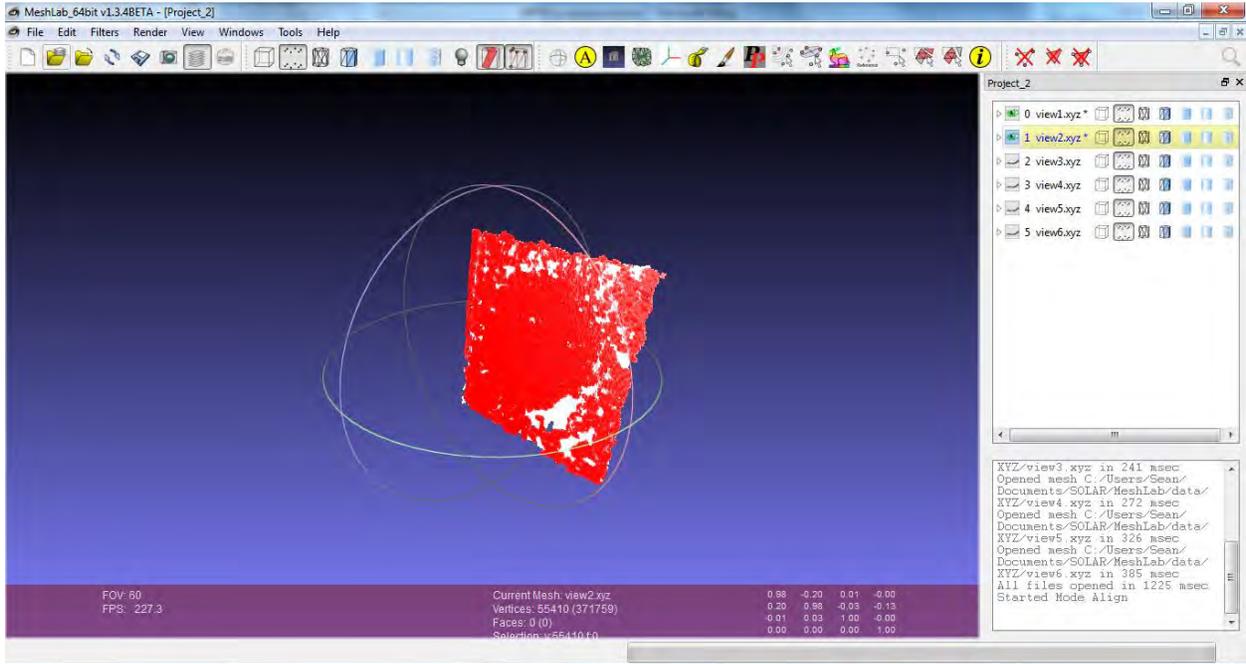
10. All six layers, aligned. Flatten the layers and export a single mesh to a .XYZ file.

00001 Rev D
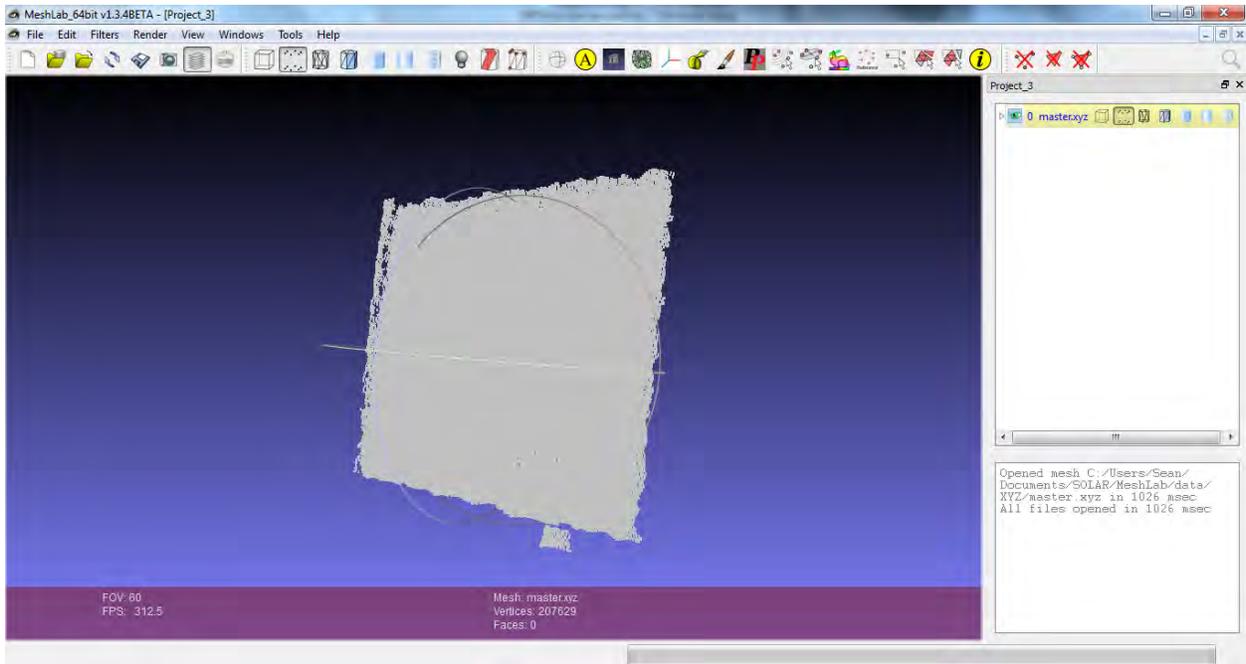
The rest of the formatting was done in MATLAB. Included in this appendix is an annotated set of commands that will load the XYZ data, fit and remove a plane from the data, and interpolate and smooth the points.

MATLAB commands

```
d = importdata('master.xyz'); % Load the XYZ data into a Nx3 matrix d, with N data points.

% Assign variables to the X, Y, and Z columns
x = d(:,1);
y = d(:,2);
z = d(:,3);

% The affine_fit() function, found here, fits a plane to the data points. It takes x, y, and z vectors as an
input, and outputs the normal vector of the fit plane.
[n,V,p] = affine_fit(d);

% Assign the normal to a new variable, P.
P = n;

% Generate a vector that orients the data to the +Z direction upon rotation.
u=cross(P/norm(P),[0,0,1]);
% Calculate the angle of this vector.
deg=asind(norm(u));

% Rotate the data points about this vector to align the average plane of the mirror to the +Z direction.
This function is found here.
[XYZnew, R, t] = AxelRot(d', deg, u, [0;0;0]);

% Assign new variables to the X, Y, and Z columns of the rotated data.
x = XYZnew(1,:) - (max(XYZnew(1,:)) + min(XYZnew(1,:)))/2; % center x
y = XYZnew(2,:) - (max(XYZnew(2,:)) + min(XYZnew(2,:)))/2; % center y
z = XYZnew(3,:) - min(XYZnew(3,:));

% Scale x and y to a max radius of 6 inches.
x = x/max(x(:))*6*25.4;
y = y/max(y(:))*6*25.4;

% Generate new x and y values at equal spacing.
xg = linspace(min(x),max(x),20);
yg = linspace(min(y),max(y),20);

% Create an interpolation object for the scattered data.
F = scatteredInterpolant(x',y',z');

% Grid the x and y interpolant values.
[Xg,Yg] = meshgrid(xg,yg);
```

```
% Evaluate the interpolant at the grid values.
zg = F(Xg,Yg);

% Crop the values to only include the mirror surface.
zg = zg(4:18,4:18);

% Also crop the x and y grid.
Xgc = Xg(4:18,4:18);
Ygc = Yg(4:18,4:18);

% Bring the minimum value of z down to zero, and scale it to 30mm.
zg = zg - min(zg(:));
zg = zg/max(zg(:))*30;

% Put the data through a lowpass filter.
h = 1/9*ones(3);
zs = filter2(h,zg);
```

If the output of this script, zs, is plotted, it looks like:
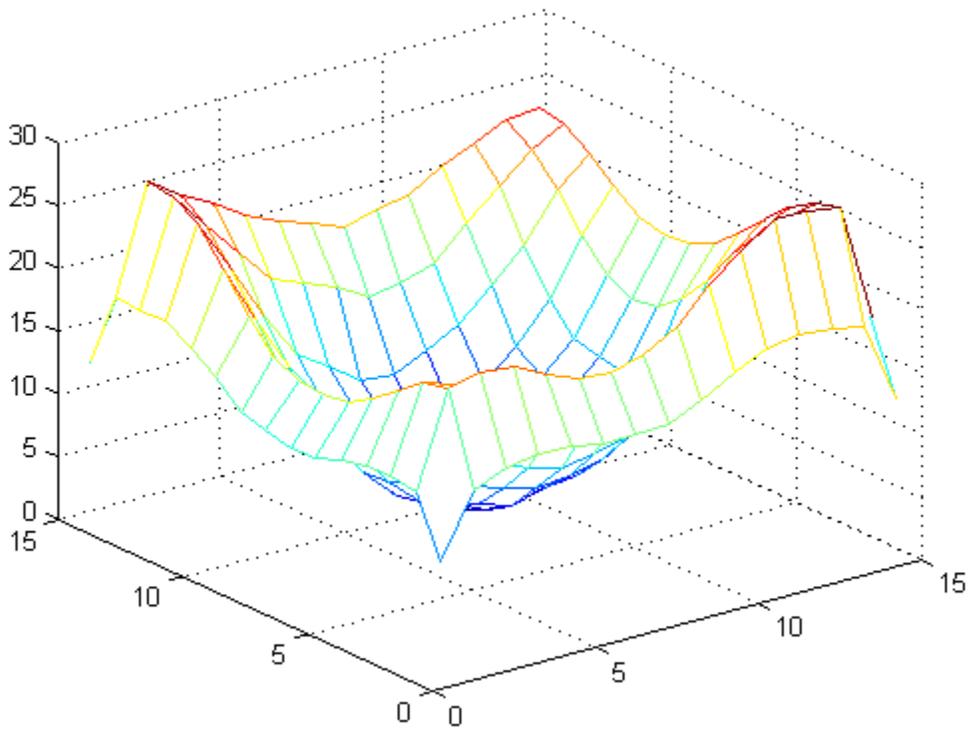
The format of zs, a 15x15 matrix, can be easily put into LightTools with the freeform surface tool.

Image of LightTools model:

Nov 13, 2015
solar1.3
LightTools 8.3

00001   Rev D
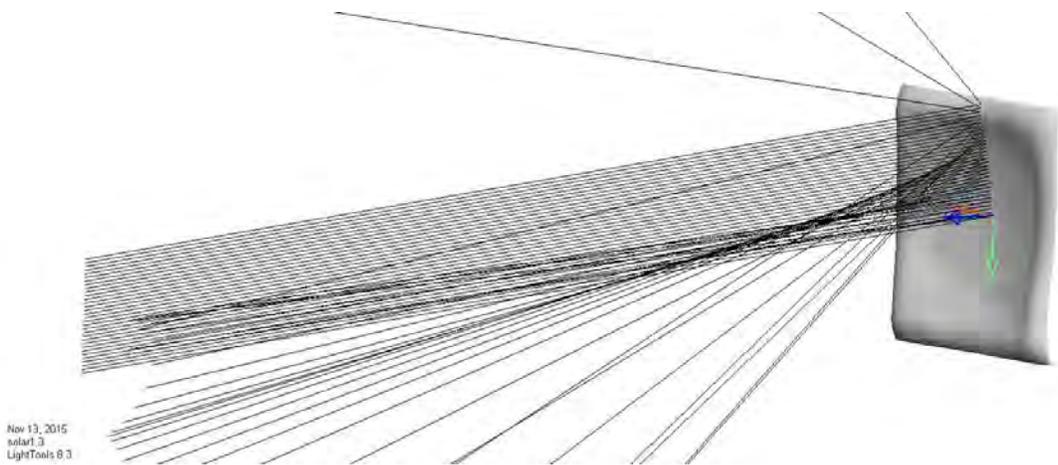
Appendix E: Sketches of preliminary designs