Origami Solar-Tracking Concentrators

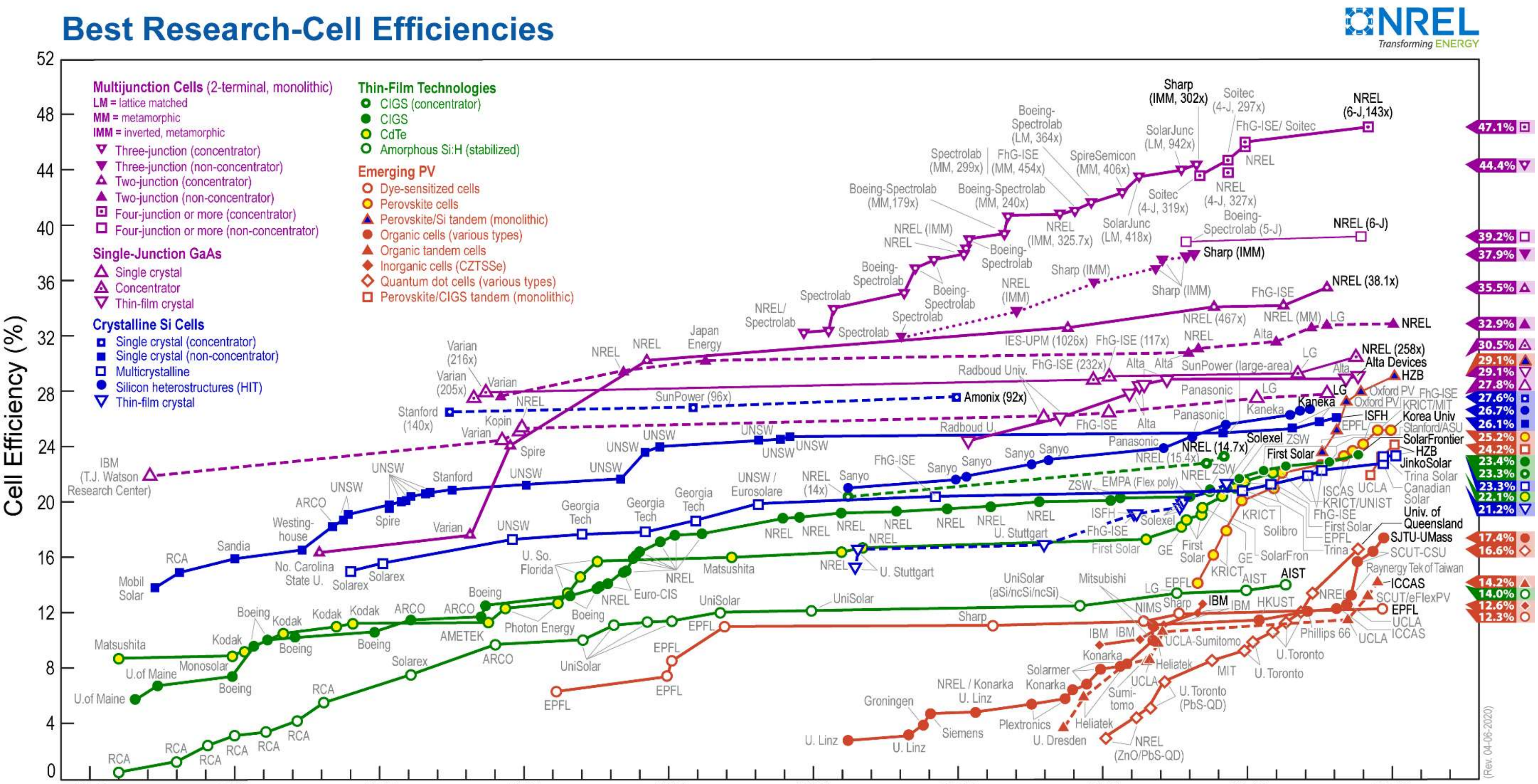
Tainon Chen
Prof. Pei-Cheng Ku

Introduction: Solar Cell Semiconductors

- Conventional solar cells use crystalline silicon
  - ~$5.7 / m^2 for Si
- Newer semiconductors are more efficient, but more expensive
  - ~$8,200 / m^2 for GaAs

- Kirigami Solar Module Cost Analysis, U-M EECS Department
- Crystalline Silicon Photovoltaic Module Manufacturing Costs and Sustainable Pricing: 1H 2018 Benchmark and Cost Reduction Road Map, National Renewable Energy Laboratory

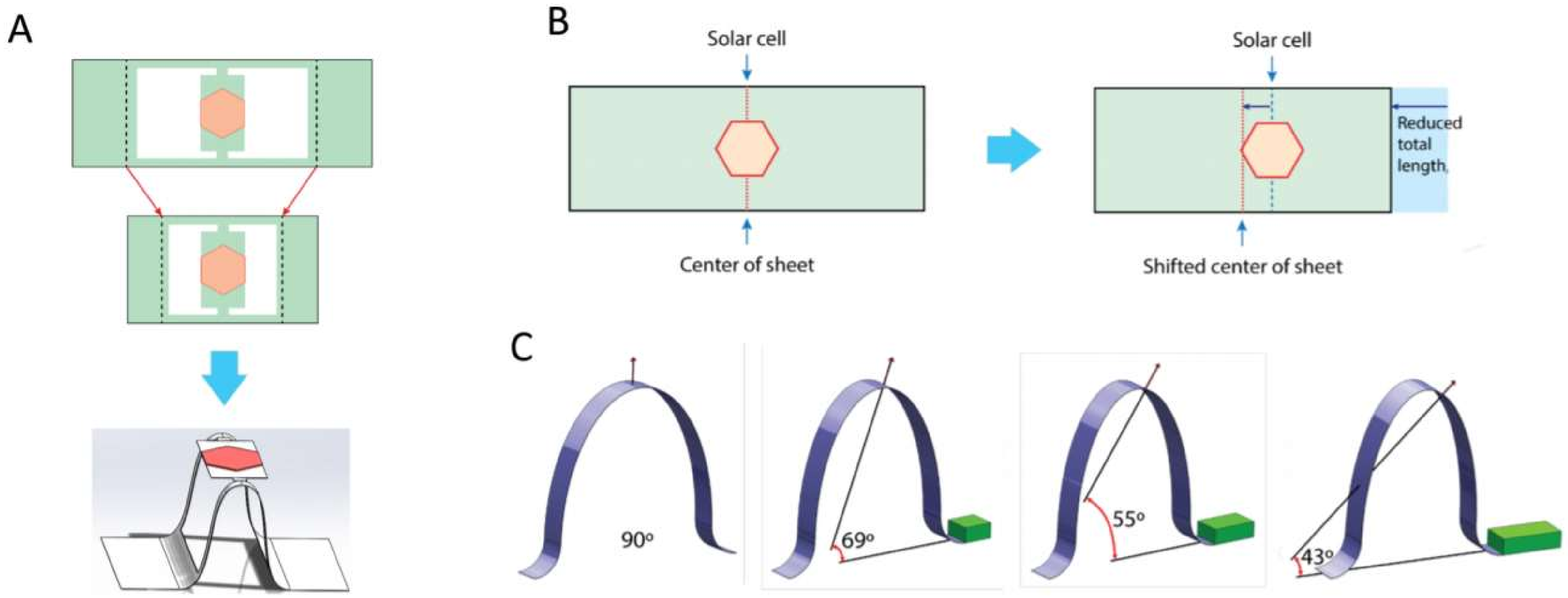
Best Research-Cell Efficiencies

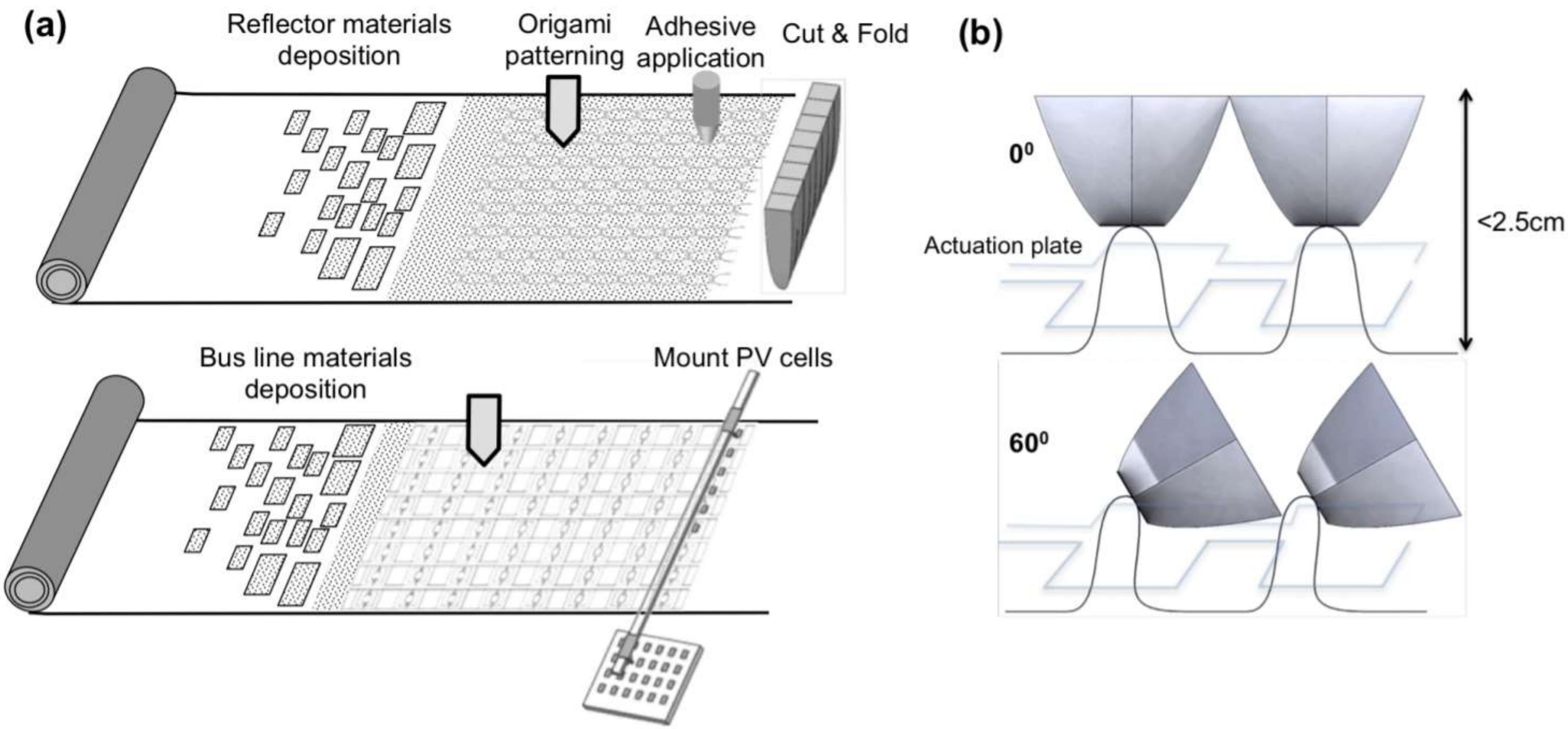


National Renewable Energy Laboratory (NREL)

Introduction: Solar Cell Tracking Array

- Increases effectiveness of light collection by modifying tilt of concentrator
- Can tilt concentrator ±60° relative to normal

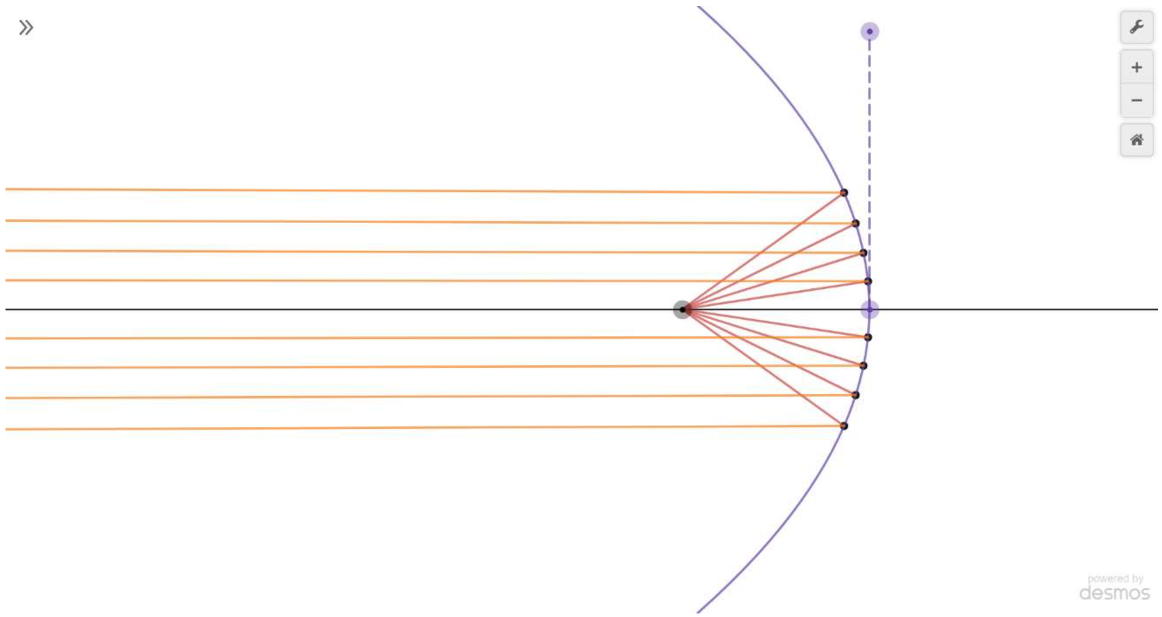




Fixed-Tilt Flat Panels Based on Origami Micro-Concentrators

Introduction: Simple Parabolic Concentrators

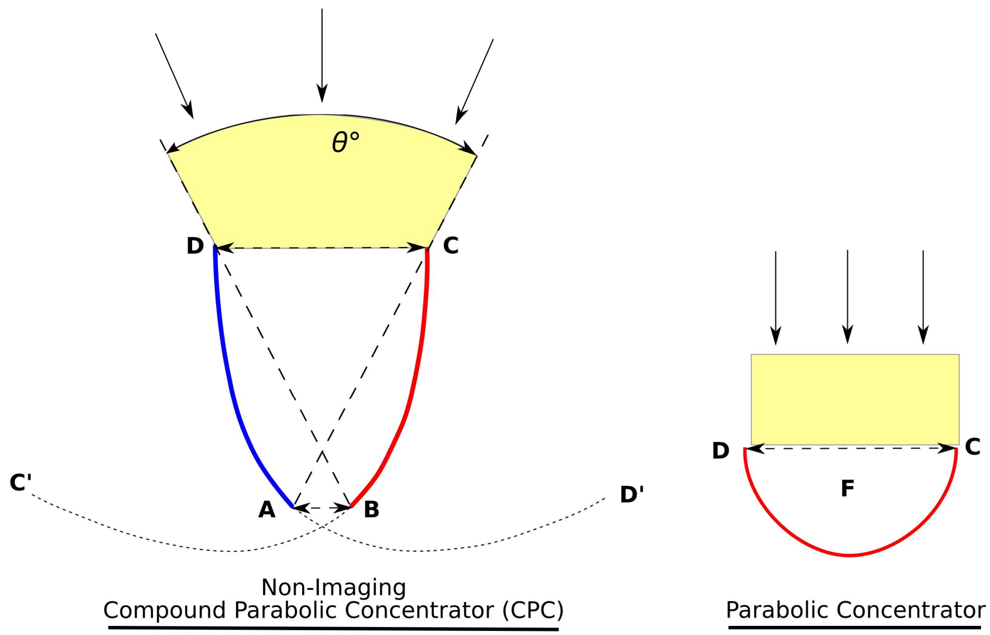
- Composed of a single parabola
- All incoming rays parallel to axis are reflected to focus
- Nonparallel rays are reflected unpredictably



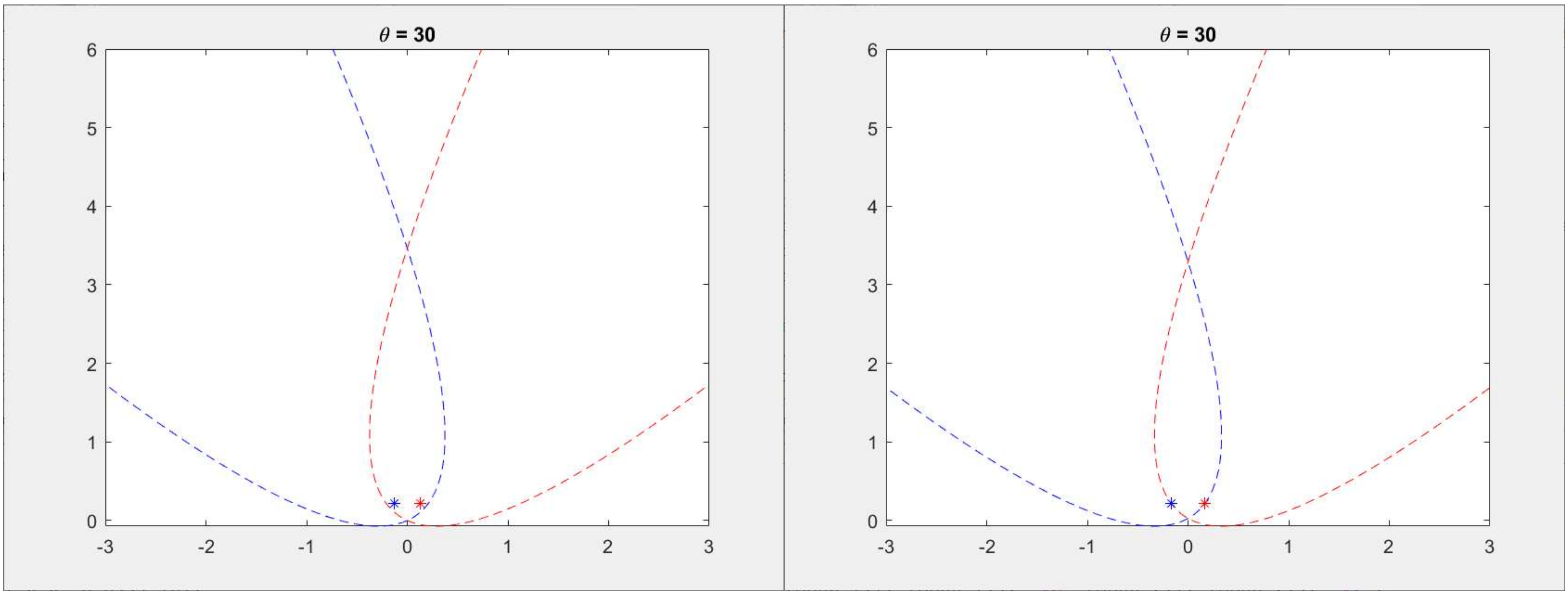
- Parabolic Reflector, Wikipedia

Introduction: Compound Parabolic Concentrators

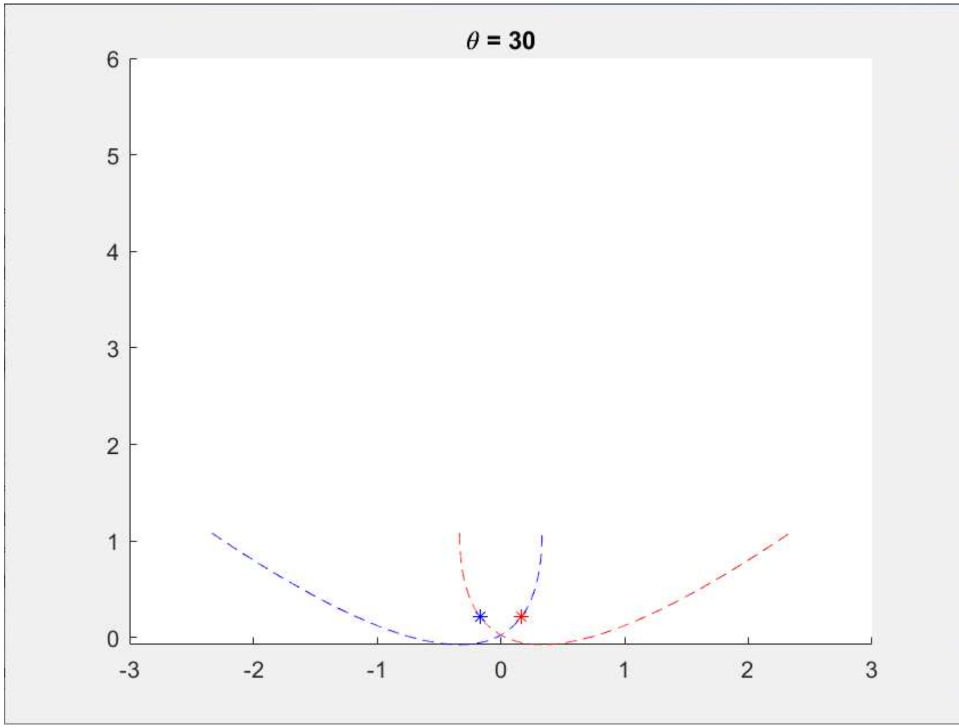
- Abbreviation: CPC
- Rotate two parabolas by angles +θ and -θ
- Overlap parabolas so that focus of each parabola intersects shape of the other

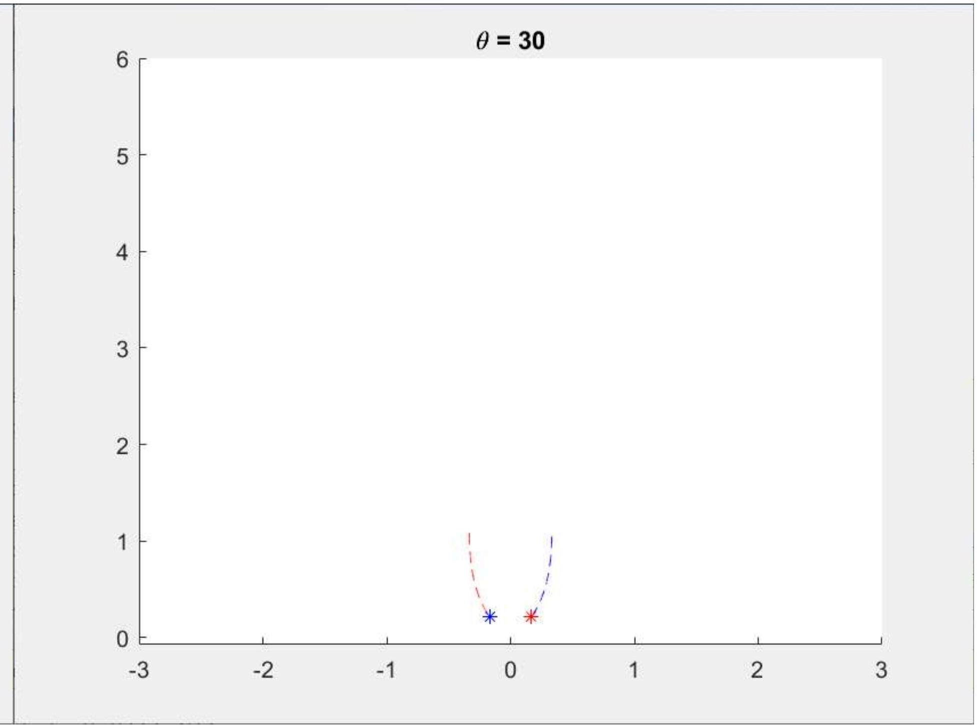


- Nonimaging Optics, Wikipedia

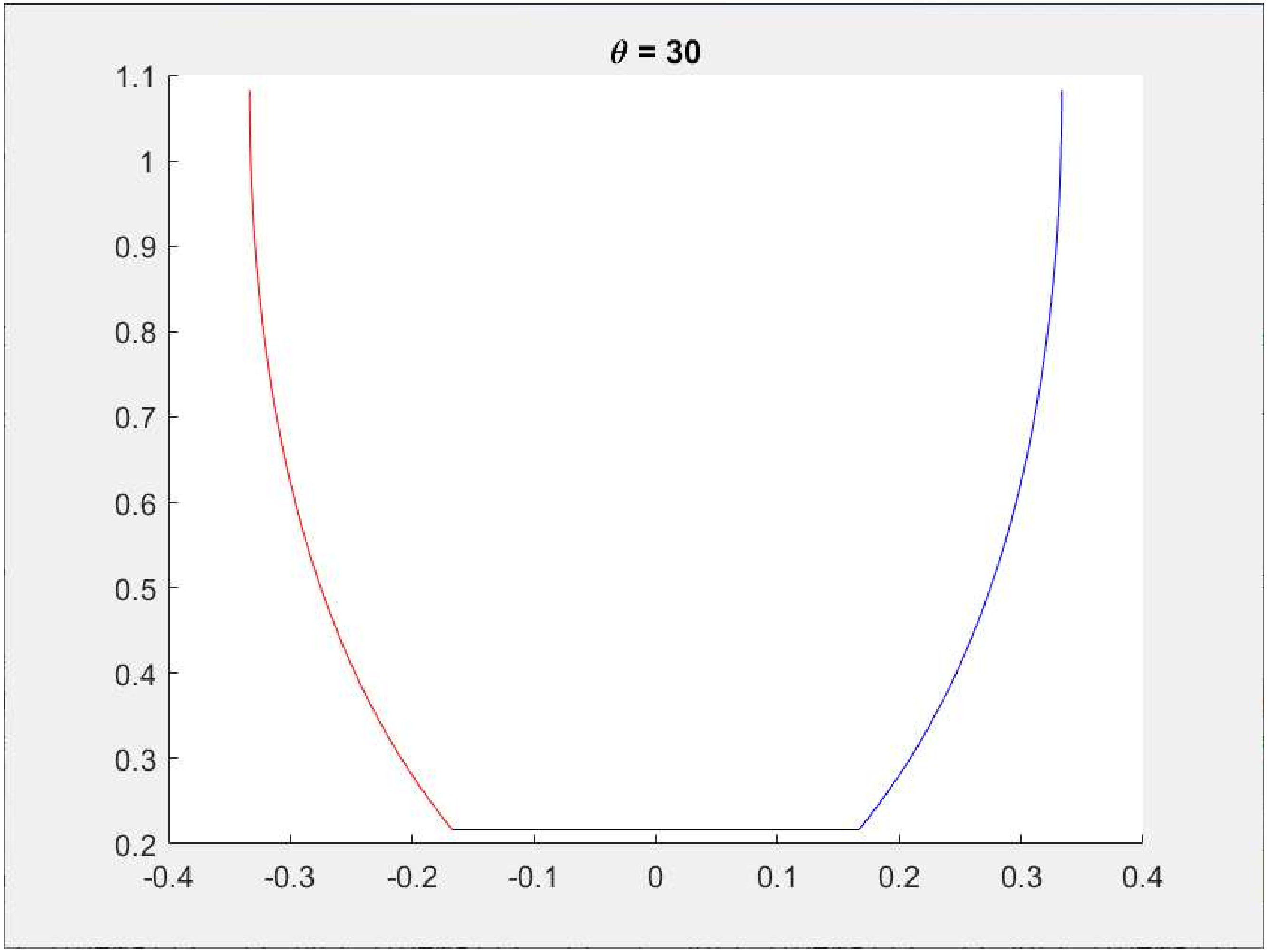


Compound Parabolic Concentrator Creation





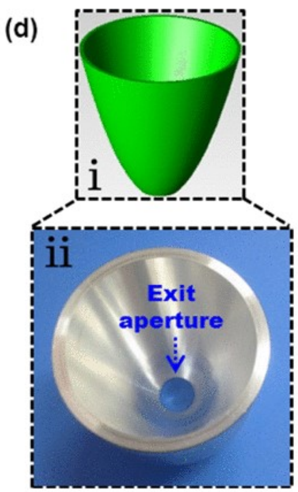
Compound Parabolic Concentrator Creation

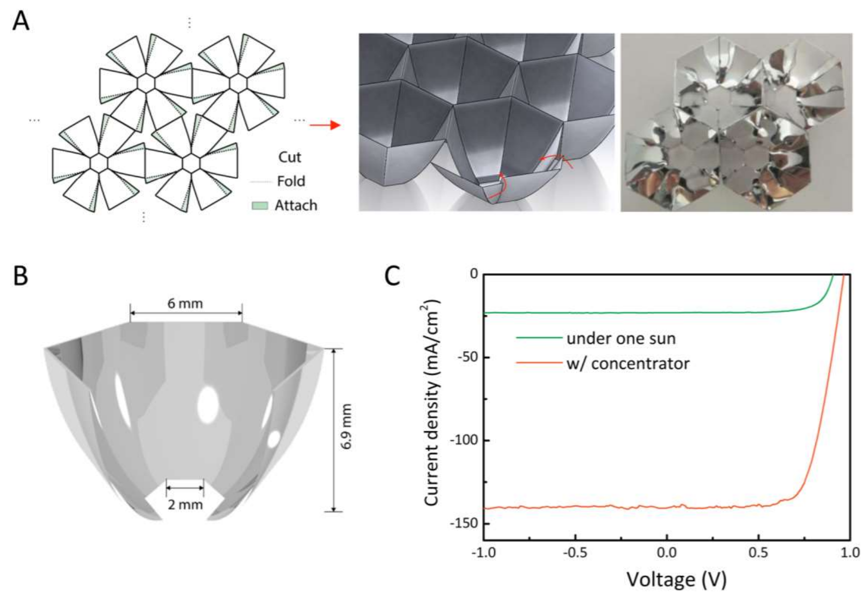


Compound Parabolic Concentrator Creation

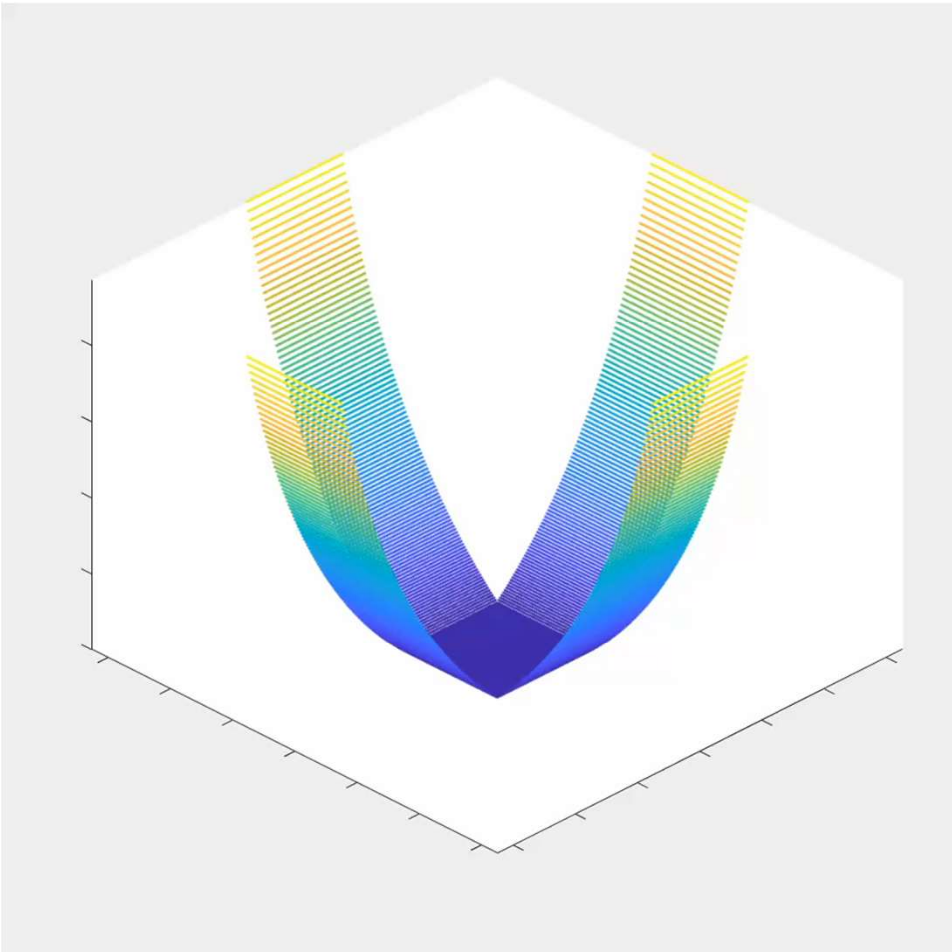
Introduction: CPC Variations

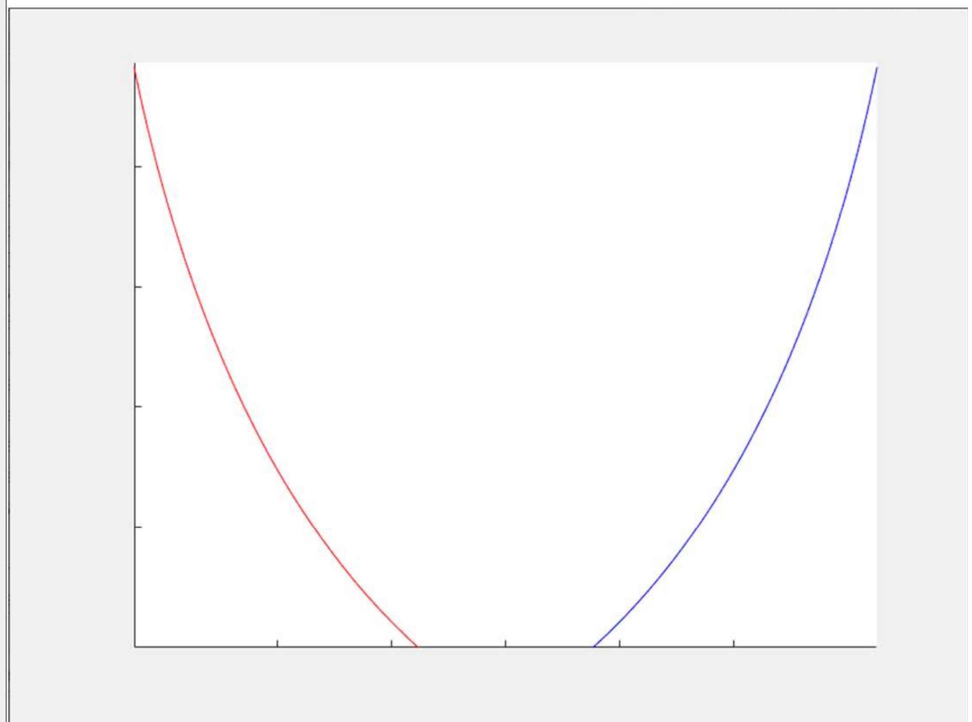
- Ideal 3D CPC has circular base
  - Difficult to manufacture
- CPCs with polygonal bases are more easily created
  - Trade-off due to decrease in ray collection effectiveness



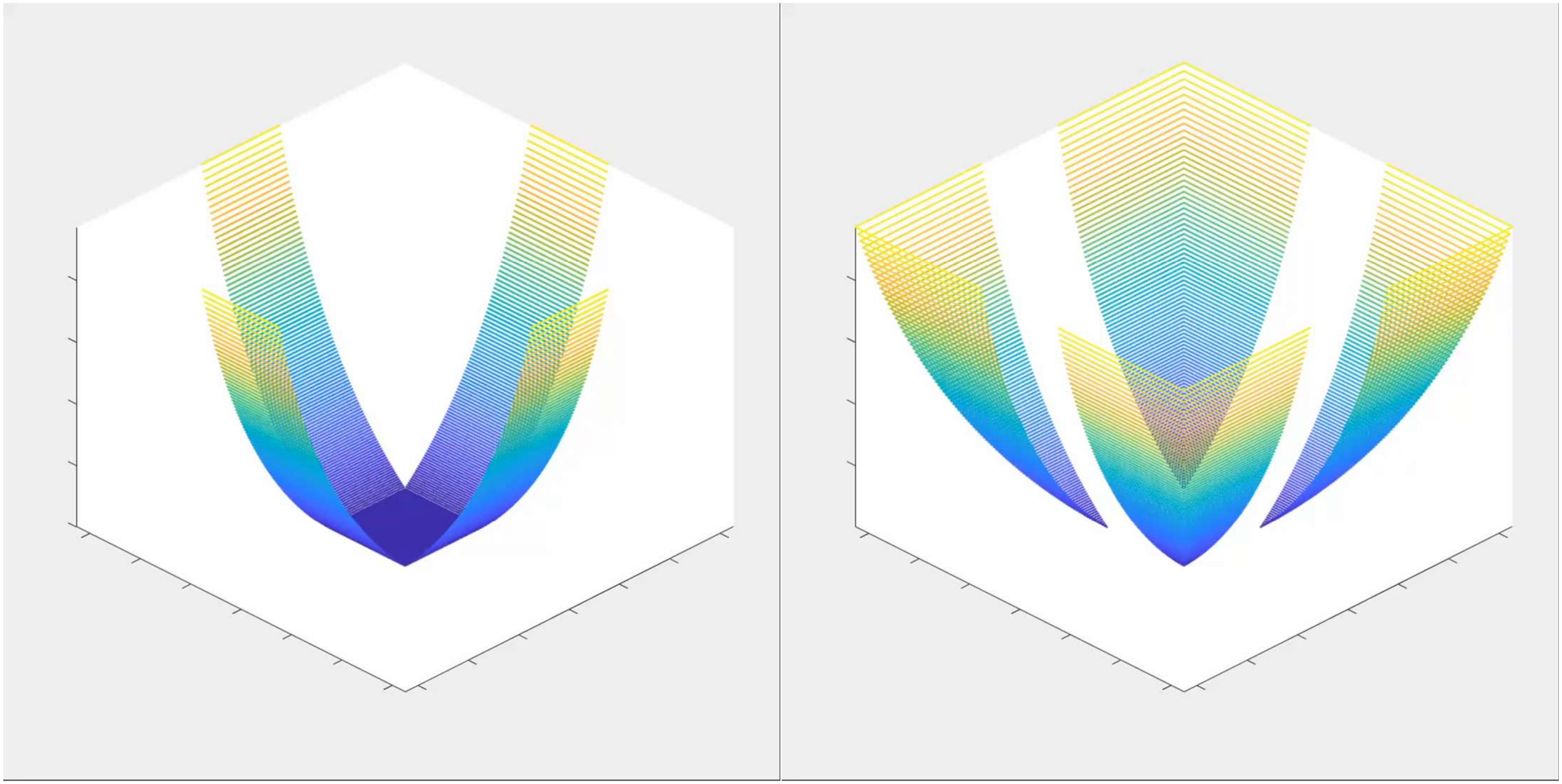


- Nonimaging Optics, Wikipedia
- A Comparison of Compound Parabolic and Simple Parabolic Concentrating Solar Collectors, Los Alamos Scientific Laboratory

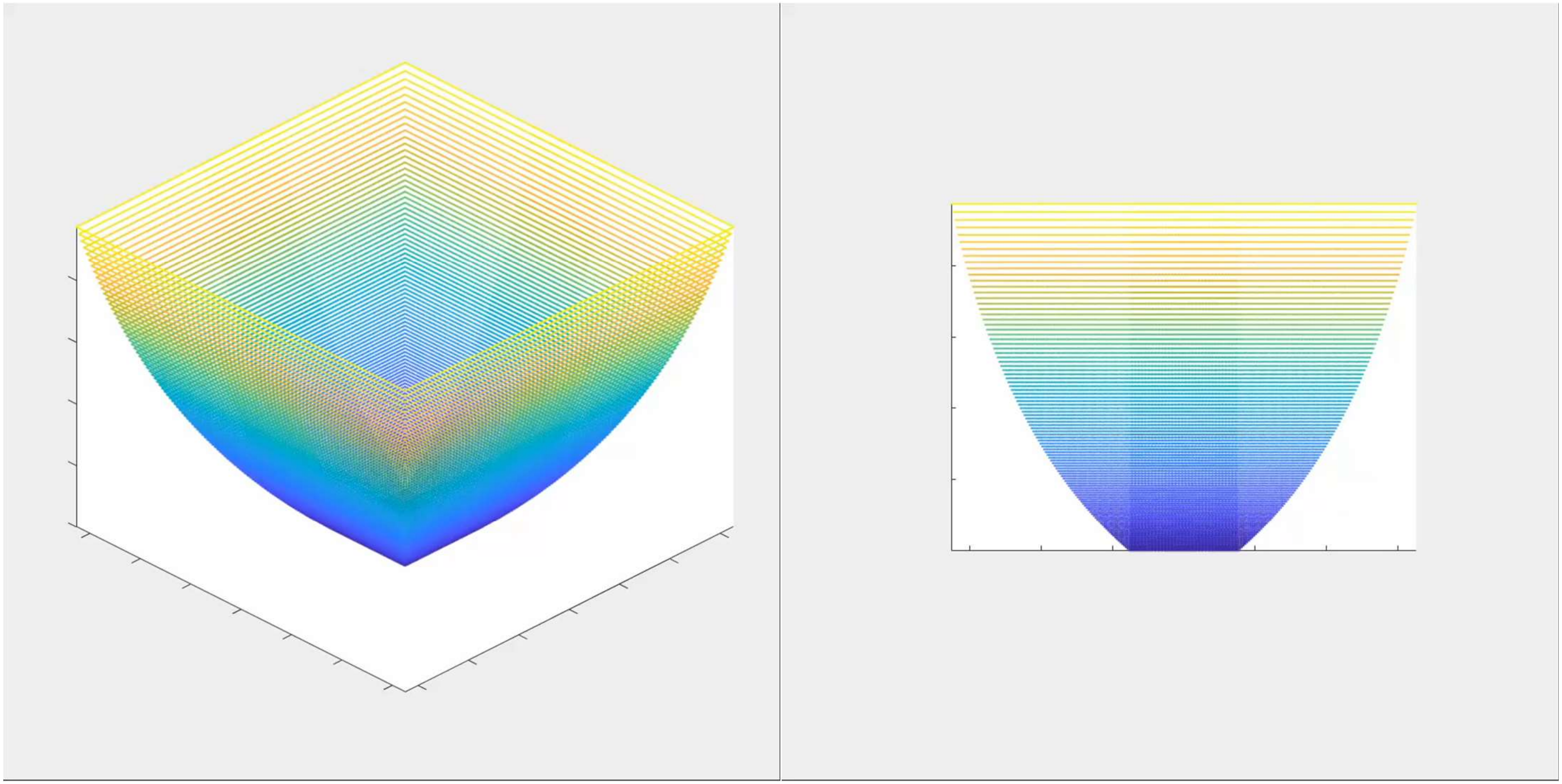




3D Concentrator Sides



3D Concentrator Sides and Corners



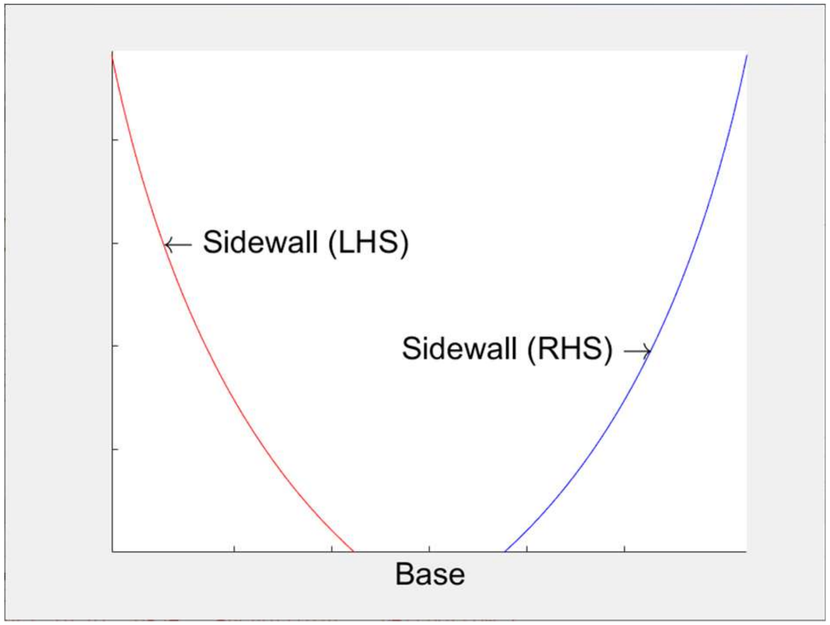
3D CPC Concentrator

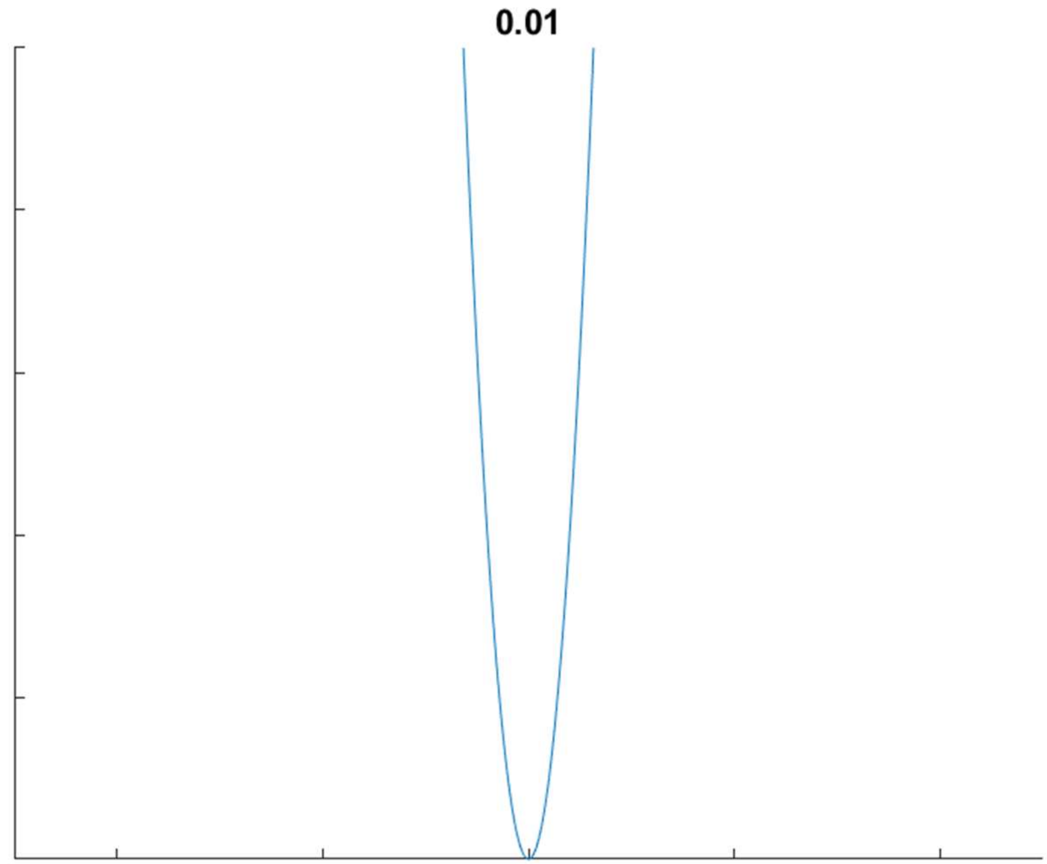
Introduction: Project Scope

- Optimize origami concentrator design
  - Use two overlapping (compound) parabolas to generate 2D shape
  - Combine 2D models for 3D square-based concentrator
  - Determine limitations of dimensions imposed by tracking array
  - Simulate light collection

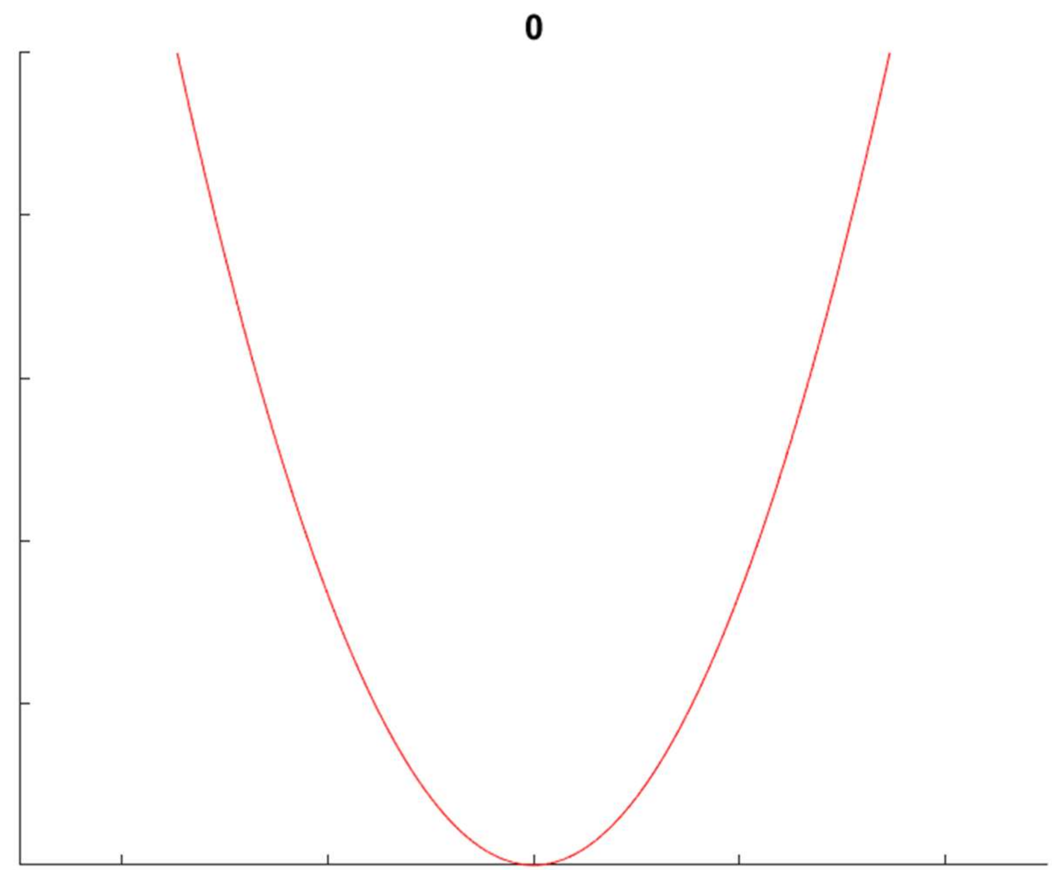
Methods: 2D Concentrator Creation

- Use **parabola coefficient** to generate two parabolas
- Rotate parabolas in opposite directions by **angle**
- Horizontally translate parabolas by **separation**
- Shift concentrator base according to **base position**
- Find the maximum **height factor**, and adjust concentrator height accordingly

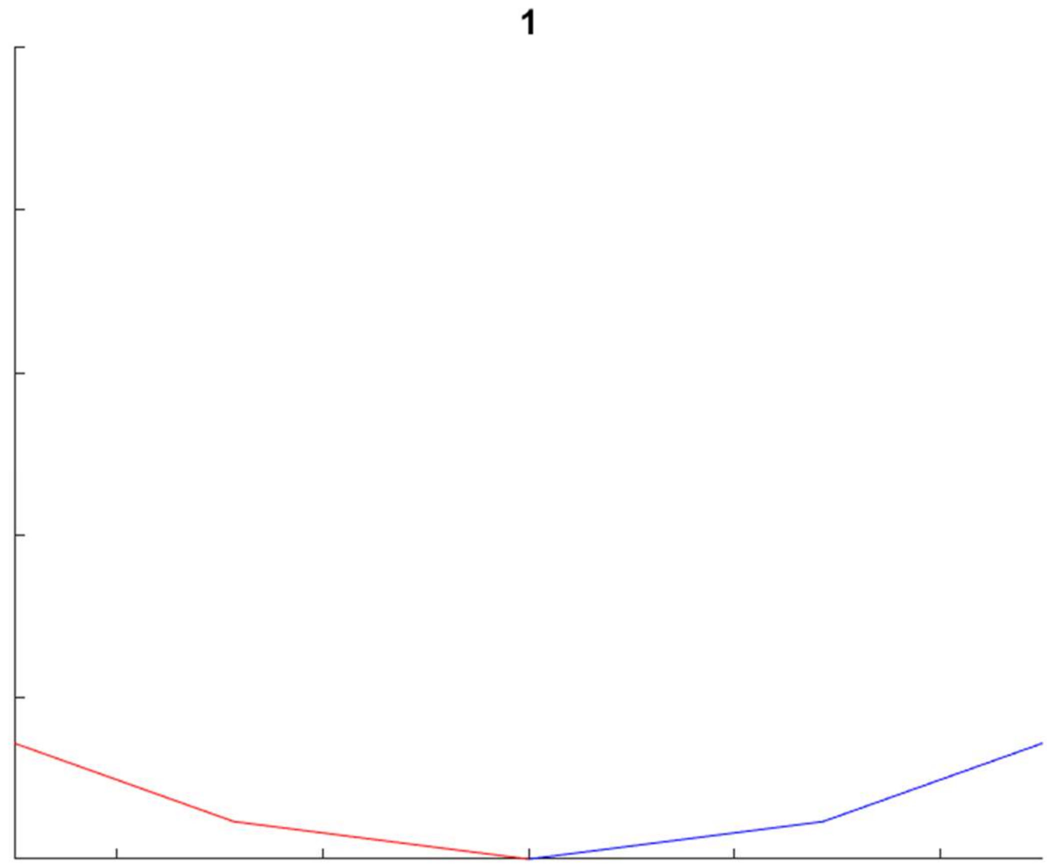




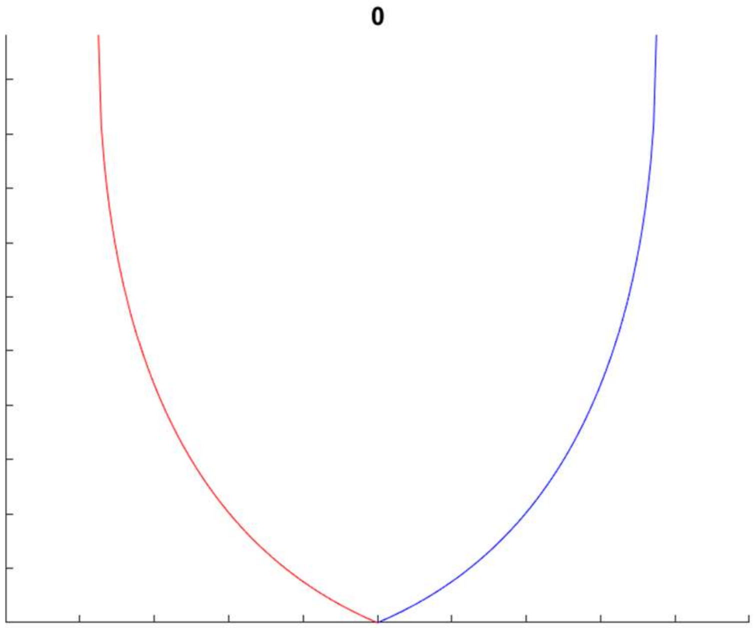
Parabolas with Coefficients 0.01:0.01:1

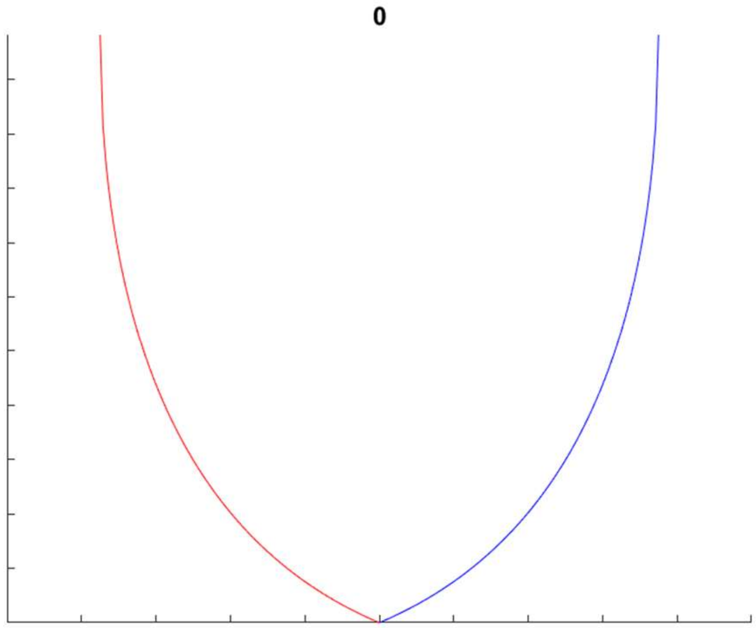


Parabolas with Separation Distance 0:0.01:1

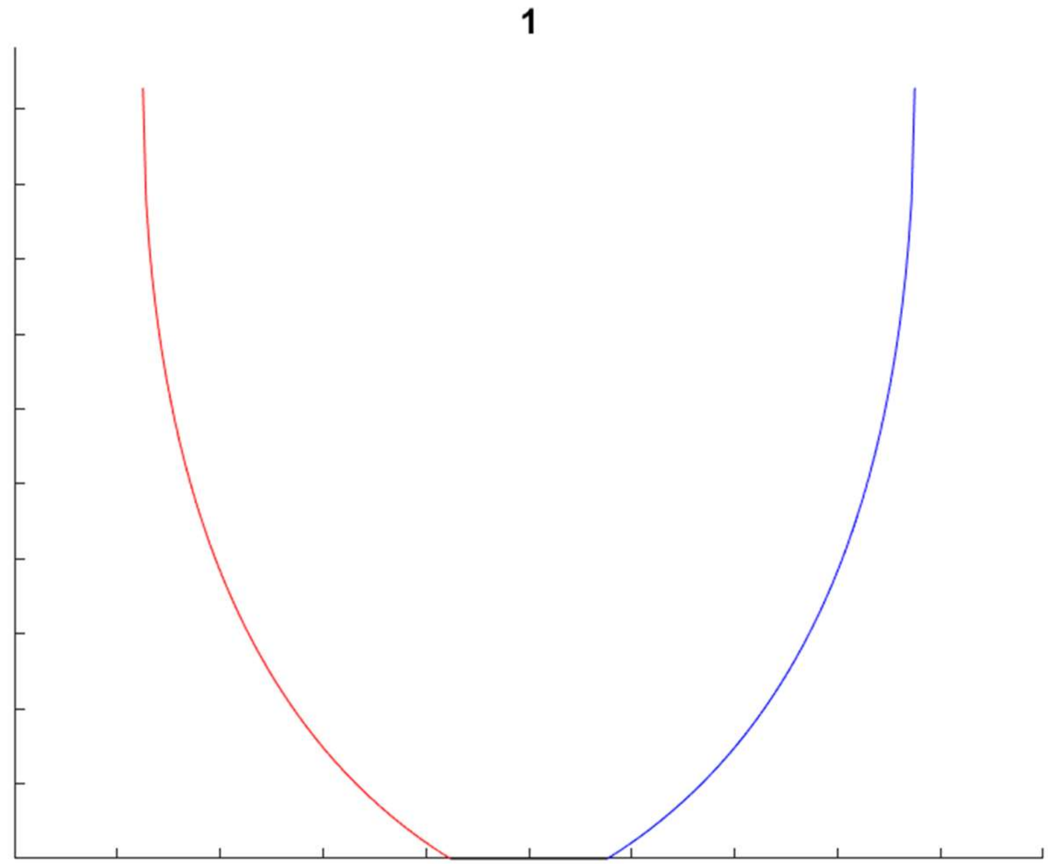


Concentrators with Angles 1:1:45





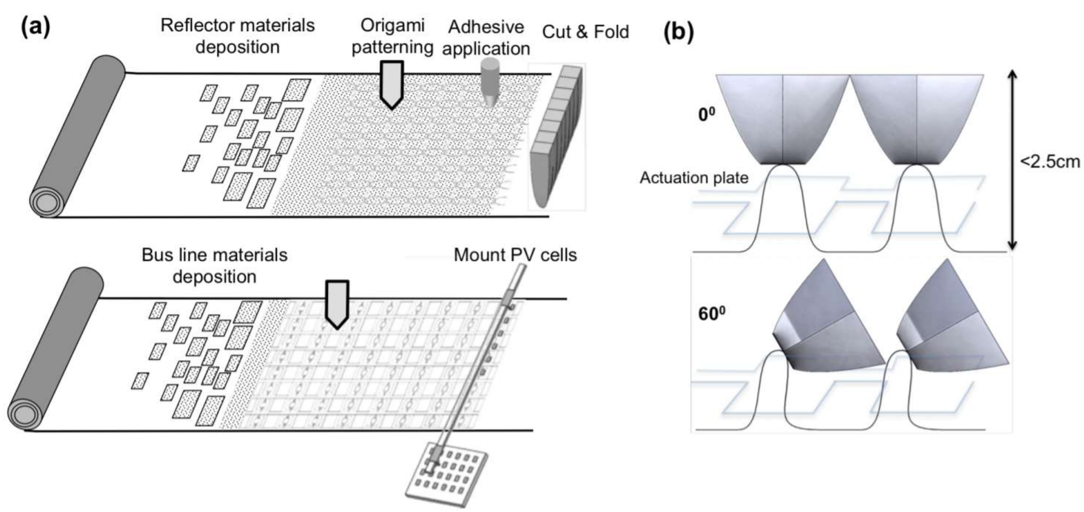
Concentrators with Base Positions 0:0.01:1

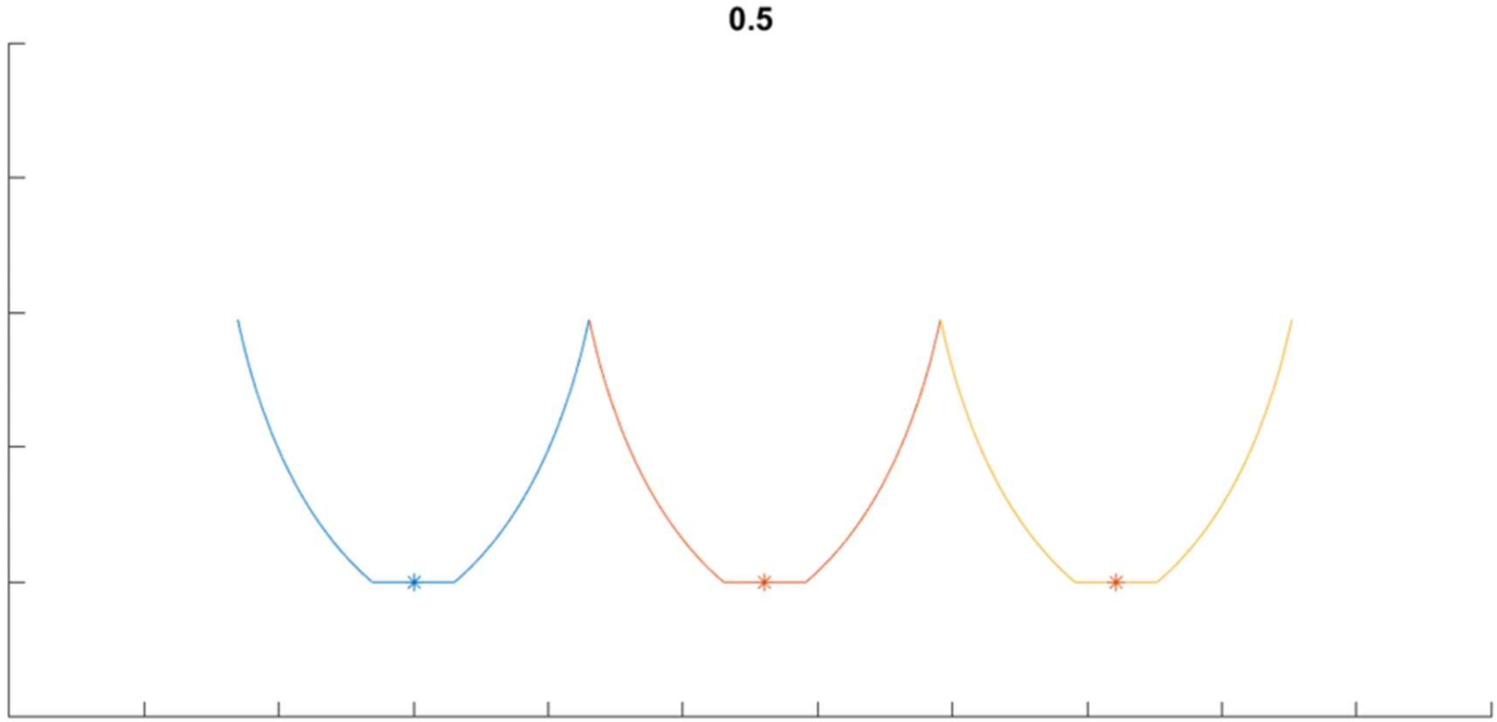


Concentrators with Height Factors 1:-0.01:0

Methods: Determining Optimal Height

- All five parameters, except height factor, are set arbitrarily
  - Other four parameters: parabola coefficient, parabola separation, angle, base position
- Increasing height factor always increases CF
- Concentrators are placed in close proximity on tracking array
  - Too tall: concentrators collide within ±60°
  - Too short: lower CF

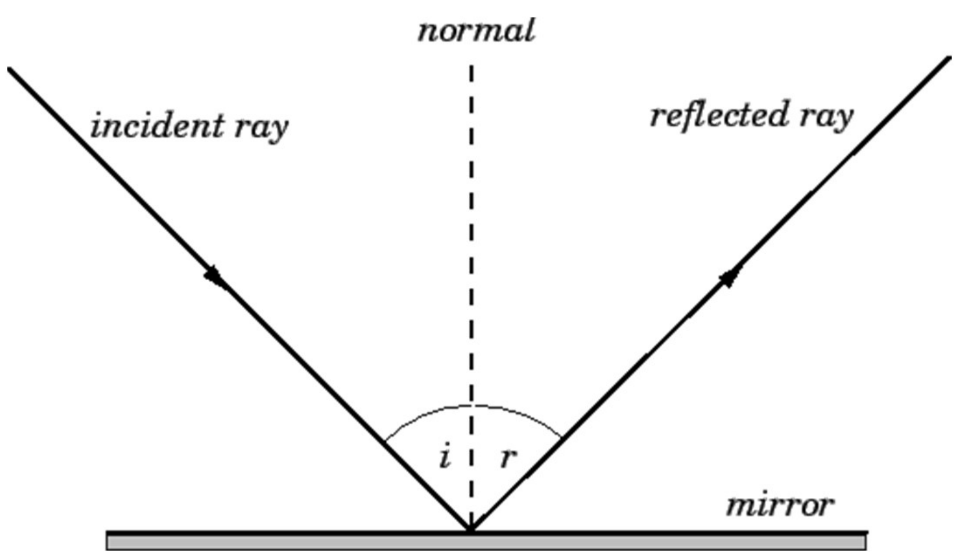


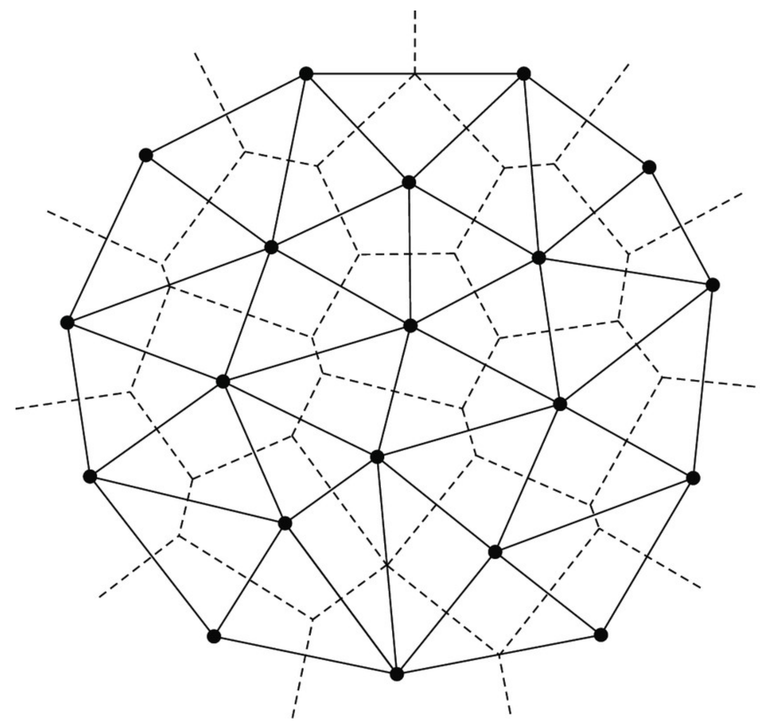


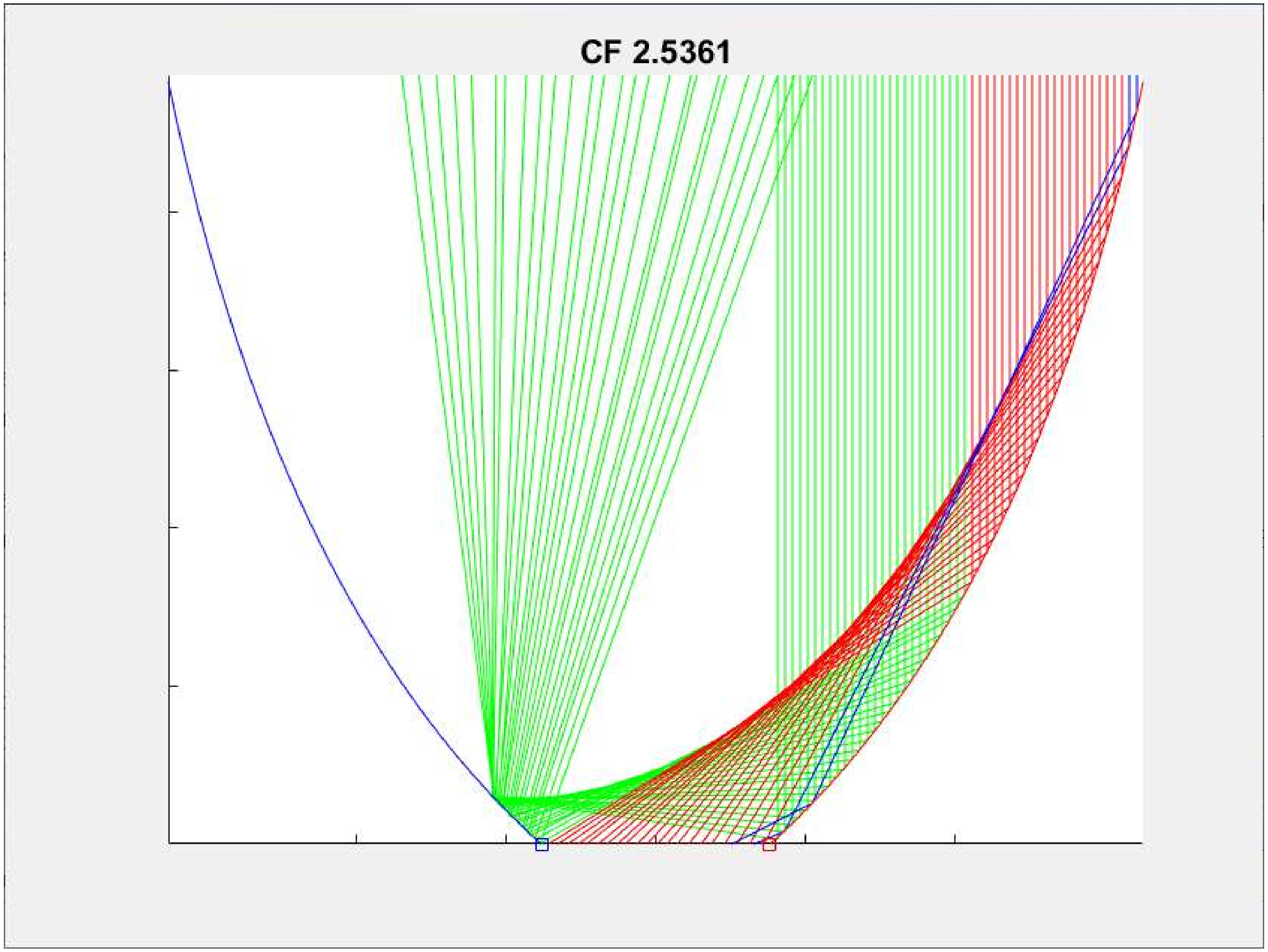
Binary Search for Optimal height

Methods: Determining Light Collection

- Simulated light follows law of reflection, assuming sidewalls were perfect reflectors
- All incident rays perpendicular to base
- Delaunay triangulation to determine slope of 3D concentrator







Determining 2D Ray Collection

Methods: Concentration Factor

- Concentration factor (CF): measure of effectiveness of light collection
  - Also reflective of cost-saving of concentrator
- $CF = \frac{Rays\ Collected}{Total\ Rays} * \frac{Top\ Area}{Base\ Area}$

Methods: CF Cases - No Concentrator

- $CF = \frac{Rays\ Collected}{Total\ Rays} * \frac{Top\ Area}{Base\ Area}$
- No concentrator
  - $Rays\ Collected == Total\ Rays$
  - $Top\ Area == Base\ Area$
  - $CF = 1$
- “Base case”: No cost savings

Methods: CF Cases - Example Concentrator

- $CF = \frac{Rays\ Collected}{Total\ Rays} * \frac{Top\ Area}{Base\ Area}$
- Concentrator with $\frac{Top\ Area}{Base\ Area} = 2$, which collects 80% of rays
  - $\frac{Rays\ Collected}{Total\ Rays} = 0.8$
  - $\frac{Top\ Area}{Base\ Area} = 2$
  - $CF = 1.6$
- Less semiconductor is used, but not all the light can be collected
  - Still more effective than base case

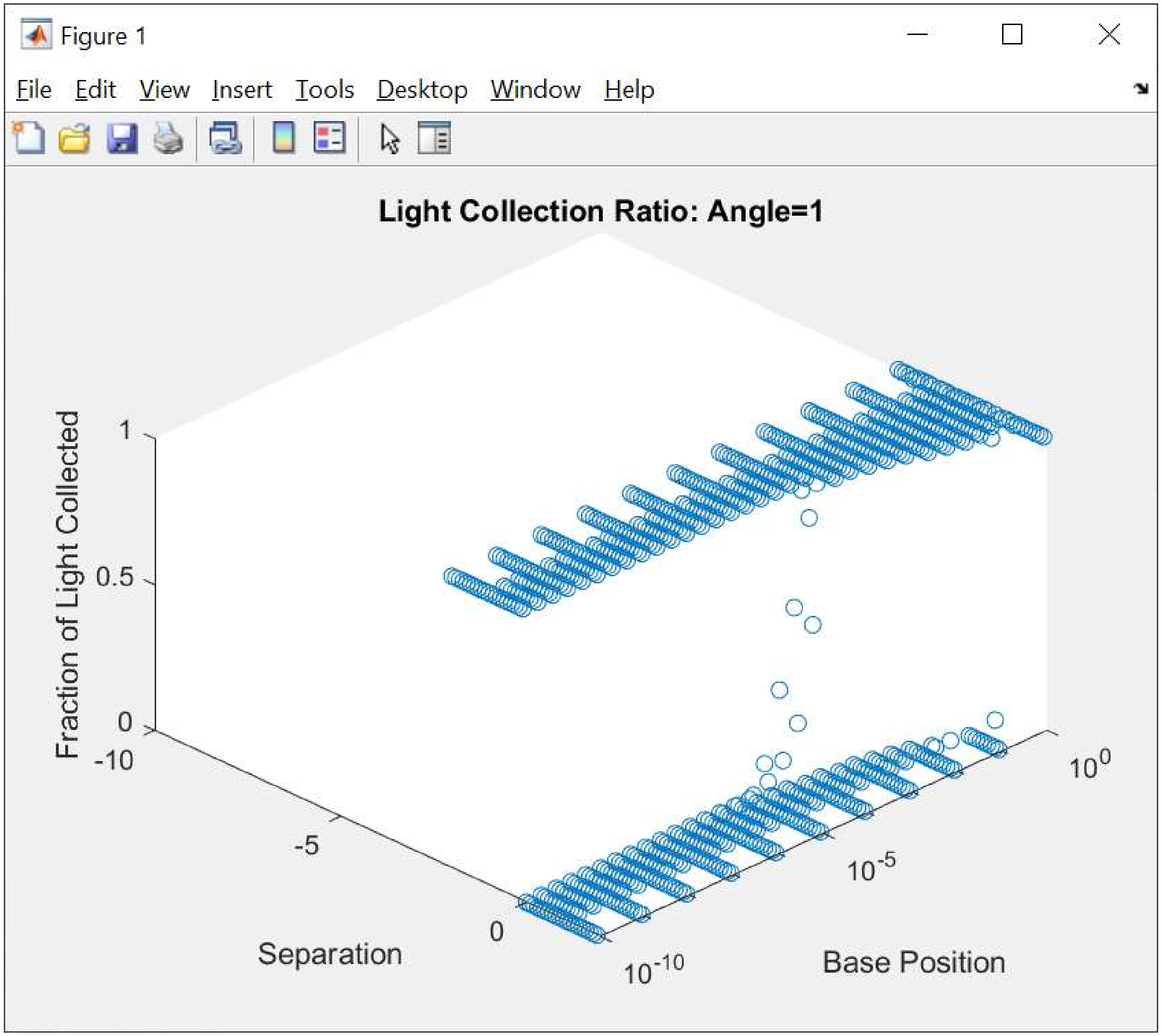
Results

- Parameters
  - Parabola coefficient
  - Angle
  - Parabola separation
  - Base position
  - Height factor
- Outputs
  - Light collection ratio
  - Top-to-base ratio
  - Concentration factor

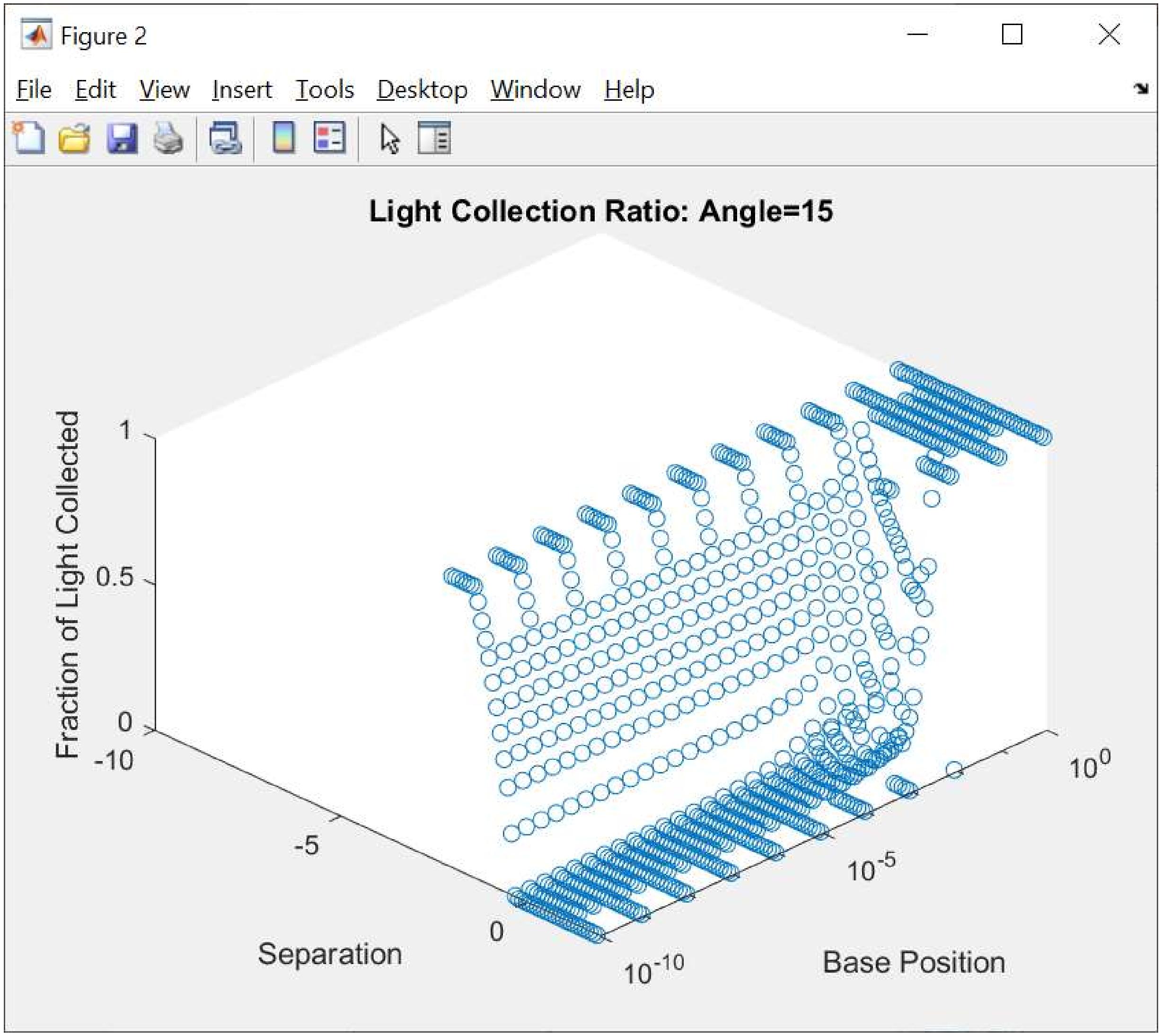
Results: Parabola Coefficient

- Parabola coefficient did not affect concentration factor
- All parabolas are geometrically similar

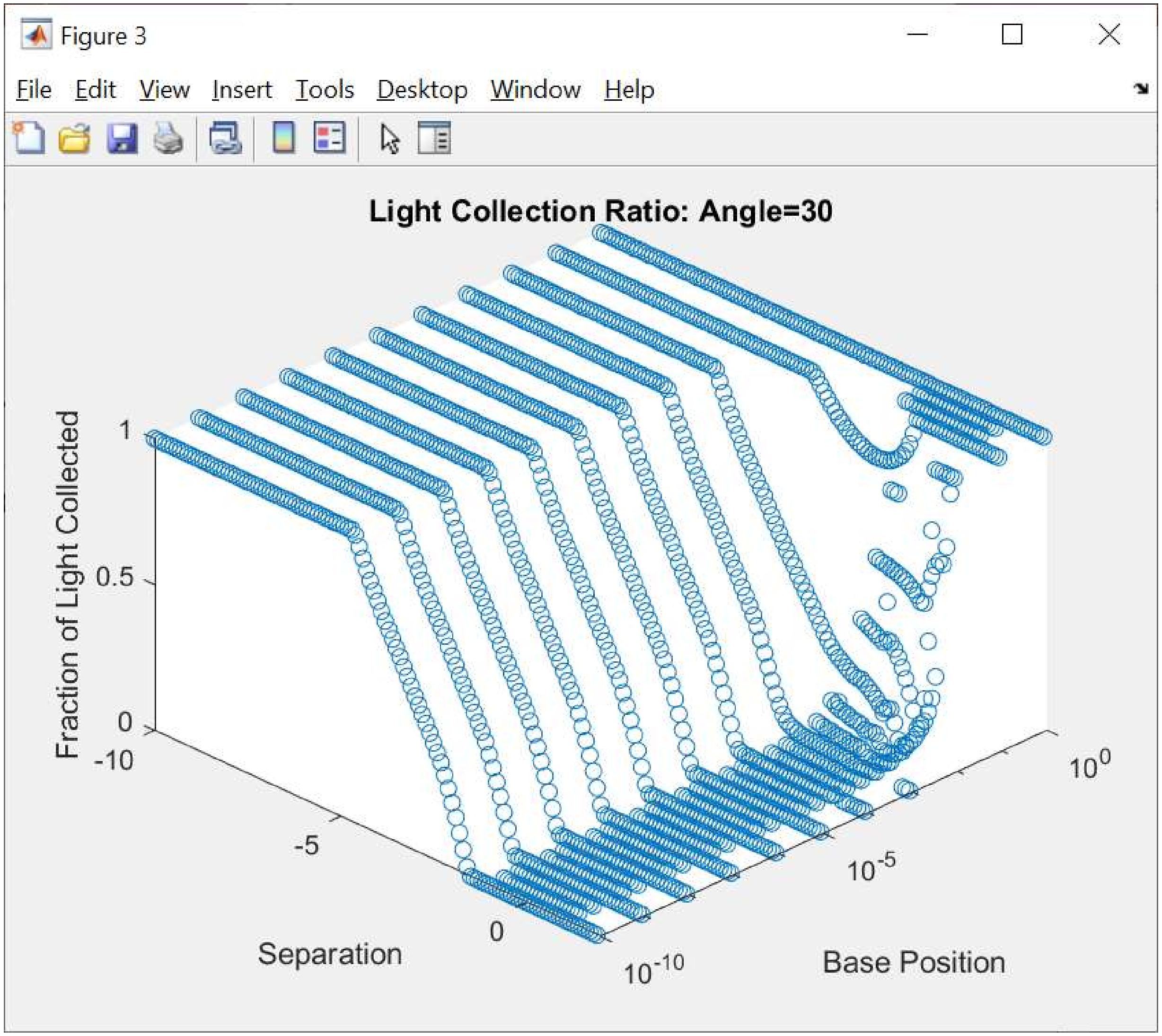
Results: Light Collection, Angle = 1



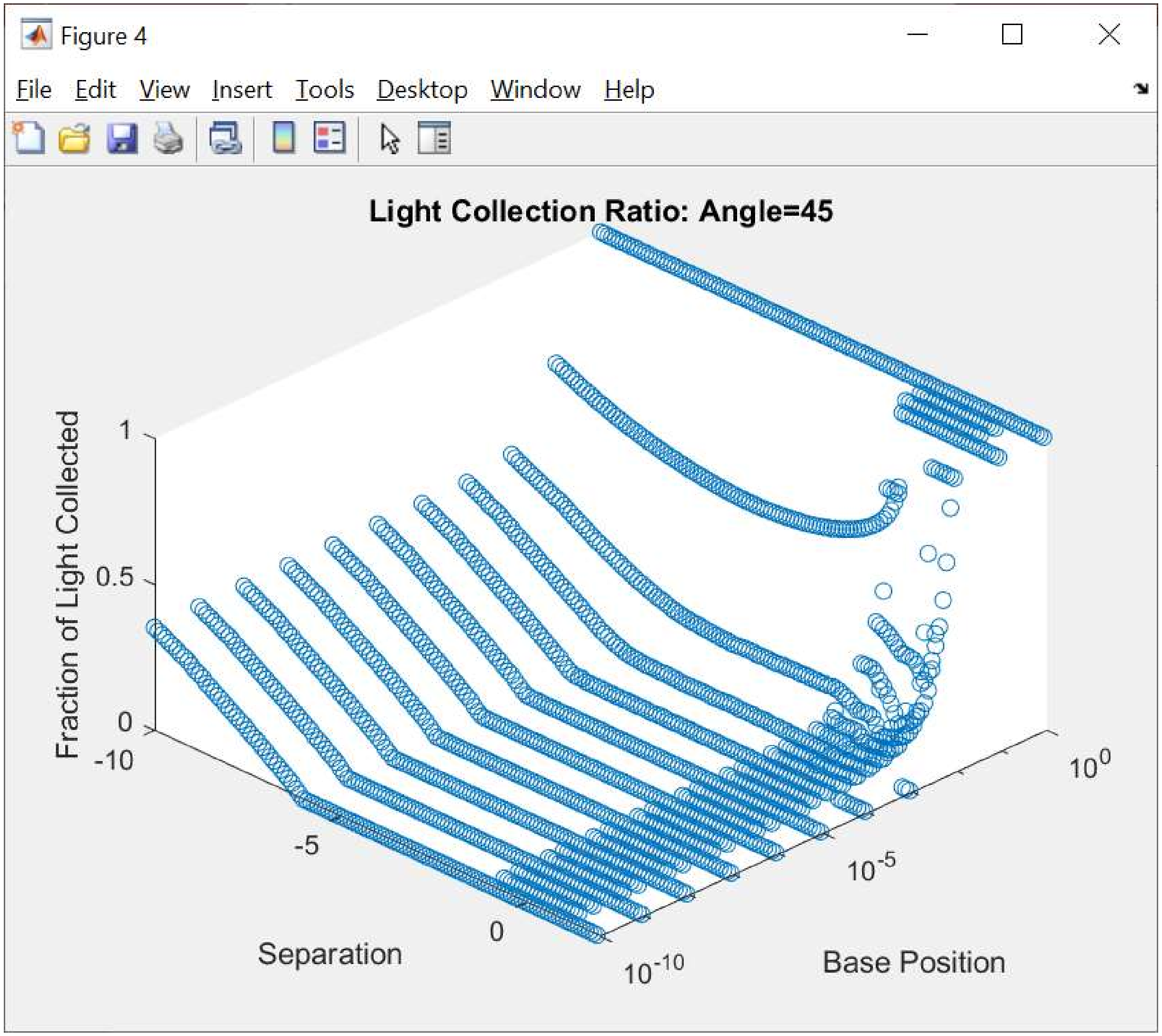
Results: Light Collection, Angle = 15



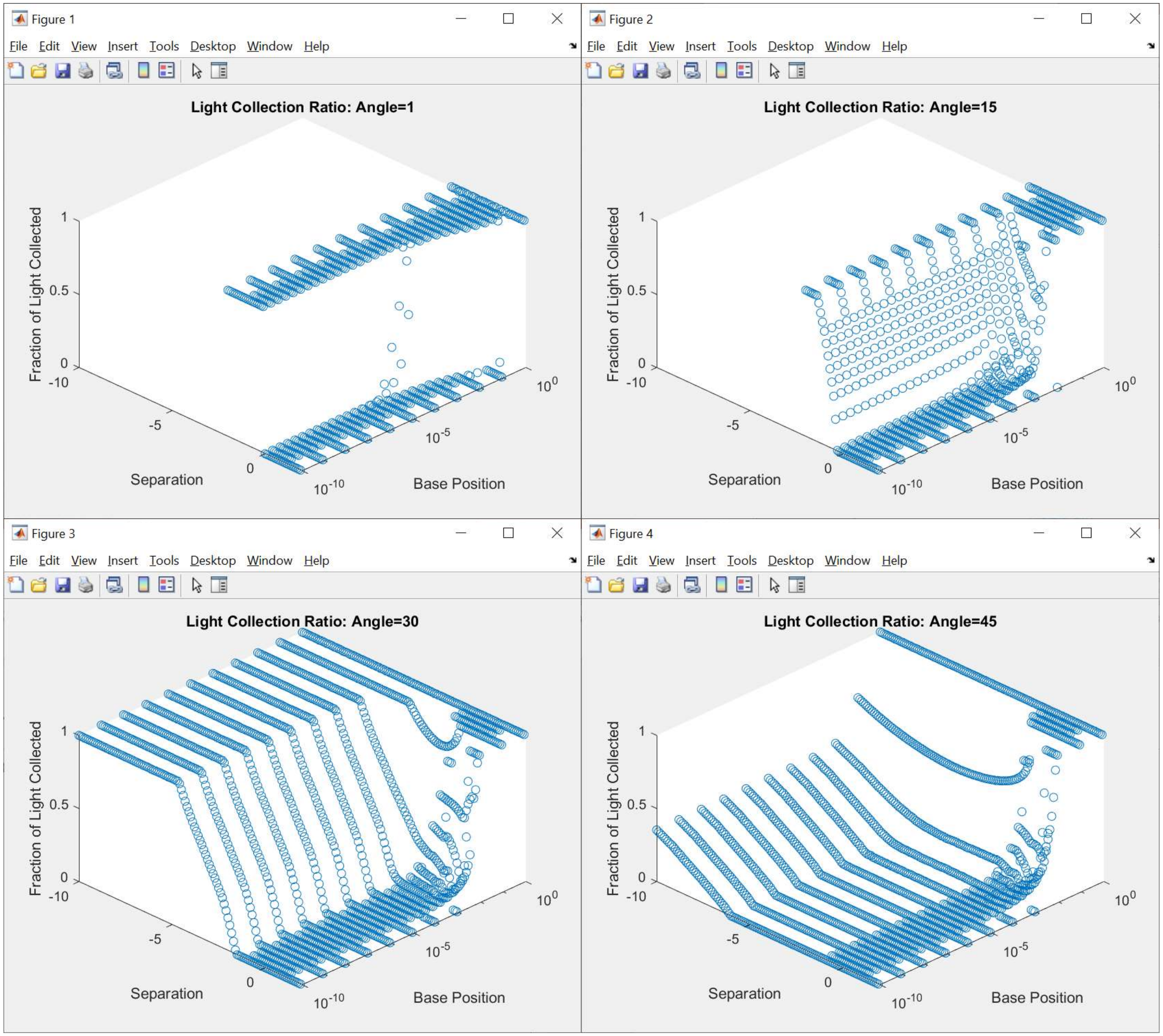
Results: Light Collection, Angle = 30



Results: Light Collection, Angle = 45

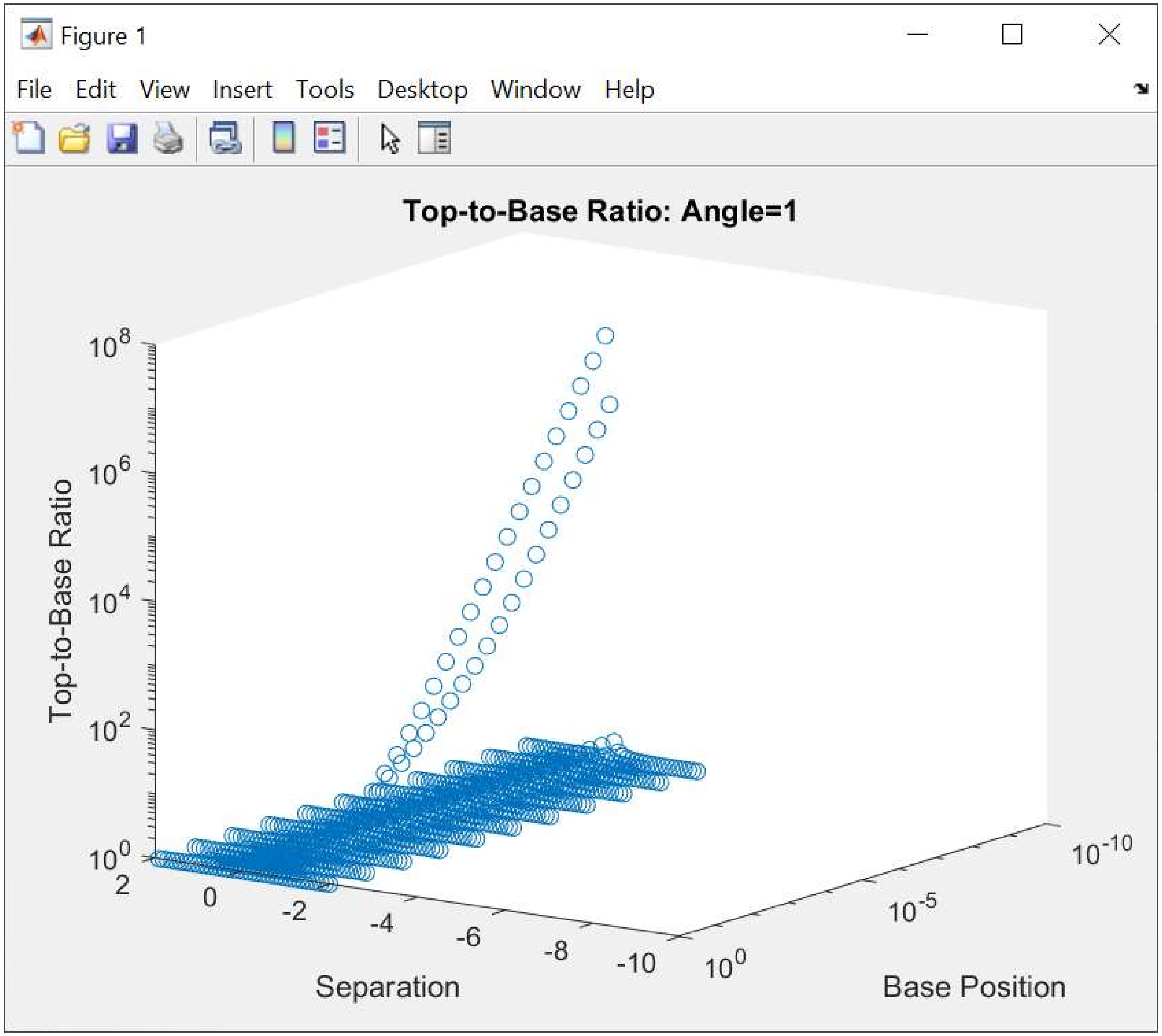


Results: Light Collection

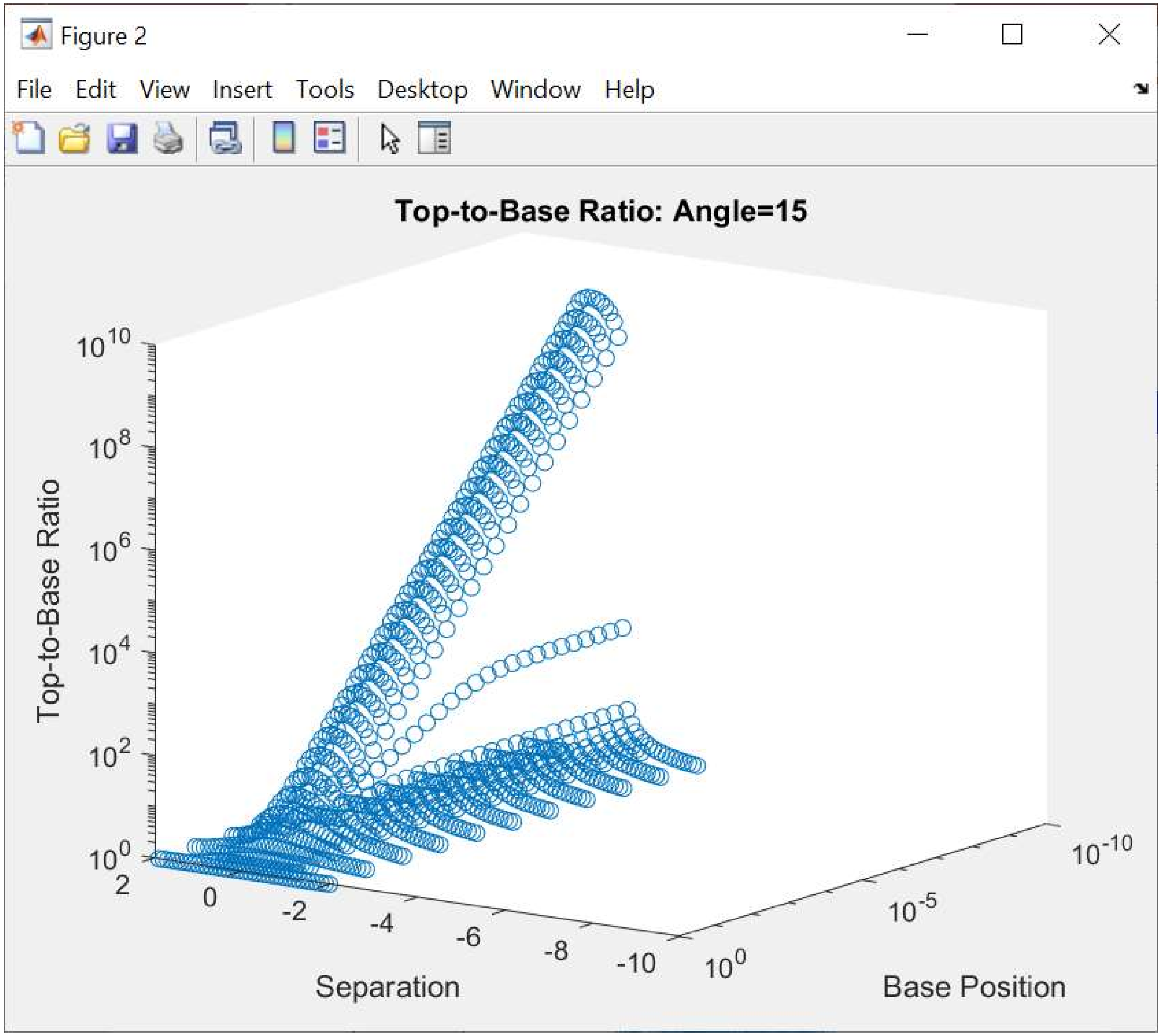


- As angle increases, changes in parabola separation lead to greater changes in light collection
- Light collection approaches a constant 1 as base position approaches 1

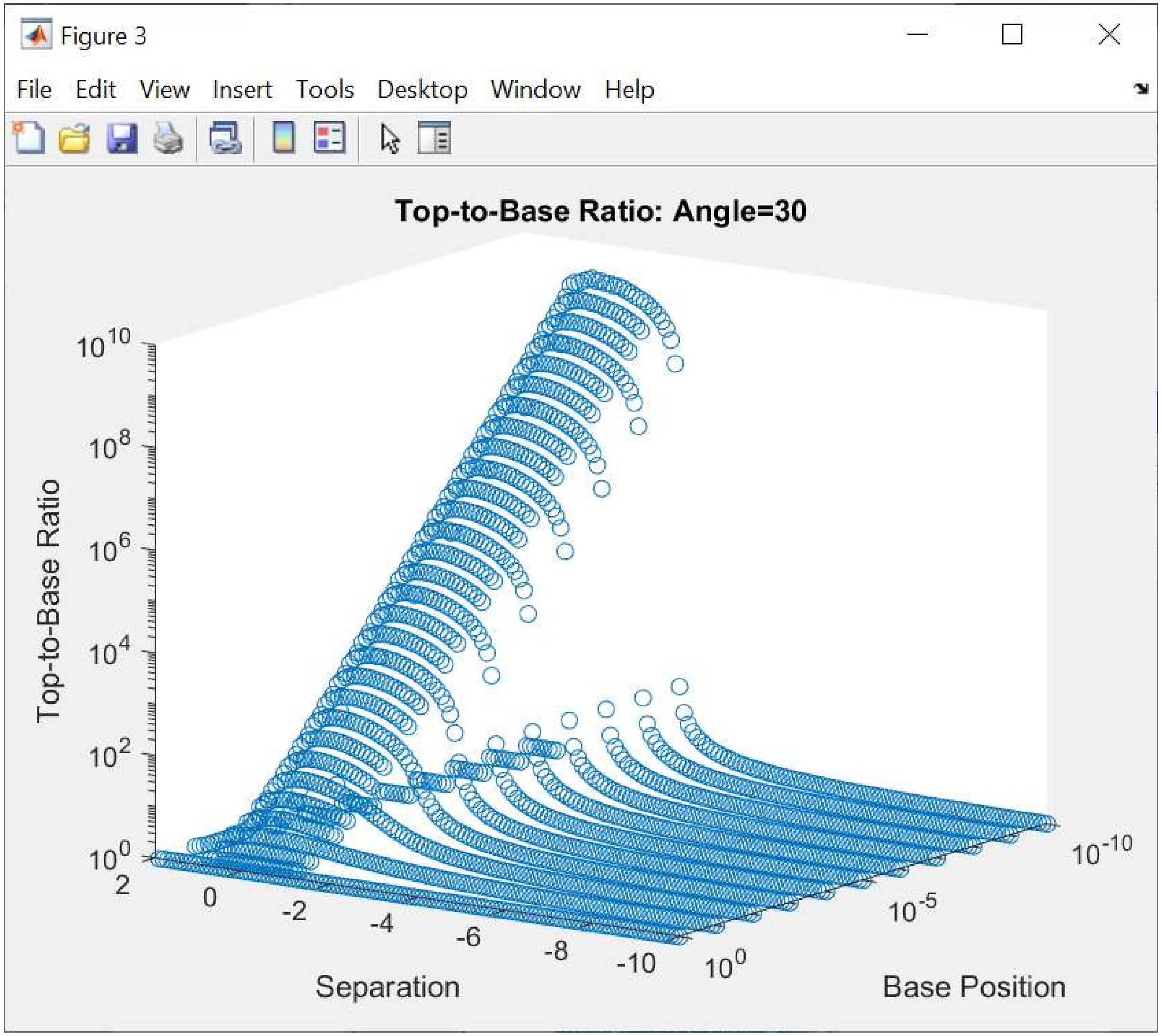
Results: Top-to-Base Ratio, Angle = 1



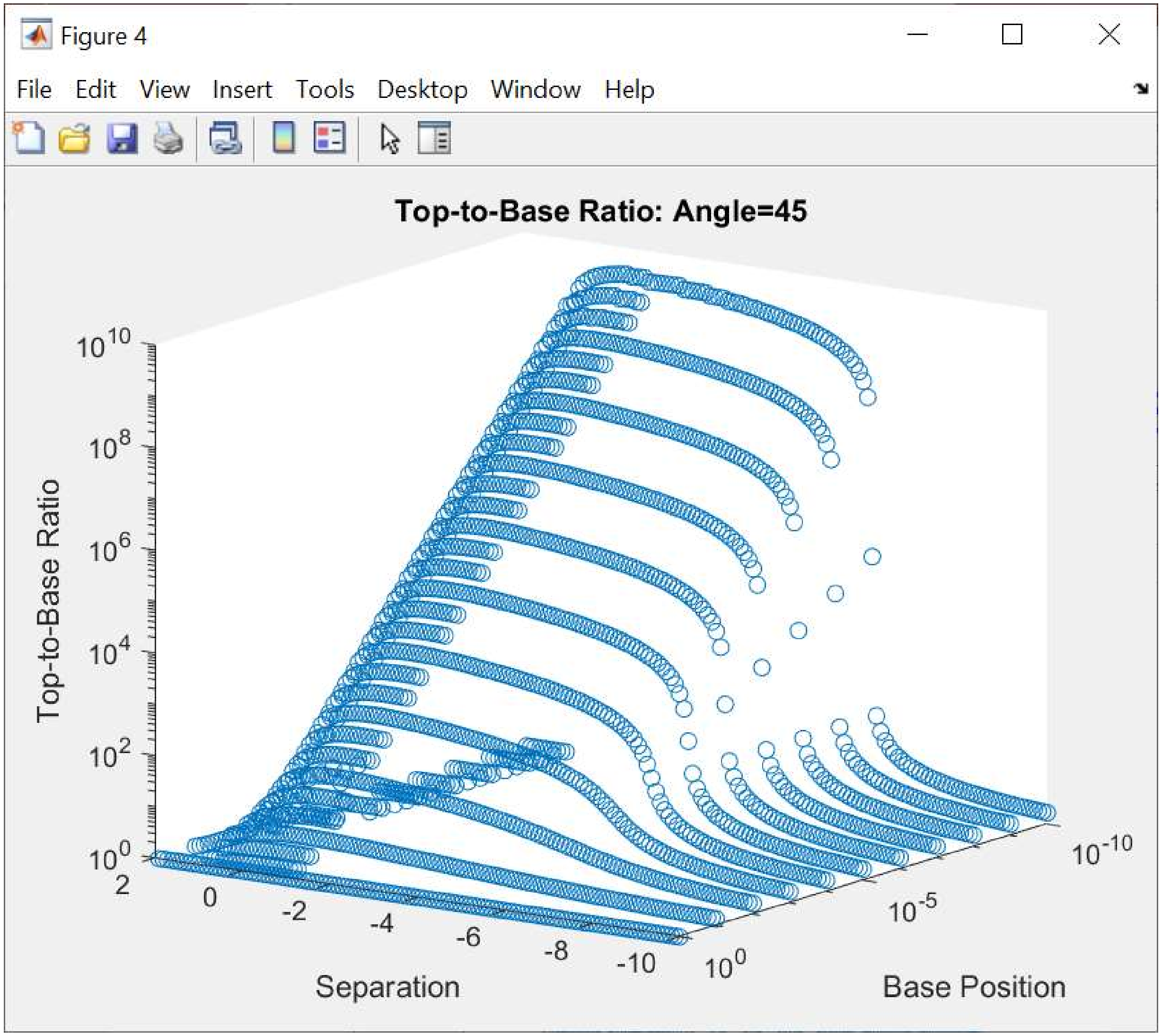
Results: Top-to-Base Ratio, Angle = 15



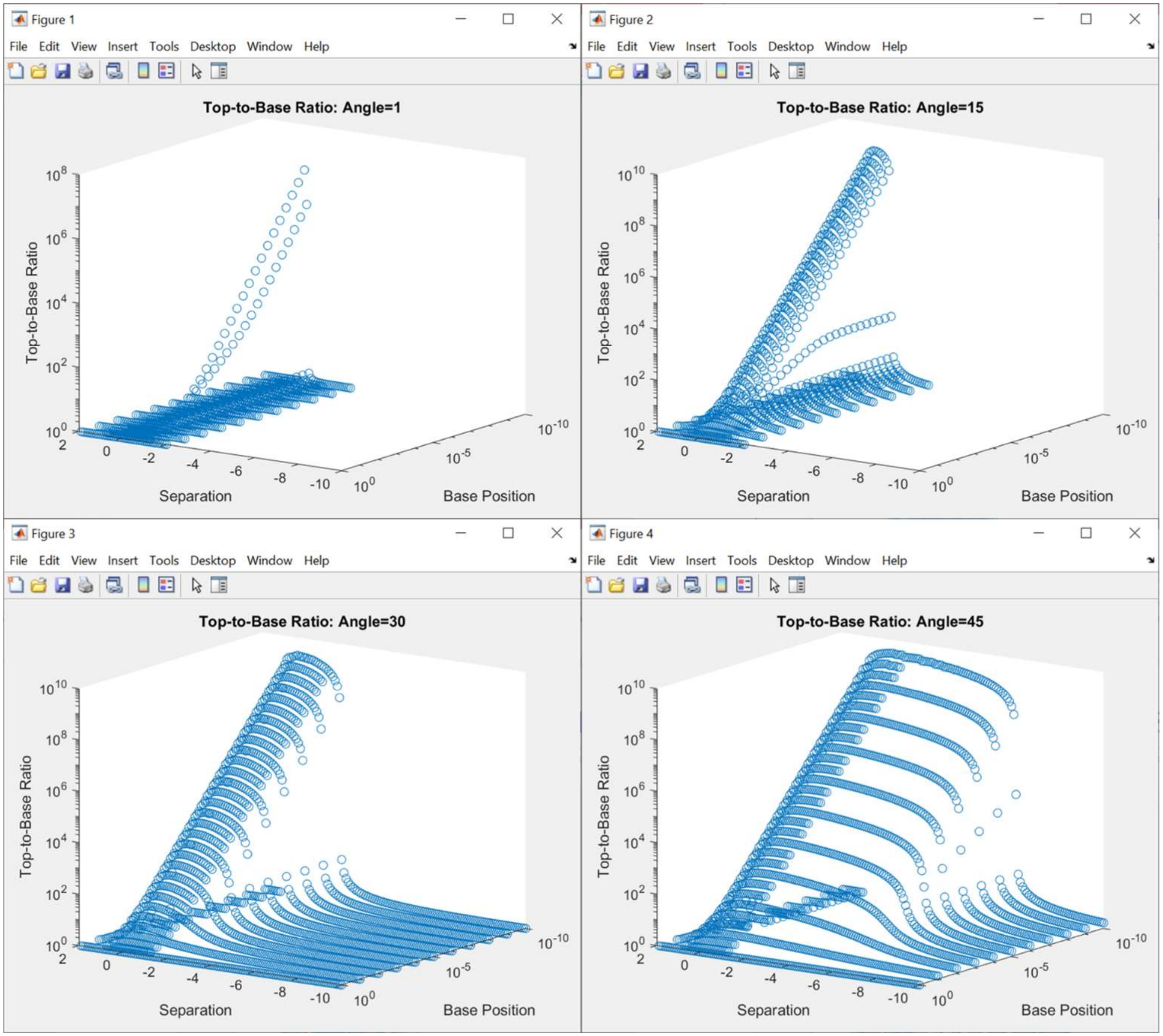
Results: Top-to-Base Ratio, Angle = 30



Results: Top-to-Base Ratio, Angle = 45

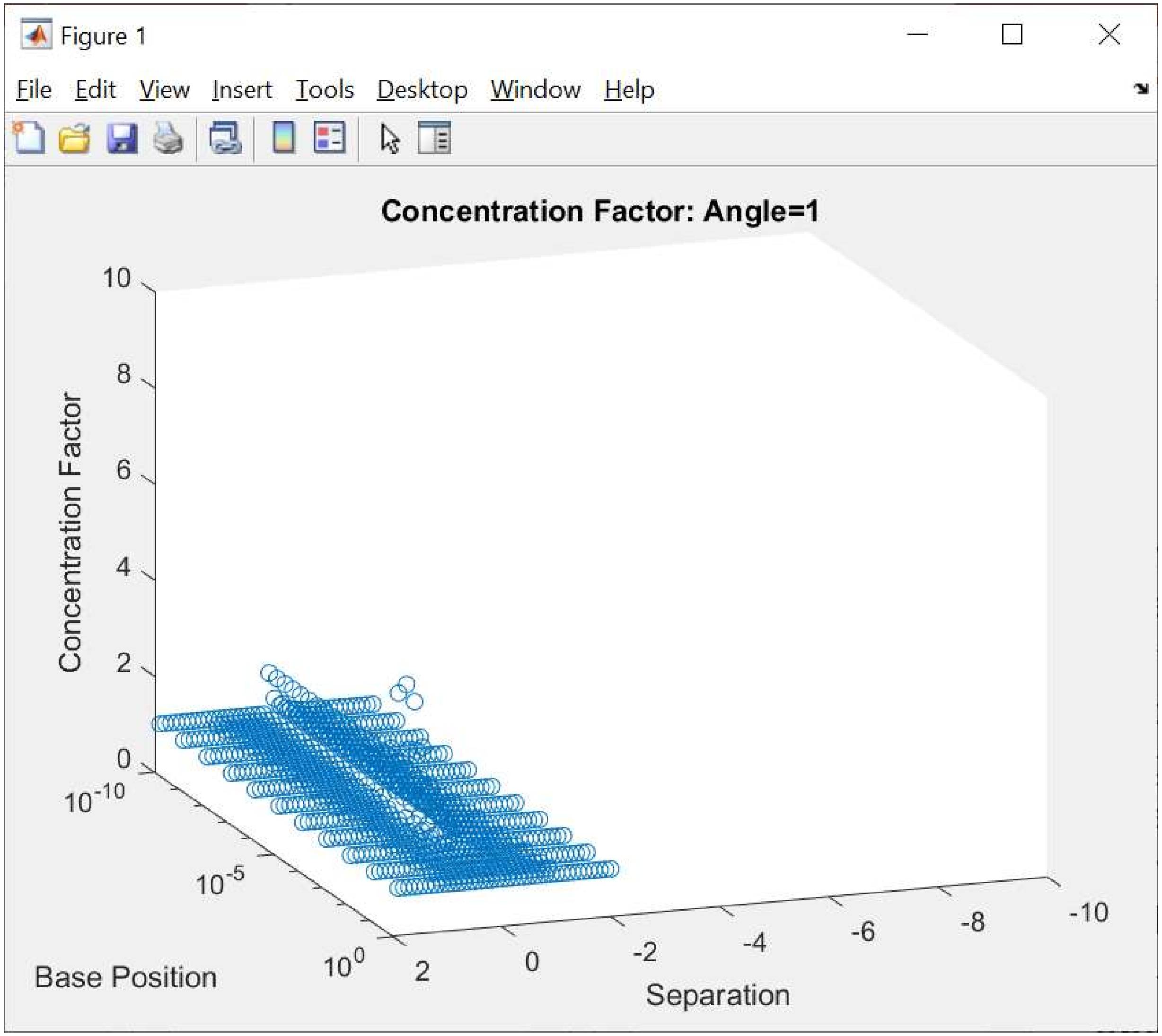


Results: Top-to-Base Ratio

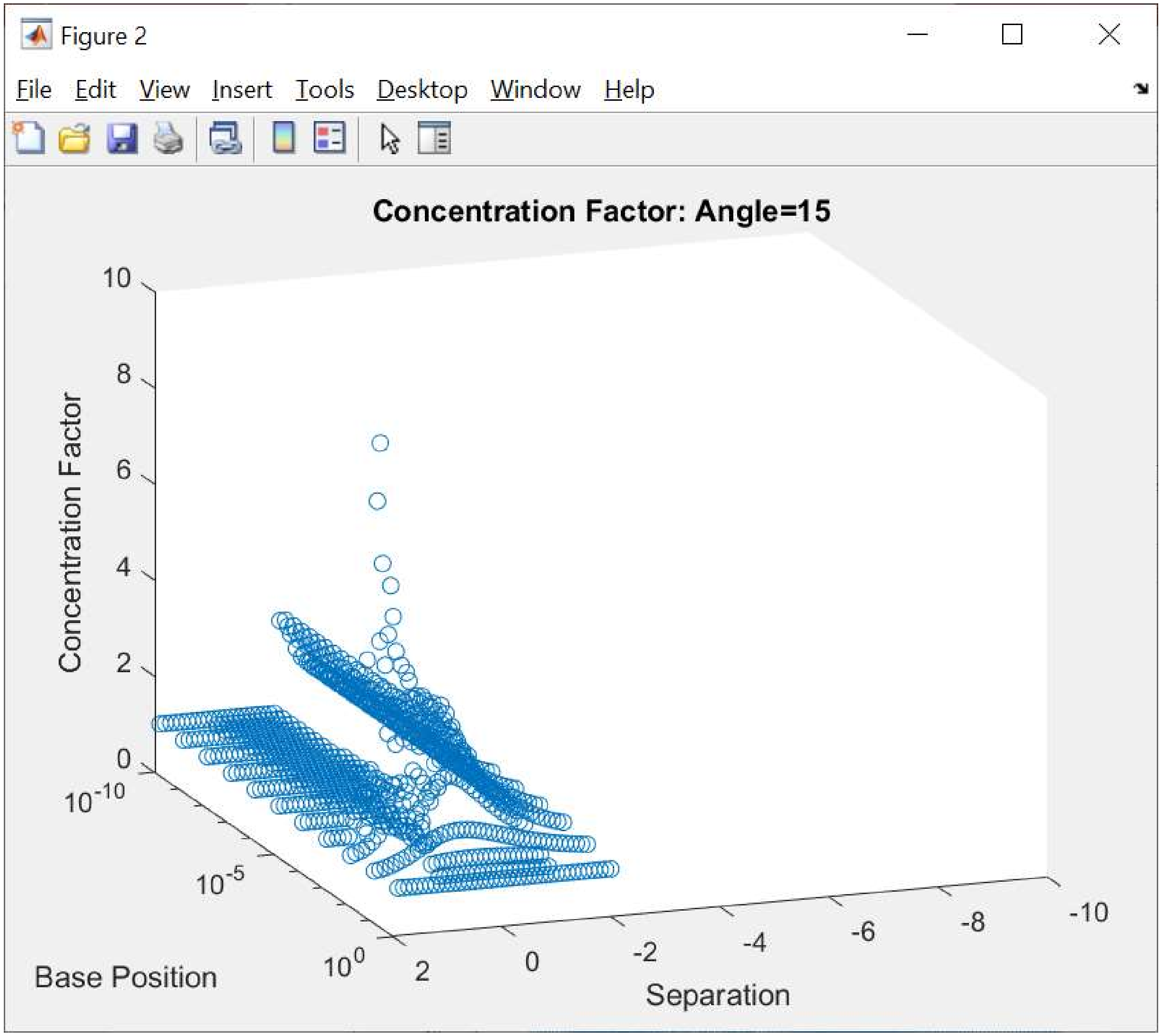


- As angle increases, changes in parabola separation lead to greater changes in top-to-base ratio
- Top-to-base ratio increases exponentially as base position decreases exponentially

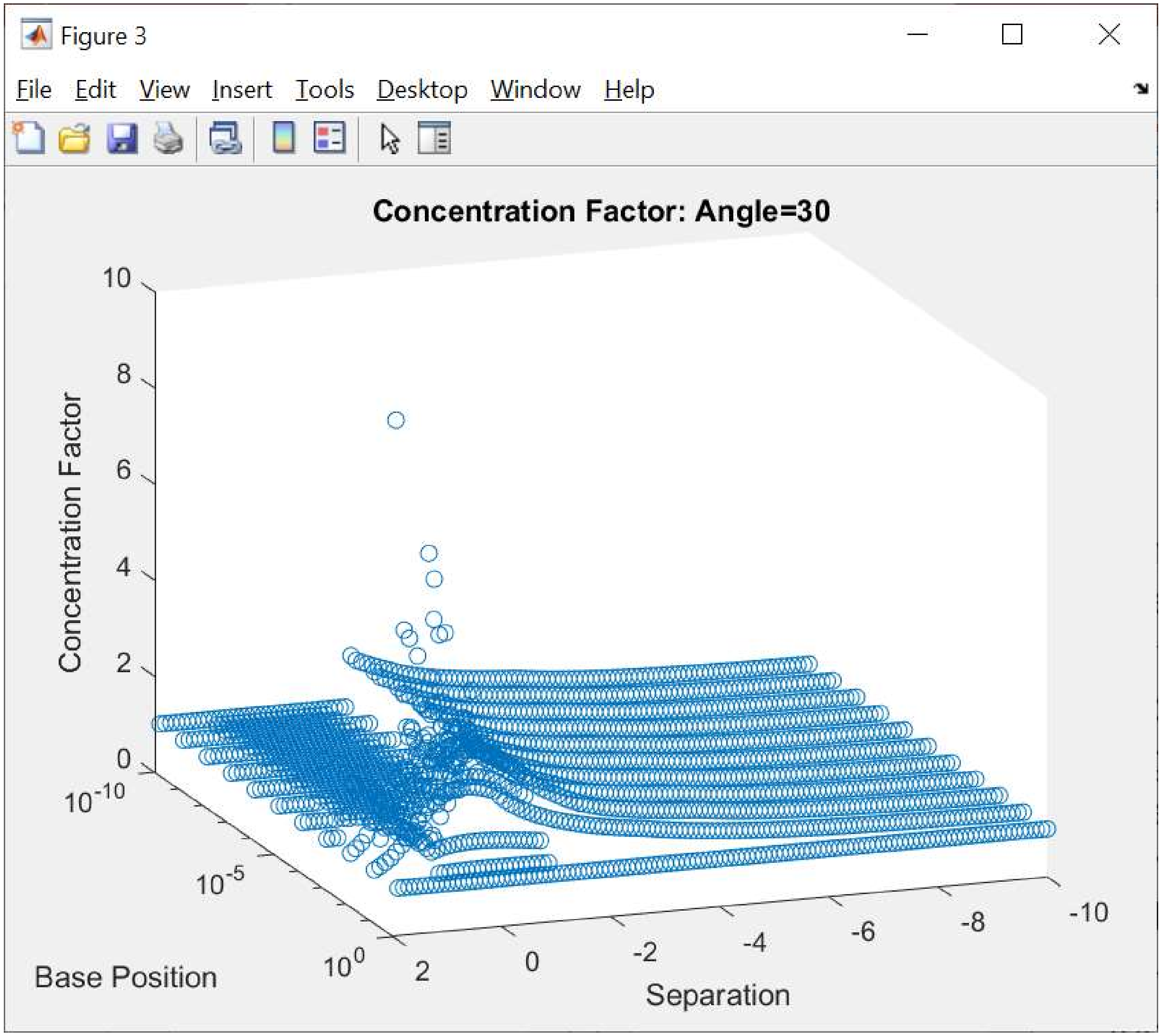
Results: Concentration Factor, Angle = 1



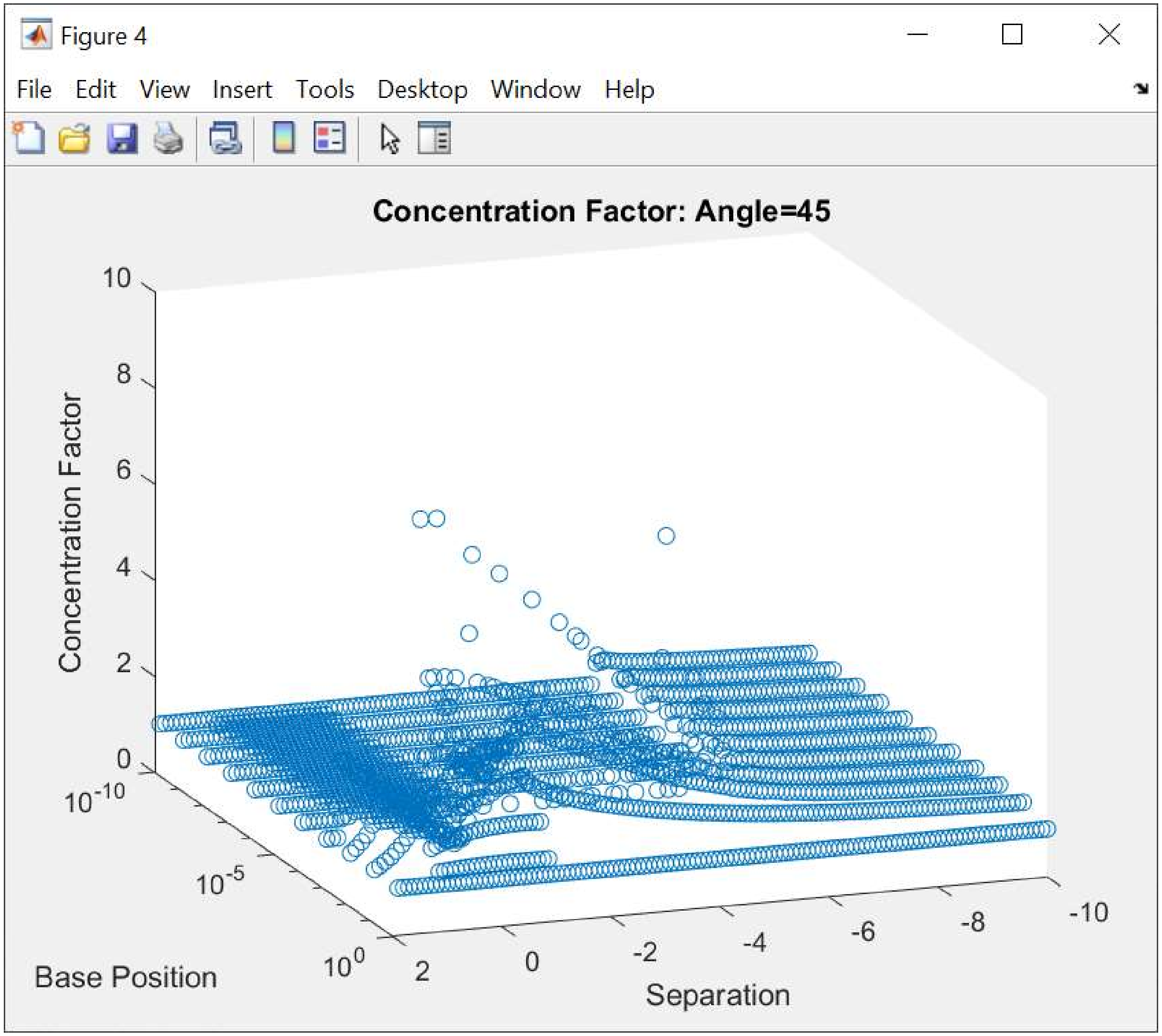
Results: Concentration Factor, Angle = 15



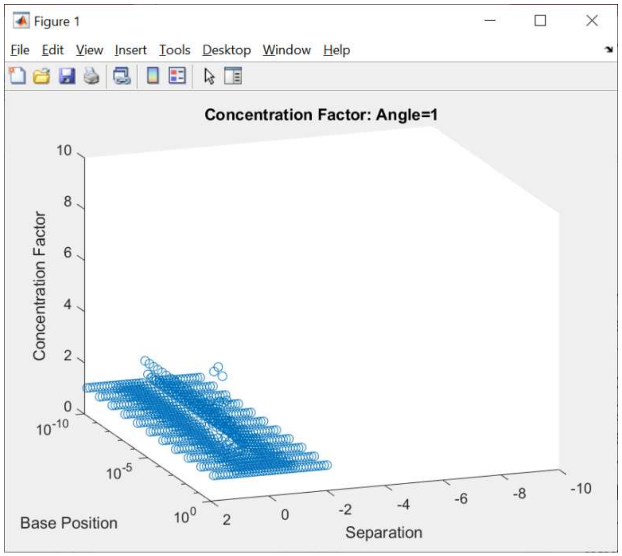
Results: Concentration Factor, Angle = 30

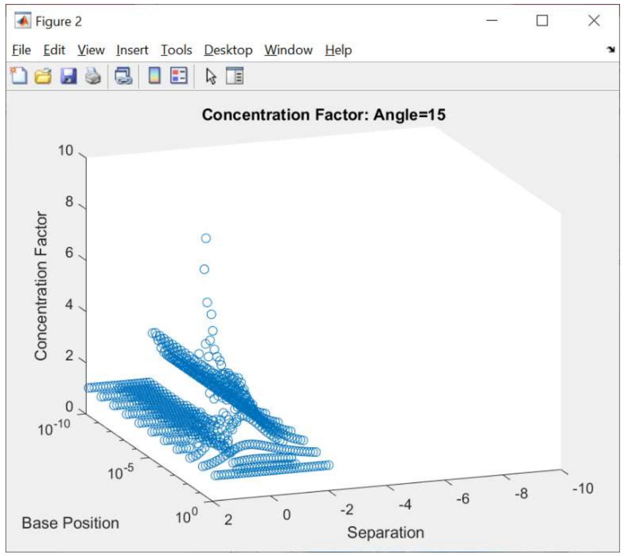


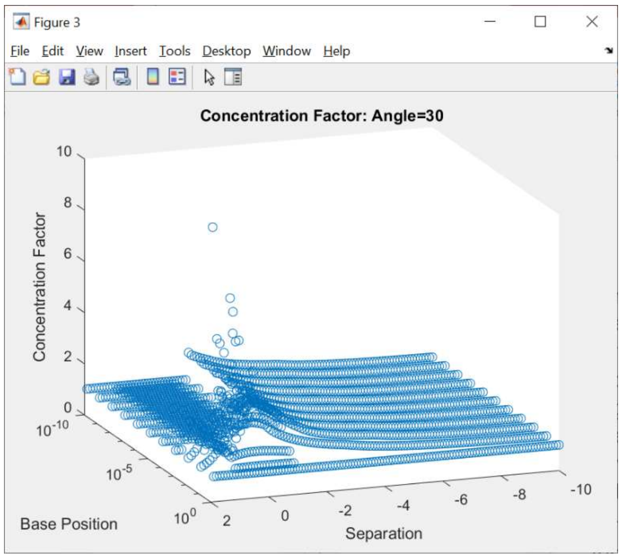
Results: Concentration Factor, Angle = 45

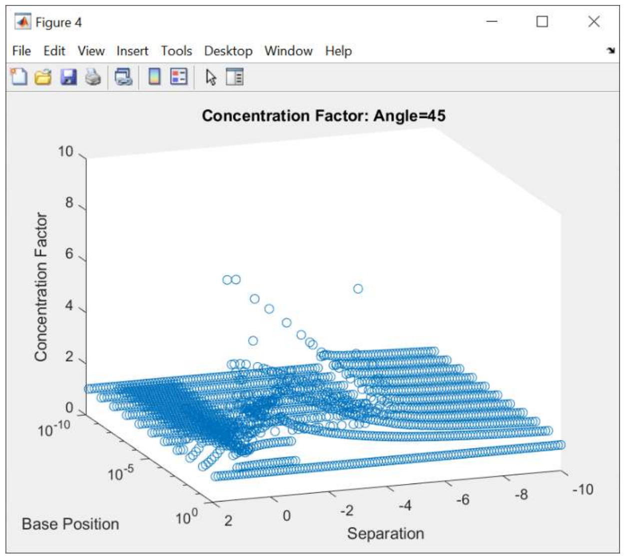


Results: Concentration Factor



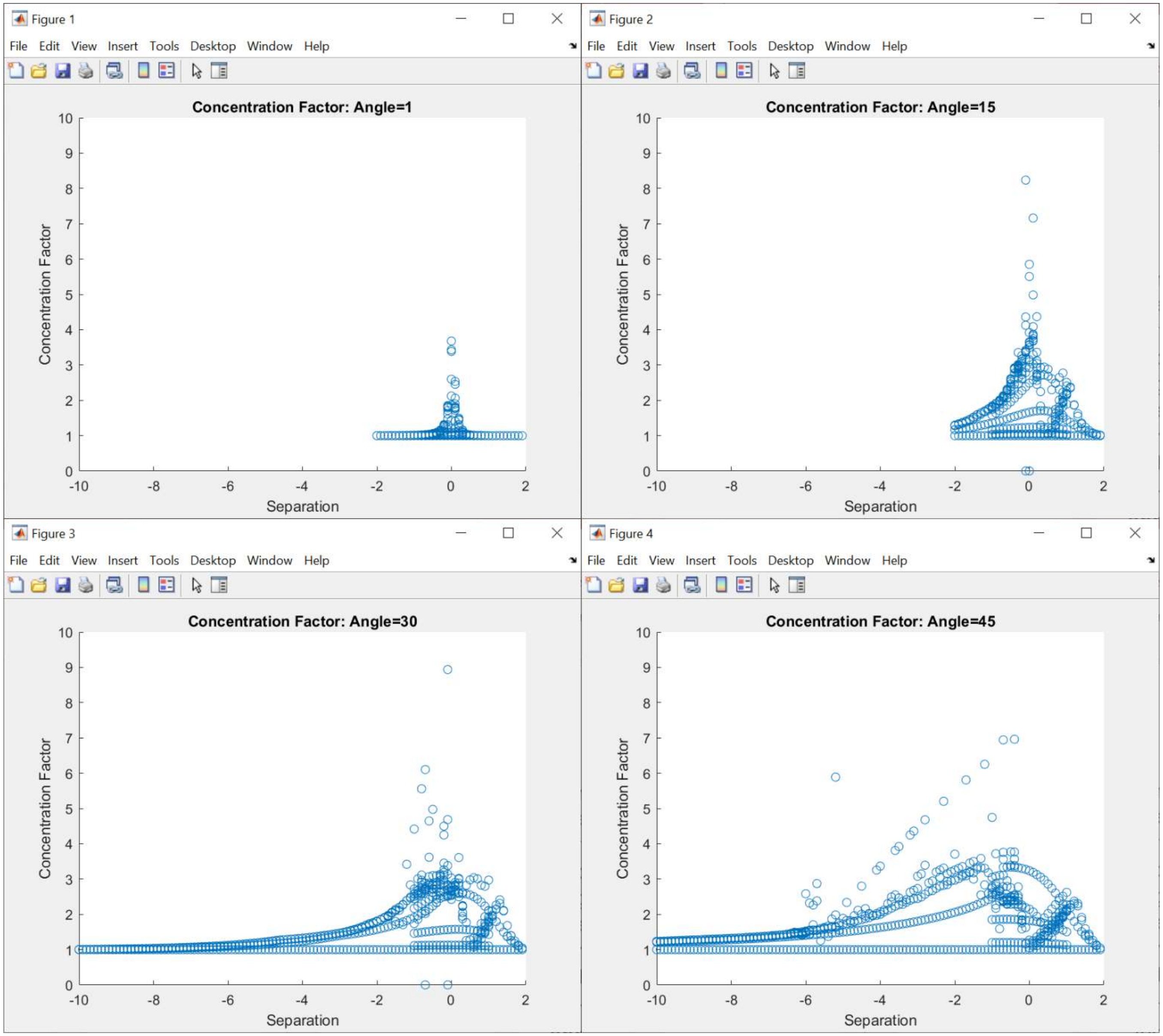






- As angle increases, changes in parabola separation lead to greater changes in concentration factor
- At higher angles, CF is less sensitive to changes in separation

Results: Concentration Factor



- As angle increases, changes in parabola separation lead to greater changes in concentration factor
- At higher angles, CF is less sensitive to changes in separation

Discussion

- Proposed a square-based concentrator design to increase ease of manufacturability
- Analyzed effects of different parameters on 2D concentration factor

- Convert promising 2D concentrator designs to 3D
- Measure concentration factor, and verify using Multiphysics software

Thank you for listening!