SAND2014-2957C

Application of Concentrating Solar Power:

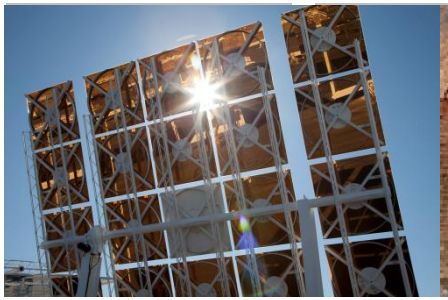
Archimedes Solar (Death) Ray

Clifford K. Ho
Sandia National Laboratories
Concentrating Solar Technologies Dept.
Albuquerque, New Mexico
ckho@sandia.gov, (505) 844-2384

April 5, 2014

Exceptional service in the national interest

Sandia National Laboratories



U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

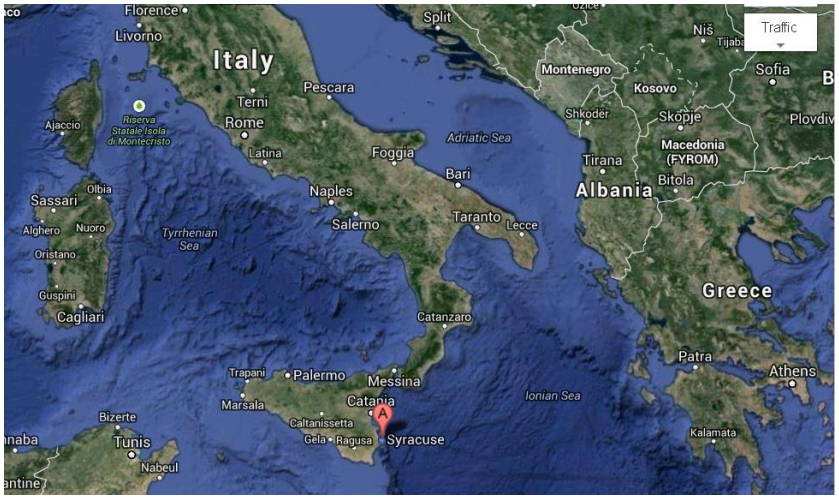
Overview

Sandia National Laboratories

- Background of the Legend
- Can ships burn from concentrated sunlight?
- How many mirrors would be required?
- Is it possible?

Background

- Siege of Syracuse (c. 214–212 BC)
  - Roman ships attacked Syracuse, Sicily, home of Archimedes



- Archimedes Heat Ray
  - Historical writings state that Archimedes used a “burning glass” to focus sunlight onto ships anchored within bow shot to start a fire
  - Others postulate that many polished bronze or copper mirrors or shields may have been used

A woodcut from Alhazen, opticae thesaurus, by Federico Risnero, Basel. 1572 *(Wikipedia)*

Overview

Sandia National Laboratories

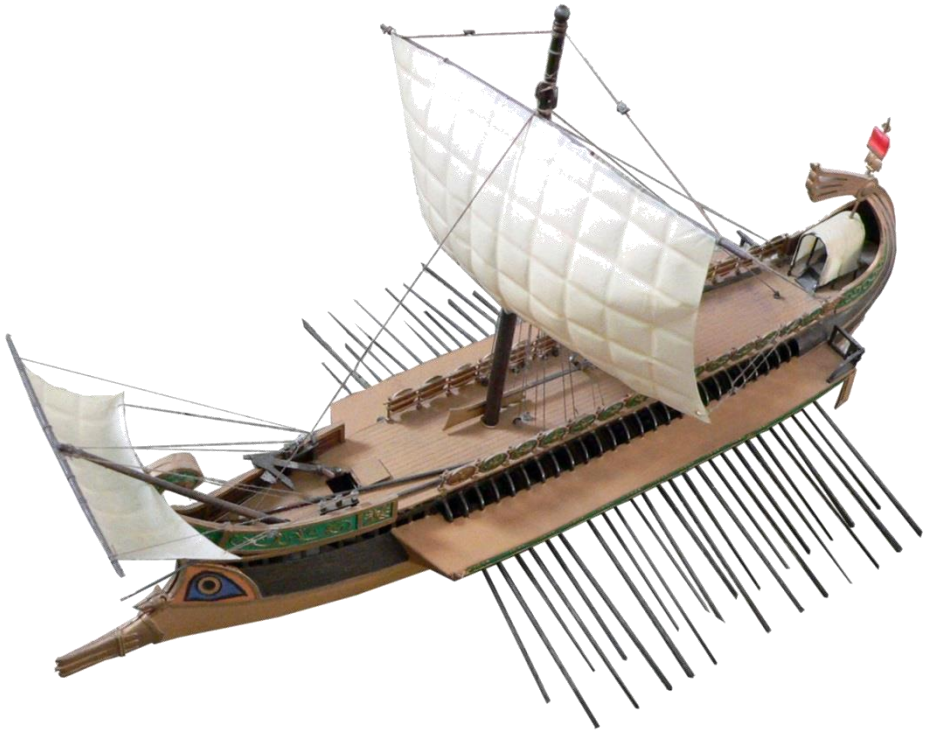
- Background of the Legend
- Can ships burn from concentrated sunlight?
- How many mirrors would be required?
- Is it possible?

Process

- Determine which part of the ship is most likely to ignite with concentrated sunlight
- Determine the autoignition temperature of that material
- Determine the required heat flux (W/m^2) to reach the autoignition temperature
  - Assume that the time to reach ignition temperature should be ~10 – 20 seconds or less

Sail vs. Hull?

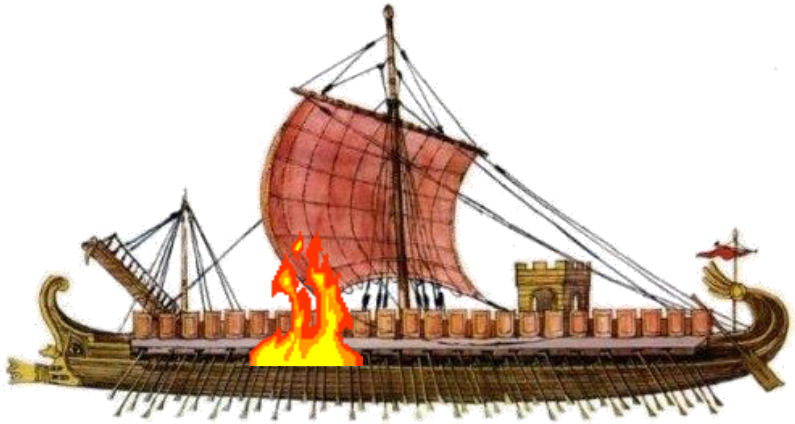
- It is postulated that the sails would have been furled when the ships were anchored or in battle
- Cooling effect from wind on the thin sails and the lower absorptance of a lighter colored material would have made it more difficult to set on fire
- Hull is a more stable target
- Hull could have been coated with black pitch, which increases the solar absorptance



Source: Wikipedia, http://en.wikipedia.org/wiki/Roman_navy

Autoignition Temperature of Wood

- Autoignition temperature of wood is ~400 – 500 C
  - Babrauskas, V., 2001, “Ignition of Wood: A Review of the State of the Art,” in Interflam, 2001, Interscience Communications Ltd., London, pp. 71 - 88.
  - Moisture content of wood is important
- Ancient roman ships were made of various woods (e.g., oak, cedar)
  - Giachi, G., et al., 2003, “The wood of “C” and “F” Roman ships found in the ancient harbour of Pisa (Tuscany, Italy): the utilisation of different timbers and the probable geographical area which supplied them”, *J. of Cultural Heritage*, 4, 269–283.

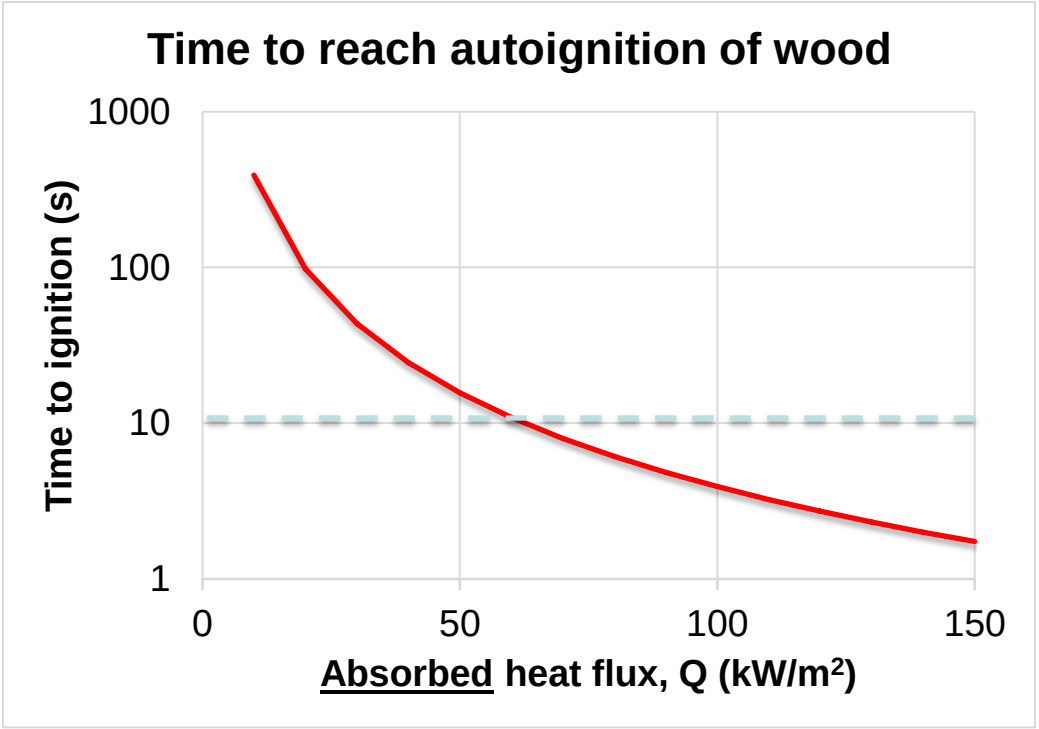


Source: http://www.ancientworlds.net/aw/Places/Property/1103933

Required Heat Flux to Ignite Wood

- Use energy balance to determine time to reach autoignition temperature of 500C for an applied heat flux
  - Minimum heat flux to ignite wood within a minute or so reported between ~30 - 100 kW/m^2 (Babrauskas, V., 2001)
  - Mills and Clift (1992) assume 60 kW/m^2 minimum heat flux
  - Need to also add 10 – 20 kW/m^2 to account for radiative and convective heat losses at 400 – 500 C

➡ Assume minimum <u>incident</u> flux of ~60 – 80 kW/m^2 required to ignite wood



$$t_{ig} = \left(\frac{\pi}{4}\right)(k\rho c)\left[\frac{T_{ig} - T_o}{q''}\right]^2$$

Principles of Fire Behavior, ISBN 0-8273-7732-0, 1998

Thermal properties from Incropera and DeWitt (1985) for oak

Overview

Sandia National Laboratories

- Background of the Legend
- Can ships burn from concentrated sunlight?
- How many mirrors would be required?
- Is it possible?

Process

- Determine minimum distance between mirrors and ships
- Determine optical and geometric characteristics of mirrors
- Assume time of day and location of ships relative to mirrors
- Use ray tracing to determine peak heat flux from single mirror
- Divide 60 kW/m^2 by the peak heat flux from a single mirror to get number of mirrors required to reach

Minimum distance

- Ships were said to be within bow shot
  - Modern target archery ranges between 30 – 90 m
  - Assume distance of **60 m** between mirrors and ships

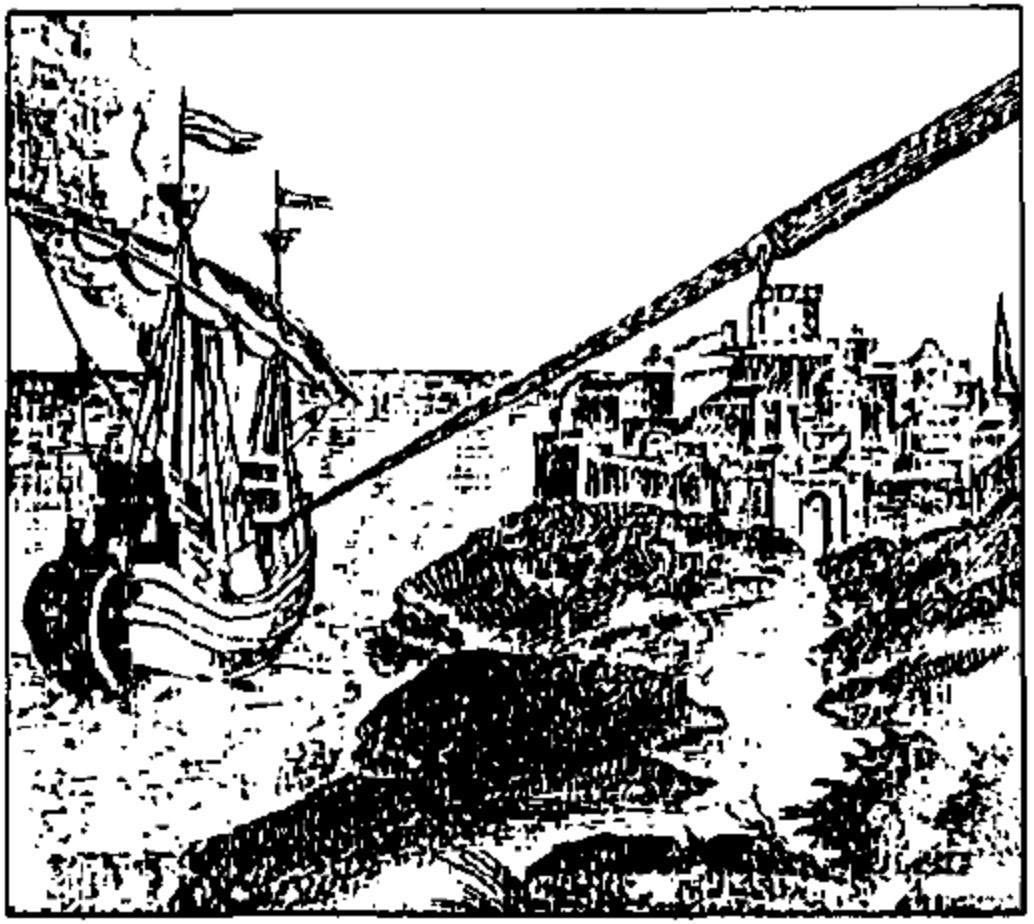


Figure 1. Part of a woodcut in *Grande art de la lumiere et de l'ombre* by Athanasius Kircher, 1646.

Source: Mills and Clift (1992)

Mirror characteristics

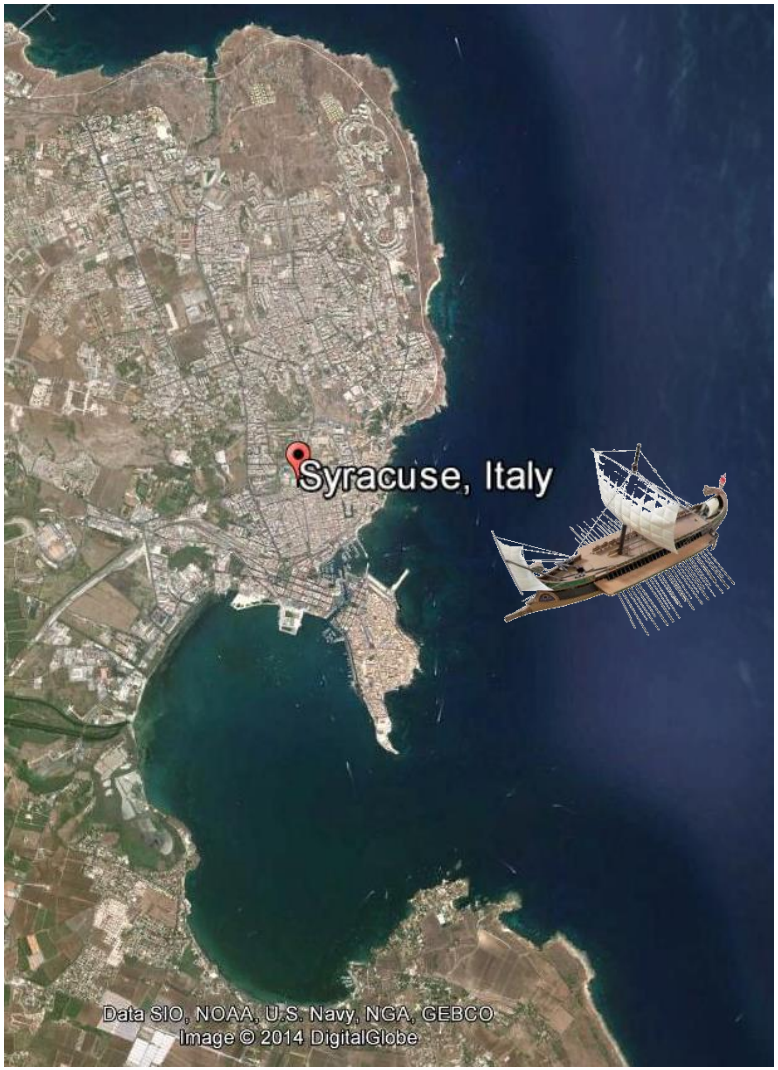
- If multiple mirrors were used, polished bronze plates or shields could have been used
  - Assume the following:
    - Reflectivity = 0.7
    - Slope error = 5 - 10 mrad
    - Area = 0.5 m^2
      - 1 m x 0.5 m rectangle OR
      - 0.8 m diameter circle
    - Flat vs. focused
      - Focused would have radius of curvature equal to twice the focal length

http://www.rudis-kuenstlerwerkstatt.de/fenster-helm-xanten-engl.htm

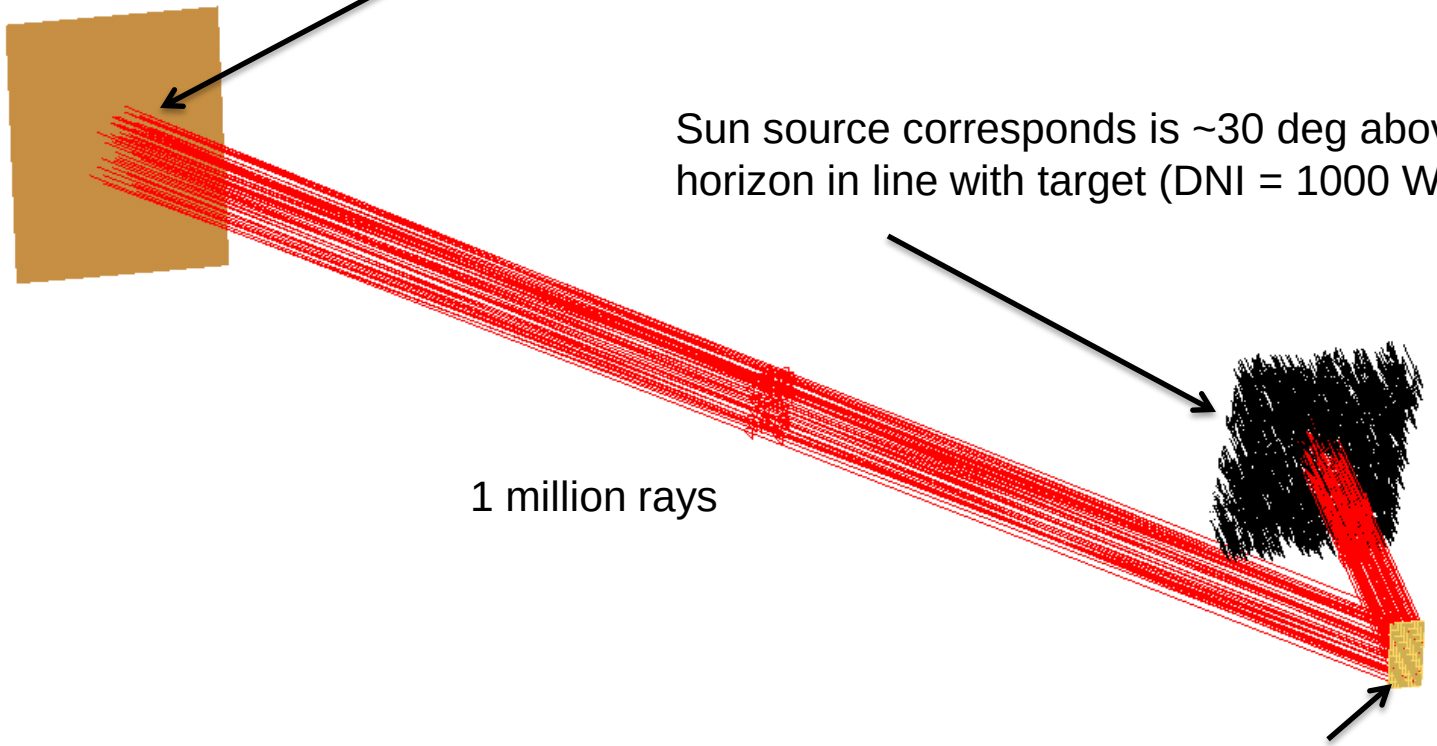
http://world4.eu/roman-costume-history/armor-romans/

Time of day and location of ships

- Siege of Syracuse was in the spring of 213 BC (Mills and Clift, 1992)
- Best optics would be during morning when sun is rising in the east/southeast
  - Ships located directly between mirrors and sun
  - Assume sun elevation is ~30 deg above horizon
  - Assume direct normal irradiance from sun of 1000 W/m^2

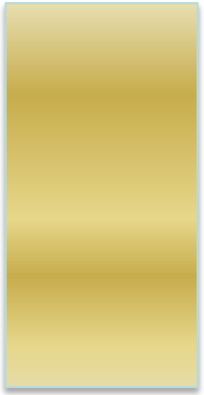


Ray Tracing – Single Mirror

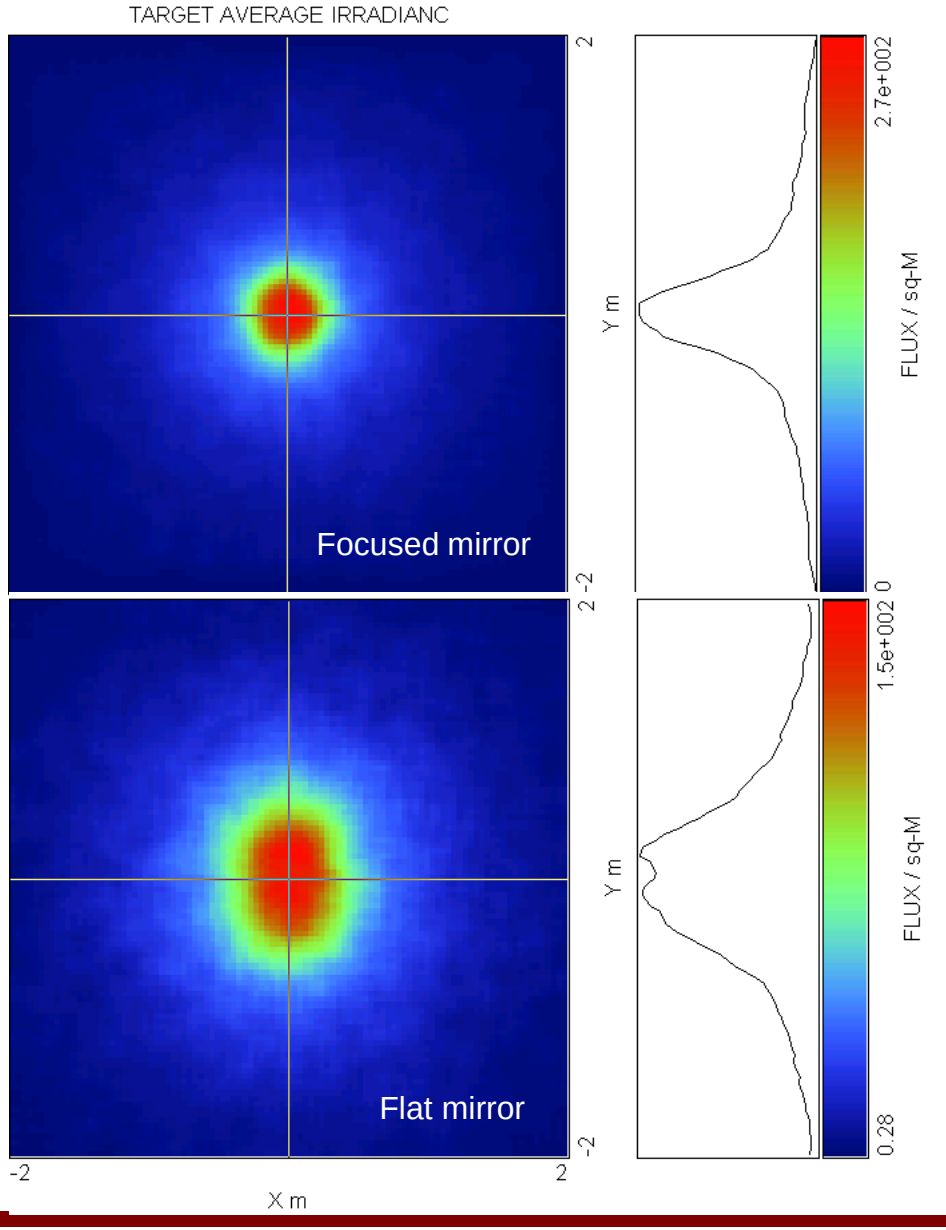


Ray Tracing – Effect of Focusing

- Single 0.5 m^2 rectangular mirror (1 m x 0.5 m)
  - Top image is for focused mirror
  - Bottom image is for flat mirror
  - 10 mrad slope error
- Peak flux is nearly twice as high for the focused mirror
  - For a 1 m mirror, the curvature would only be about 1 mm for a focal length of 60 m

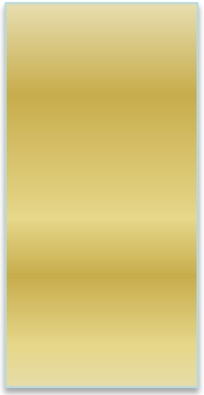


Rectangular mirror

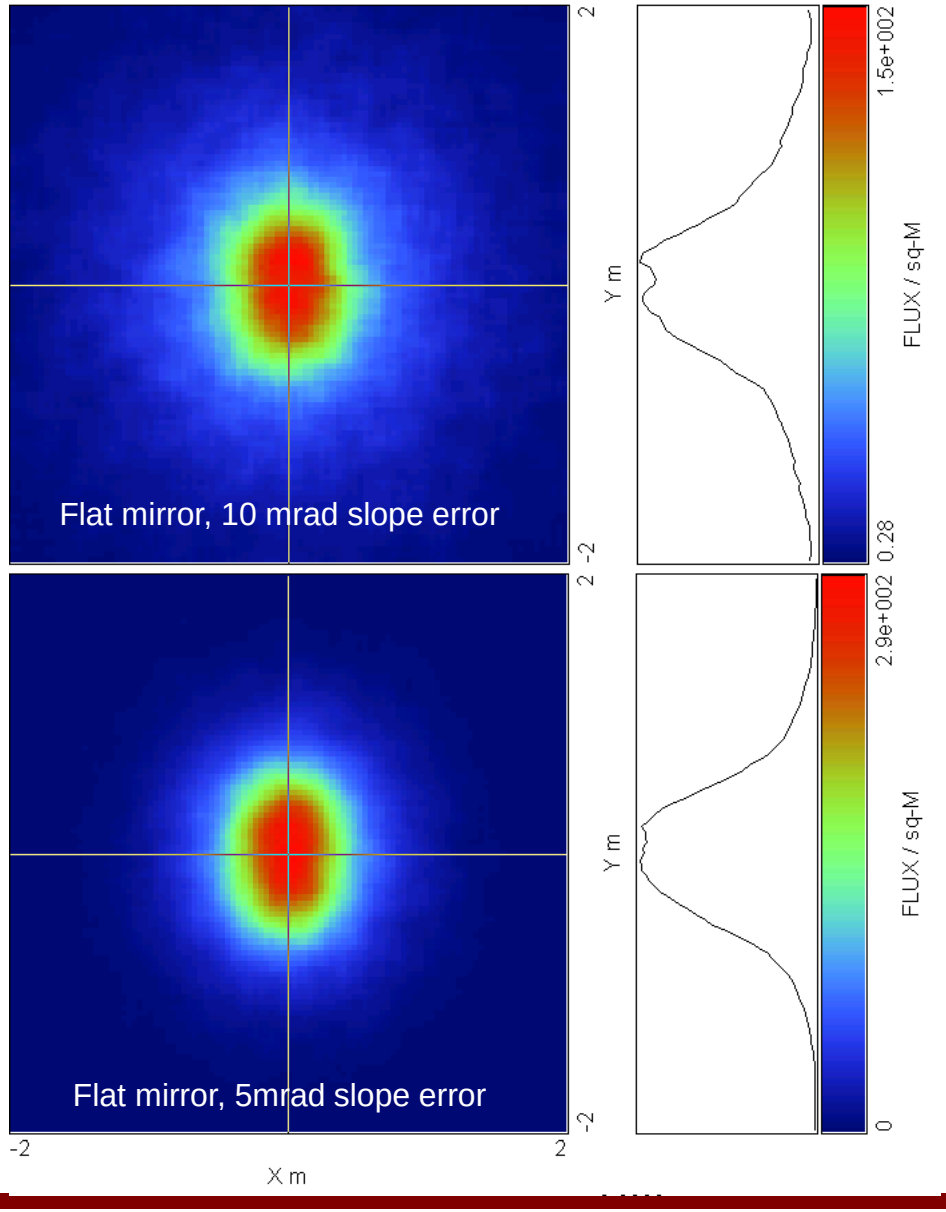


Ray Tracing – Effect of slope error (scattering)

- Single 0.5 m^2 flat rectangular mirror (1 m x 0.5 m)
  - Top image: 10 mrad slope error
  - Bottom image: 5 mrad slope error
- Peak flux is nearly twice as high (290 vs. 150 W/m^2) for 5 mrad vs. 10 mrad slope error
  - Less scattering of reflected light

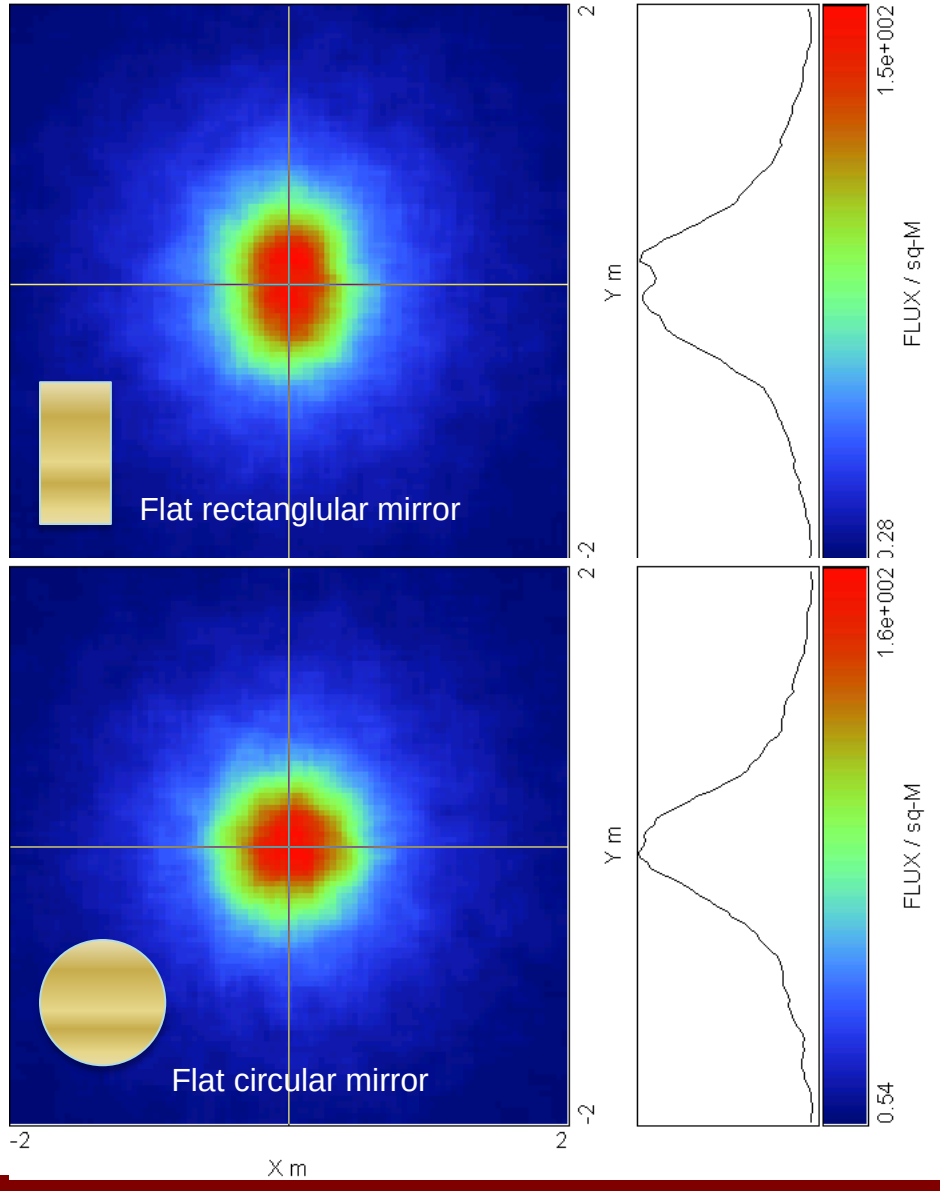


Rectangular mirror



Ray Tracing – Effect of mirror shape

- Single 0.5 m^2 flat mirror
- (0.8 m diameter)
  - Top image: 1 m x 0.5 m rectangular mirror
  - Bottom image: 0.8 m diameter circular mirror
  - 10 mrad slope error
- Peak flux is similar between rectangular and circular mirrors of same area (0.5 m^2)



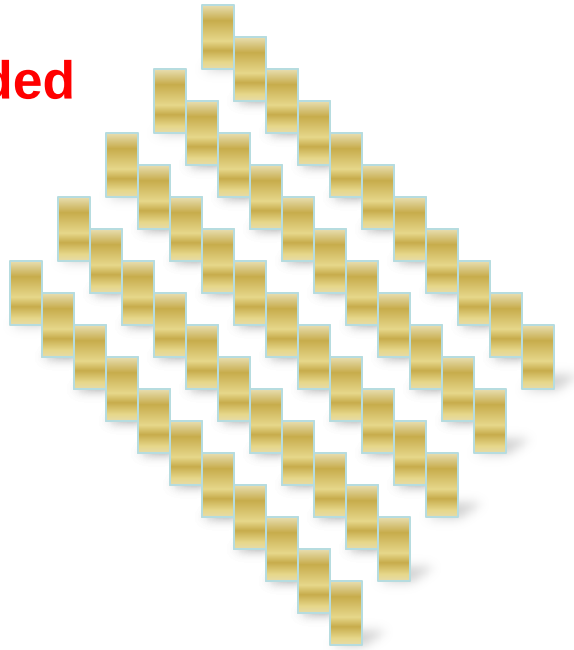
How many mirrors are required?

- Based on ray-tracing results, assume peak flux is 200 - 300 W/m^2 per mirror
- Divide the required incident heat flux to ignite wood (60 kW/m^2) by the peak heat flux from a single mirror

➡ **200 – 300 mirrors (100 – 150 m^2) are needed**

- Area = 0.5 m^2 per mirror
- Reflectivity = 0.7
- Slope error = ~5 – 10 mrad RMS

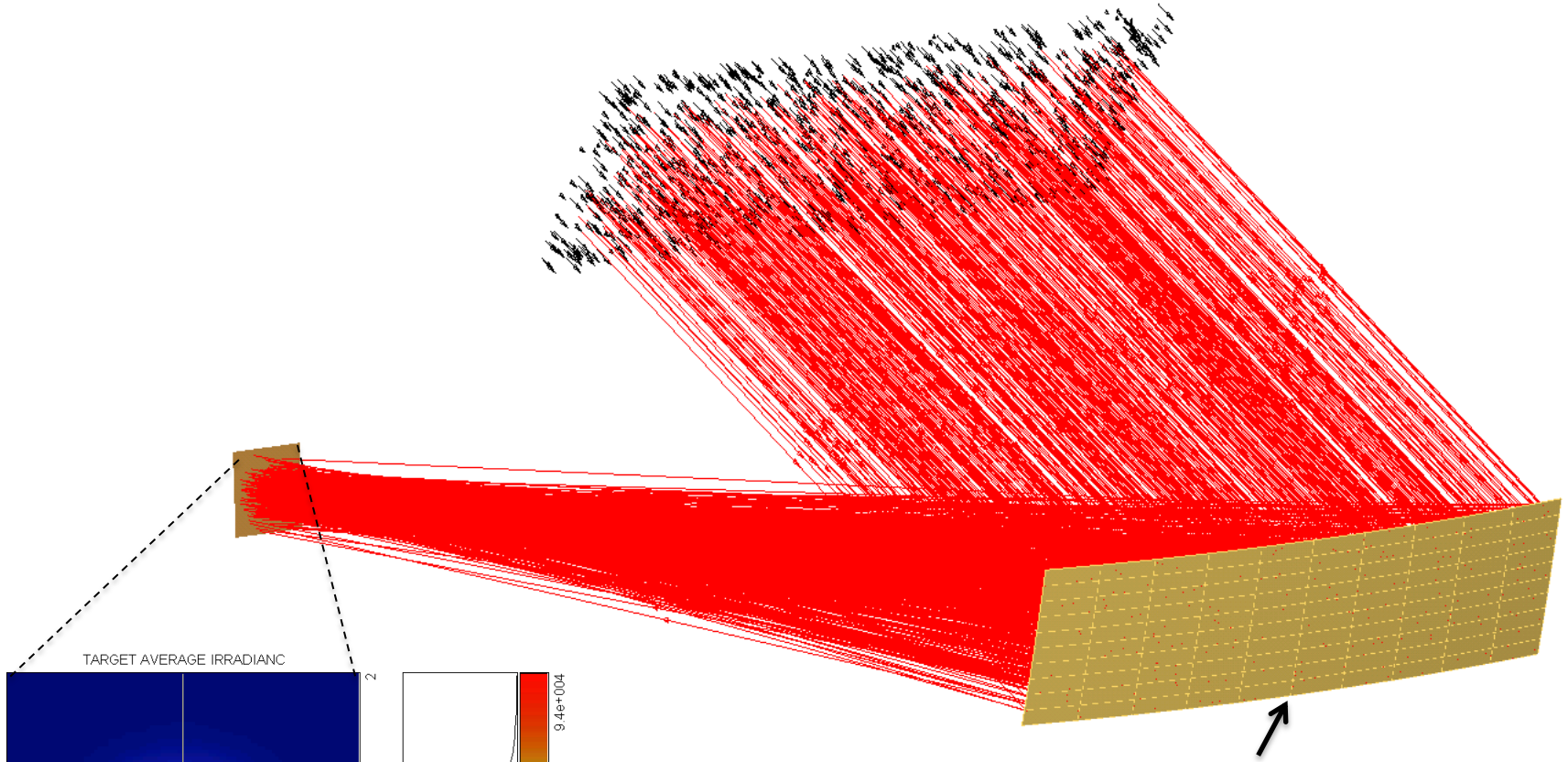
Is it possible?

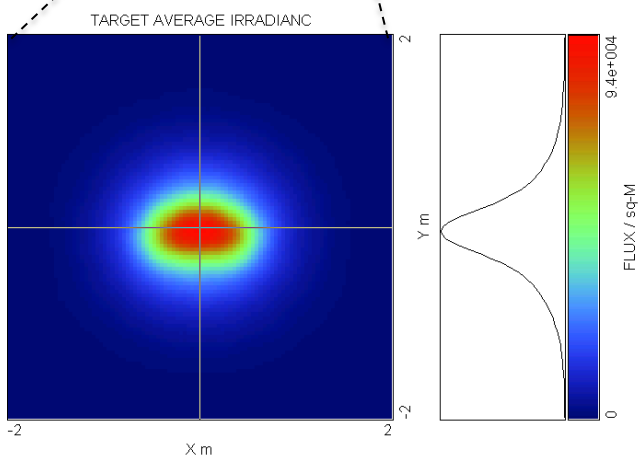


Overview

- Background of the Legend
- Can ships burn from concentrated sunlight?
- How many mirrors would be required?
- Is it possible?

Ray Tracing – Large Array of Mirrors



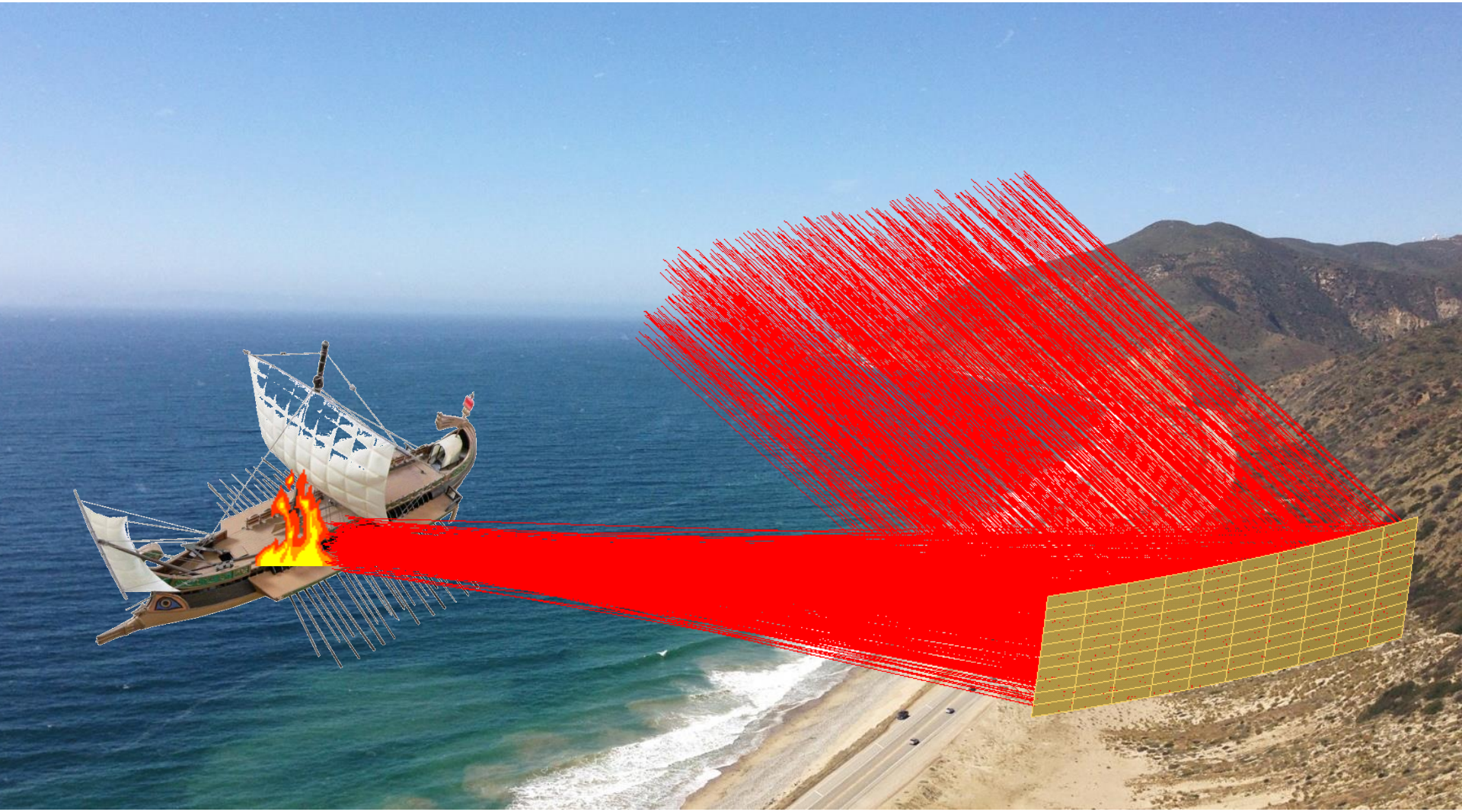


24 m (80 ft) x 6 m (20 ft) rectangular array of mirrors focused at target 60 m away

Peak flux is ~90 kW/m^2 (sufficient to ignite wood) with a beam size of about 1 m^2

Is it possible?

Sandia National Laboratories

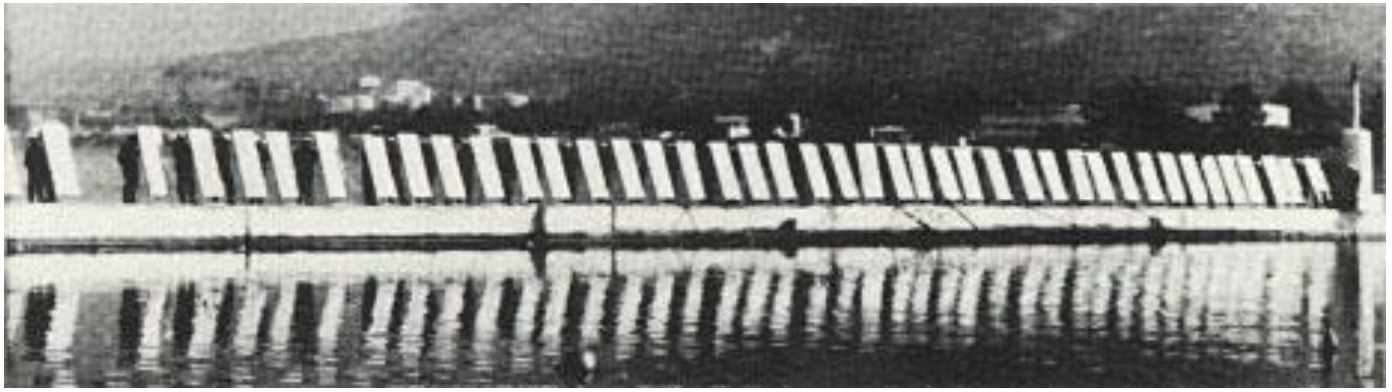


Previous Testing of Archimedes Death Ray

Newspaper report from 1973 or 1975

http://www.mlahanas.de/Greeks/Mirrors.htm
http://web.mit.edu/2.009/www/experiments/deathray/10_priorDeathRay.html

- "A Greek scientist, Dr. Ioannis Sakkas, curious about whether Archimedes could really have used a "burning glass" to destroy the Roman fleet in 212 BC lined up nearly 60 Greek sailors, each holding an oblong mirror tipped to catch the Sun's rays and direct them at a wooden ship 160 feet away. The ship caught fire at once.....Sakkas said after the experiment there was no doubt in his mind the great inventor could have used bronze mirrors to scuttle the Romans"



http://www.mlahanas.de/Greeks/Mirrors.htm
http://web.mit.edu/2.009/www/experiments/deathray/10_priorDeathRay.html

Mythbusters failed twice

- Mythbusters tried twice (2004 and 2010) to replicate Archimedes death ray and deemed the myth "busted"
  - In the first attempt, a rig was created with multiple mirrors in a circular array (top photo)
  - In the second attempt, ("The Presidential Challenge with Barack Obama"), they used numerous bronze coated mirrors
- http://www.discovery.com/tv-shows/mythbusters/videos/death-ray-minimyth.htm

MIT successfully ignited a ship

- Following the initial Mythbusters attempt in 2004, MIT used 127 mirrors (1 ft^2 each) to successfully ignite a mock-up of a Roman ship in 2005 on the MIT campus
- See cool images and description
  - http://web.mit.edu/2.009/www/experiments/deathray/10_ArchimedesResult.html

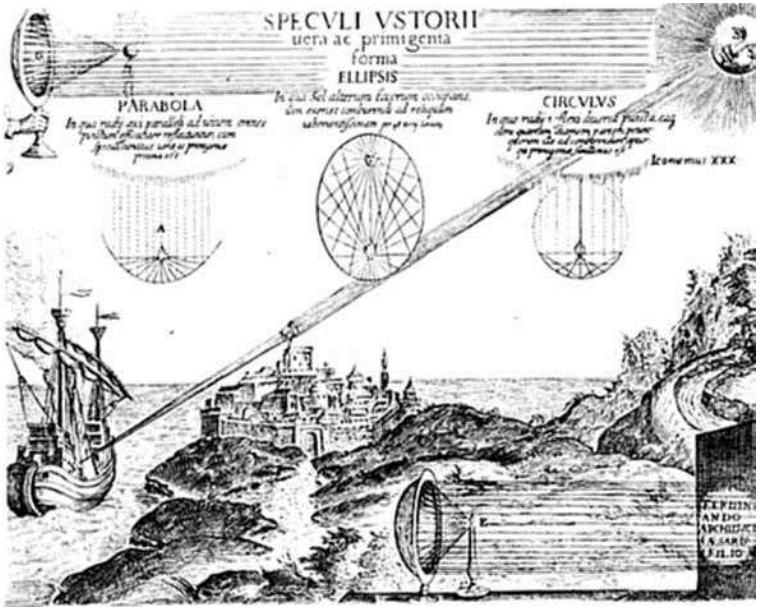
http://web.mit.edu/2.009/www/experiments/deathray/10_ArchimedesResult.html

MIT failed to ignite ship in San Francisco harbor with Mythbusters

- MIT worked with Mythbusters to revisit the Archimedes Death Ray after the failed 2004 attempt
  - In the revisited attempt, they used 300 bronze mirrors (1 ft^2)
  - Smoke and smoldering wood were observed, but no flash ignition
    - Thought moisture content of wood played a large role
  - http://web.mit.edu/2.009/www/experiments/deathray/10_Mythbusters.html

Conclusions

- Large arrays of mirrors can create sufficient heat flux (>60 kW/m^2) to ignite wood at 500 C or higher
- Challenges
  - Quality of mirrors
    - Reflectance
    - Slope error (scattering)
  - Alignment and focusing of large number of mirrors on moving object
  - Potentially high moisture content of wood
    - Increases time for ignition
- It would have been very difficult for Archimedes to pull this one off!



Source: http://www.mlahanas.de/Greeks/Mirrors.htm

- Some theories suggest blinding or burning the crew with concentrated sunlight could have turned the ships away