NATO Summer School: Optics in Astrophysics

Segmented Mirror Telescopes: Introduction

Jerry Nelson, UCSC

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Outline

- **Motivation for segmented mirror telescopes**
  - Challenges for monoliths
  - Challenges for segments
- **History of segmented mirror telescopes**
- **Segmentation geometries**
- **Segment surface asphericity**
- **Diffraction**
- **IR properties**

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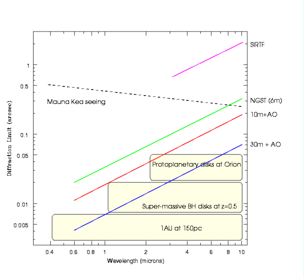
Diffraction-limited Observations

- **For many diffraction-limited observations, the signal scales as D^4**
  - Gains factors of 60-80 for unresolved sources
  - Crucial for spatial dissection accompanied by astrophysical spectroscopy
- **Diffraction limit at 1 micron is 7milli-arcsec (30-m telescope)**
  - 1 AU at 150 parsecs (the nearest star forming regions)
  - 50 parsecs at z=2-8



near-IR mid-IR

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Challenges for monolithic mirror telescopes

- **Reduced availability of blank material**
- **Passive support will allow large deflections**
- **Risk of breakage from mishandling**
- **Thermal problems larger for larger mirrors**
- **Vacuum chamber for mirror coatings is expensive**
- **Tool costs for all parts are large**
- **Shipping is difficult**

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Challenges for segmented mirror telescopes

- **Segments are difficult to polish**
  - Many segments
  - Segments are off-axis pieces (not locally axisymmetric)
- **Segments need active position control**
- **Segment edges add to diffraction and thermal background effects**
- **Telescope will have more parts leading to increase in complexity**

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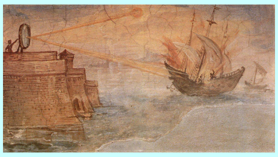
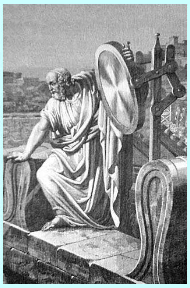
History of Segmented Mirror Telescopes: Archimedes

Archimedes constructed an array of mirrors to focus light onto the Roman navy, causing the ships to catch fire. This was done in 212BC to defend Syracuse.





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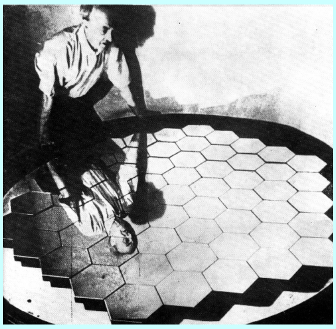
History of Segmented Mirror Telescopes: Horn d'Arturo

Horn d'Arturo (Italy) made a 1.5m segmented mirror in 1932 (vertical only, not active)



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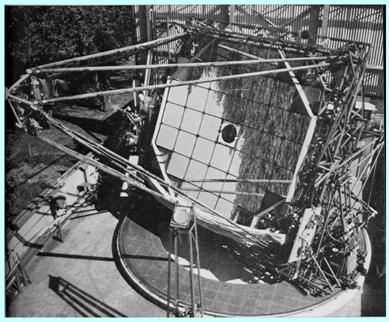
History of Segmented Mirror Telescopes: Pierre Connes

Pierre Connes made an IR light collector in the 1970's in France. The quality was too low to be useful for astronomy.



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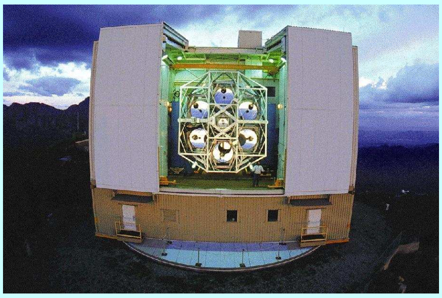
History of Segmented Mirror Telescopes: MMT 1980

The Multiple Mirror Telescope was built in the late 1970 and early 1980's with 6 primary mirrors. It has recently been replaced with a single 6.5m mirror



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Keck Observatory: Primary mirror 1993

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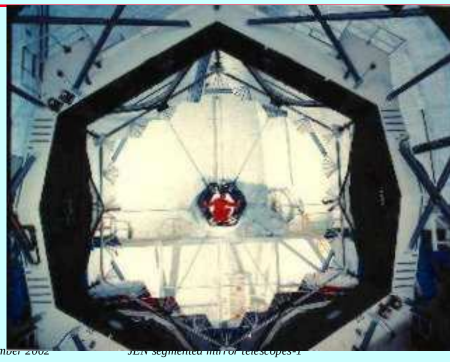

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Keck Observatory: K1 and K2, 1996 on Mauna Kea, HI

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History of Segmented Mirror Telescopes: HET 1998

The Hobby-Eberly Telescope was built in Texas and is composed of 91 hexagonal segments. The elevation angle is fixed and the primary is spherical. The primary is being fitted with edge sensors for active control of the segments.

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Segmentation Topologies

- **Numerous types of segmentation are possible**
  - Independent telescope arrays
  - Independent telescopes on a common mount
  - Random subapertures as part of a common primary
  - Annular segmentation of a common primary
  - Hexagonal segmentation
- **Dense segmentation cannot be done with regular segments (only flat surfaces can be tessellated with regular shapes)**
- **Dense segmentation gives smallest telescope ($$) for given collecting area.**
- **Less dense arrays may provide better angular resolution**

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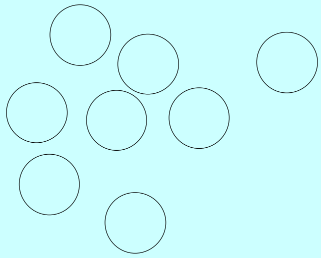
Random subapertures



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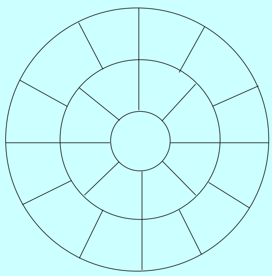
Annular segmentation



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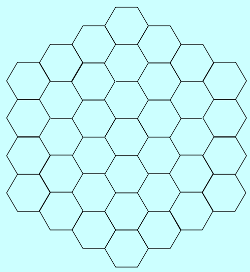
Hexagonal Segmentation



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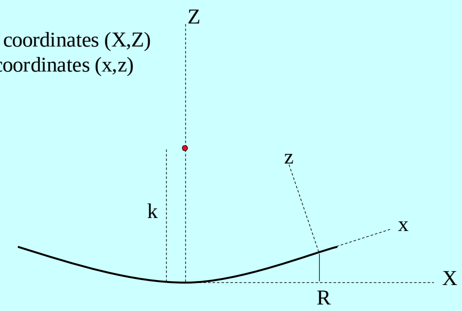
Segment surface asphericity

Global coordinates (X,Z)
Local coordinates (x,z)



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Segment surface asphericity

- **We wish to express the segment surface in its local coordinates**

$$z(\rho,\theta) = \sum_{mn} \alpha_{mn}\rho^{m} \cos n\theta + \sum_{mn} \beta_{mn}\rho^{m} \sin n\theta$$

Where ρ,θ are local coordinate system polar coordinates
With k = parent radius of curvature
K = conic constant
a = segment radius
R = off axis distance of segment center
ε = R/k

- **coordinate transforms and a lot of algebra yields**

Segment surface asphericity

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$$\alpha_{20} = \frac{a^2}{k}\left[\frac{2-K\varepsilon^2}{4(1-K\varepsilon^2)^{3/2}}\right] \cong \frac{a^2}{2k} + \frac{Ka^2\varepsilon^2}{2k} + \frac{9K^2a^2\varepsilon^4}{16k} + \ldots$$

$$\alpha_{22} = \frac{a^2}{k}\left[\frac{K\varepsilon^2}{4(1-K\varepsilon^2)^{3/2}}\right] \cong \frac{Ka^2\varepsilon^2}{4k} + \frac{3K^2a^2\varepsilon^4}{8k} + \ldots$$

$$\alpha_{31} = \frac{a^3}{k^2}\left[\frac{K\varepsilon\left[1-(K+1)\varepsilon^2\right]^{1/2}(4-K\varepsilon^2)}{8(1-K\varepsilon^2)^3}\right] \cong \frac{Ka^3\varepsilon}{2k^2} + \frac{(9K-2)K\,a^3\varepsilon^3}{8k^2} + \ldots$$

$$\alpha_{33} = \frac{a^3}{k^2}\left[\frac{K^2\varepsilon^3\left[1-(K+1)\varepsilon^2\right]^{1/2}}{8(1-K\varepsilon^2)^3}\right] \cong \frac{K^2a^3\varepsilon^3}{8k^2} + \ldots$$

$$\alpha_{40} = \frac{a^4}{k^3}\left[\frac{8(1+K) - 24K\varepsilon^2 + 3K^2(1-3K)\varepsilon^4 - K^3(2-K)\varepsilon^6}{64(1-K\varepsilon^2)^{9/2}}\right] \cong \frac{(1+K)a^4}{8k^3} + \ldots$$

Segment surface asphericity

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- **Example: Keck Observatory**
  - a=0.9 m
  - k = 35 m
  - K = -1.003683
  - D = 10.95 m

  - Outermost segment (R = 4.68m)
  - α_{20} = 11376 μm (spherical shape, varies slowly from segment to segment)
  - α_{22} = −101.1 μm
  - α_{31} = −38.1 μm
  - α_{33} = 0.17 μm
  - α_{40} = 0.09 μm

Diffraction

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- **Segments (edges) will introduce additional diffraction effects beyond the edge of the overall aperture**
- **Circular mirrors give Airy diffraction pattern, with intensity falling as θ^{-3} and are azimuthally symmetric**
- **Segment mirrors (like Keck) concentrate the diffracted energy into lines perpendicular to the edges, thus producing a diffraction pattern brighter or darker in some places than circular aperture**
- **Segmented mirrors will add diffracted energy to the image on the scale of the segment size and the scale of the gap**

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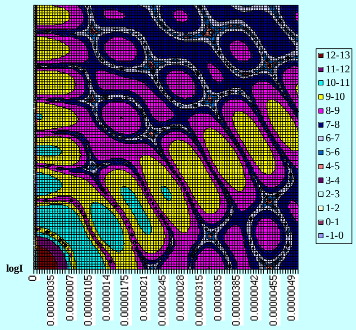
Diffraction from Hexagon log I



Infrared Properties-1

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- **In the thermal infrared (≥ 2.5 μm), the thermal emission from the environment (including the telescope) becomes an important source of background**
- **All telescopes suffer this background if they are at ambient temperatures**
- **Practical ground based telescope mirror surfaces have emissivities >1%. Net telescope emissivities are virtually always above 5%. 10% is considered good**
  - Emissivity is 1 - reflectivity
  - Fresh silver has ≤ 99% reflectivity in the IR

Infrared Properties-2

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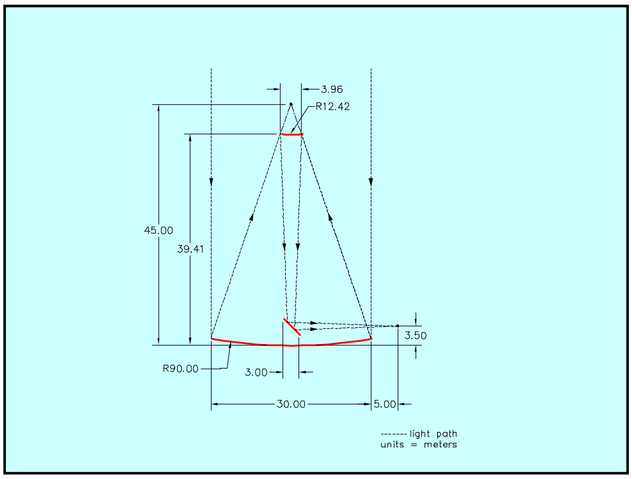
- **Segment edges and gaps will typically contribute to the net emissivity. If the blockage(lost light) is 2% of the area, the emissivity contribution will be 2%.**
- **Small edges and gaps are thus desired, but ~ 1% is sufficiently small so other sources will dominate**
- **Keck segments have 2mm bevels, 3mm gaps, net loss of light is about 0.7%**



3.96
R12.42
45.00
39.41
3.50
R90.00
3.00
30.00
5.00
------- light path
units = meters