Design optimization for x-ray telescopes

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Outline

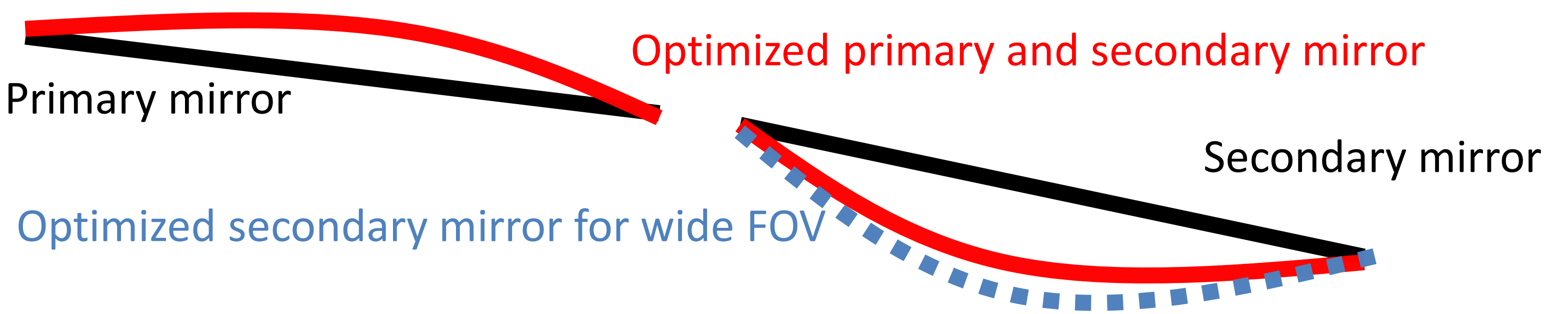
- Design nested set of Wolter (W) and Wolter-Schwarzschild (WS) telescopes in wide range of radial heights
- Introduce small Legendre polynomial deviations on the primary and secondary mirror surfaces to optimize telescopes for narrow field of view (FOV) or wide FOV applications
- Optimize Hyperboloid-Hyperboloid (HH) designs starting from base W-designs
- Optimize optical performance of W-designs and WS-designs using second, third, and fourth order Legendre polynomials
- Compare optical performance of optimized HH-telescopes, W-telescopes, and WS-telescopes
- Optimize optical performance of nested WS-telescope using second order Legendre polynomial on the secondary mirror

STARX telescope design

- Optimization processes demonstrated on individual telescopes of STARX design
  - Focal length: 5000 mm
  - Field of view: 1.0 degrees
  - Number of mirror pairs: 101
  - Range of radial heights: 250 mm - 650 mm
  - Axial length of the mirrors:100 mm
  - Gap size between the mirrors:5 mm

Optimization of HH-telescopes

- Narrow FOV optimization at the optimal focal surface
  - Start with Wolter design (paraboloid-hyperboloid)
  - Optimize P-parameter for image size at the edge of FOV
  - Amplitude of P-parameter equal but opposite on primary and secondary maintains near on-axis image quality
- Wide FOV optimization
  - Optimize P-parameter of secondary to force equal on-axis and off-axis image



$$h = \sqrt{h_0^2 + 2Kz - Pz^2}$$

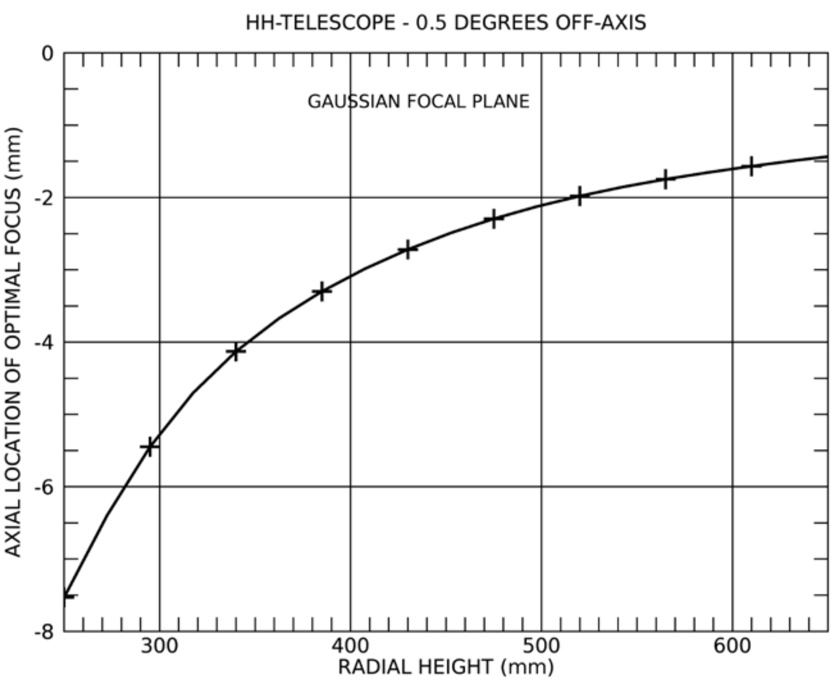
P = 0 for paraboloid

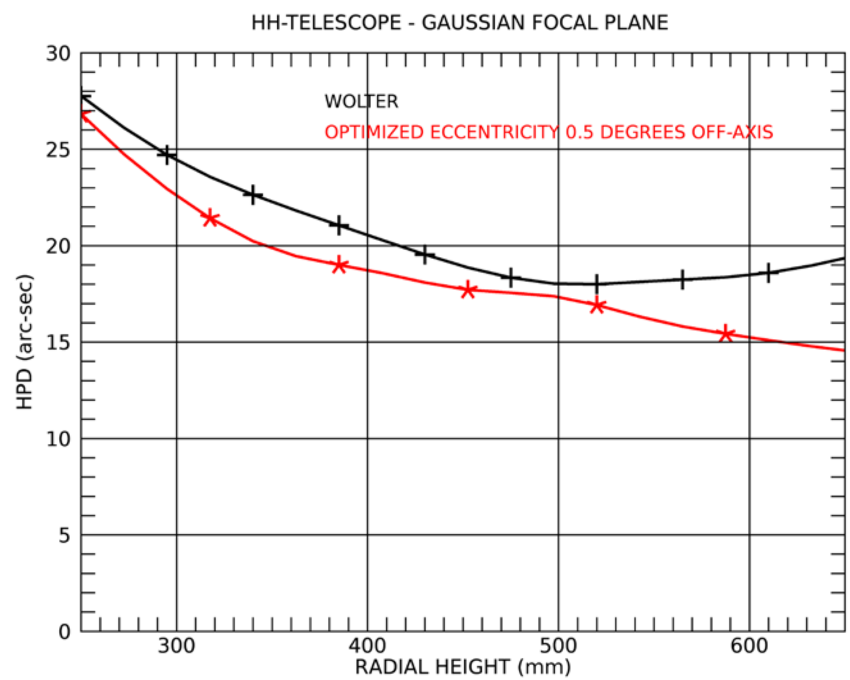
$P \neq 0$ for hyperboloid or ellipsoid

$$h = \sqrt{h_0^2 + 2Kz} - \frac{Pz^2}{2h_o^2} + higher\ order\ z - terms$$

HH-telescopes – performance –Gaussian focal plane

- Curvature of optimal focal surface is dominating image aberration
- Half power diameters (HPD) decrease when radial heights increase at Gaussian focal surface
- Optimization has minor impact on image quality (HPDs)

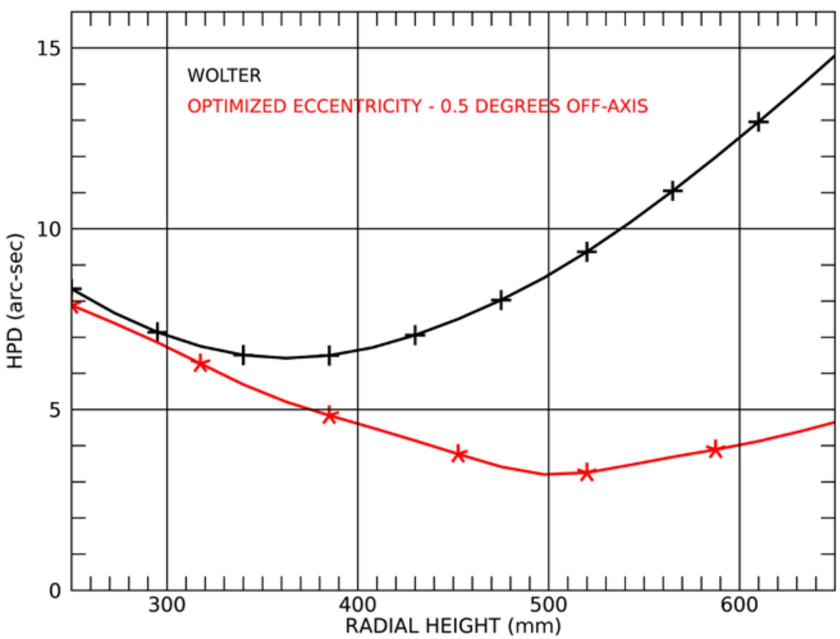




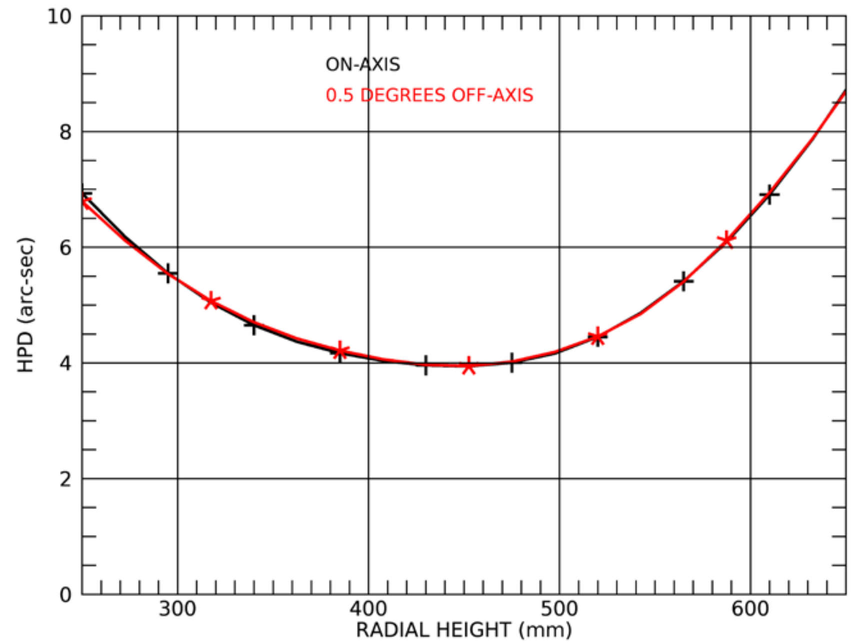
HH-Telescopes – performance – optimal focal surface

- Narrow FOV
  - HPDs of optimized HH-designs are significantly better
  - coma of Wolter telescopes is minimized
- Wide FOV
  - Radial height of ~450 mm provides best HH-telescope design

Narrow field of view

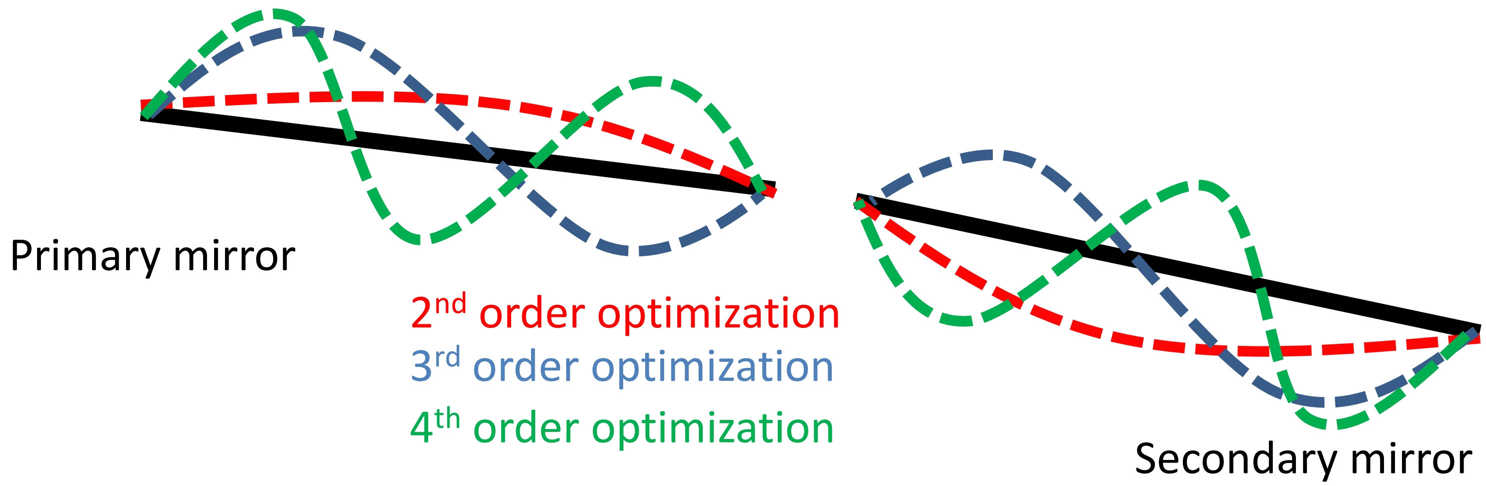


Wide field of view



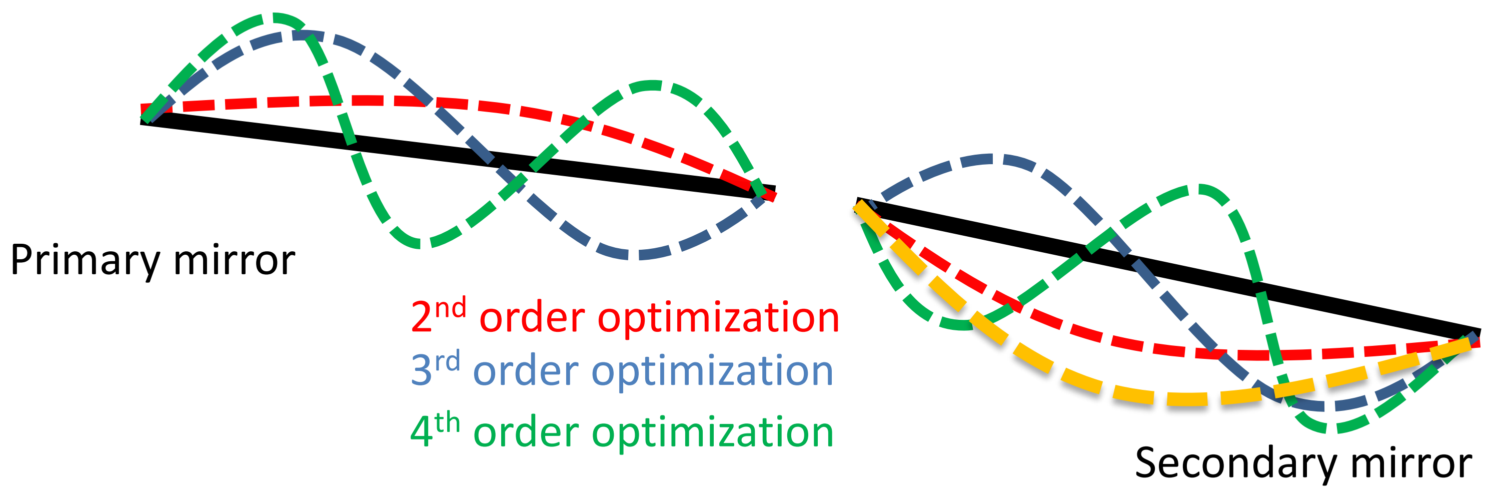
Optimization of W- and WS-telescopes – narrow FOV

- Optimize image aberrations at the edge of FOV and maintain near perfect on-axis image at the optimal focal surface
- Optimize dimensional parameters of W- or WS-telescopes
- Optimize image aberrations by adding equal but opposite second order Legendre polynomial on primary and secondary mirrors
- Optimize imaging effects of equal third order Legendre polynomial of primary and secondary
- Optimize image defects of equal but opposite fourth order Legendre polynomial of primary and secondary



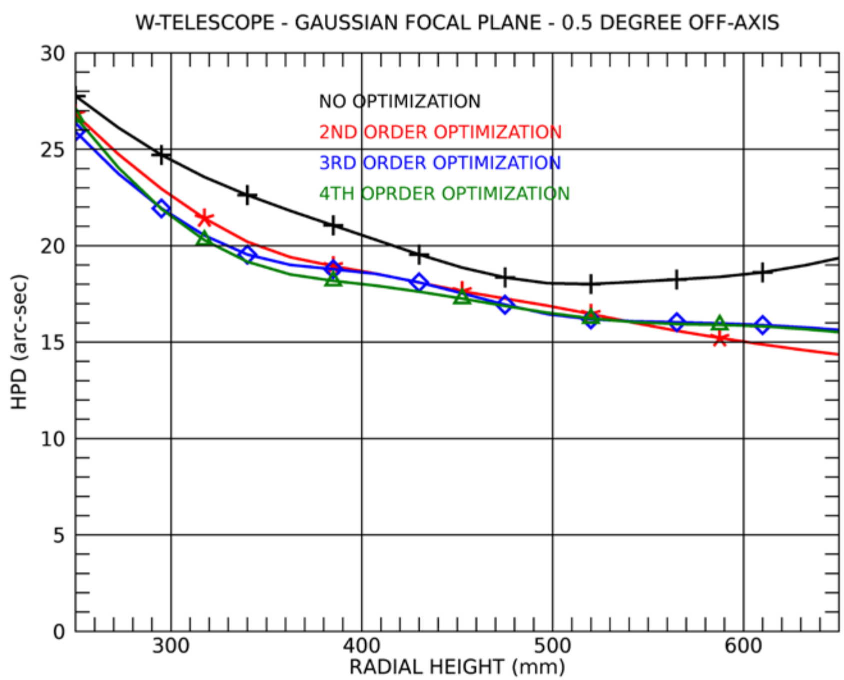
Optimization of W- and WS-telescopes - wide FOV

- Optimize image aberrations at the edge and in the center of FOV to be equal at the optimal focal surface of the telescope
- Optimization process
  - Optimize second, third, and fourth order polynomials for optimal off-axis performance
  - Re-optimize secondary mirror axial second order to produce equal on-axis and off-axis image



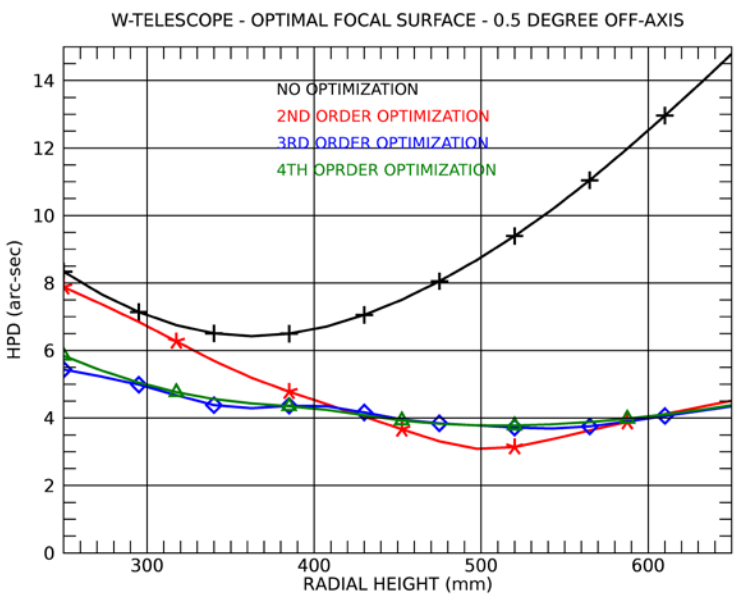
W-telescopes – Gaussian focal plane

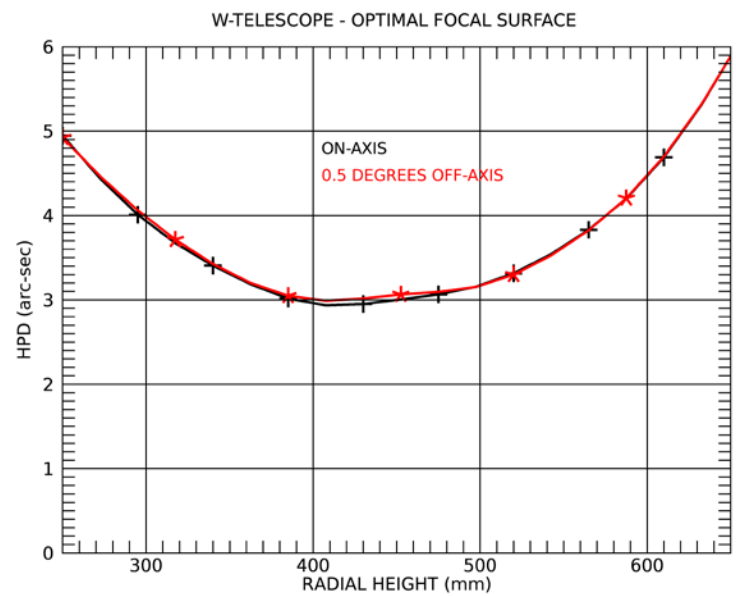
- Polynomial optimization improves HPD 5-20% at the edge of 1-degree FOV
- Field curvature is dominating aberration



W-telescopes – optimal focal surface

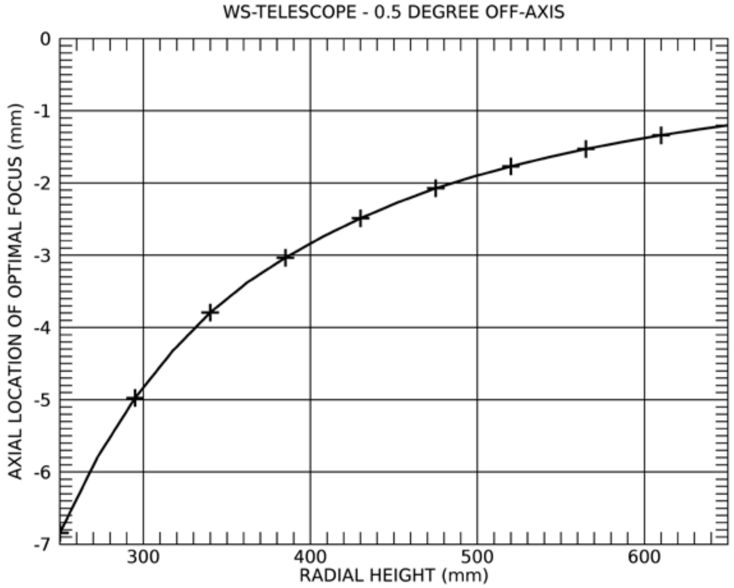
- Narrow FOV
  - Nearly perfect on-axis image quality
  - 2nd order polynomial optimization removes coma
  - 3rd order polynomial optimizations improve inner shells
  - 4th order polynomial optimization does not decrease HPDs
- Wide FOV
  - Equal on-axis and off-axis image quality
  - Radial heights in 400-450 mm range provide best image

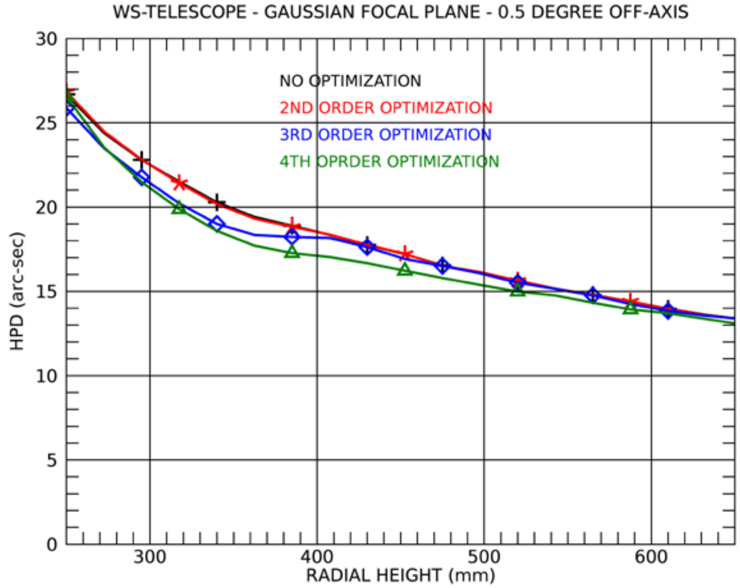




WS-telescopes – Gaussian focal plane

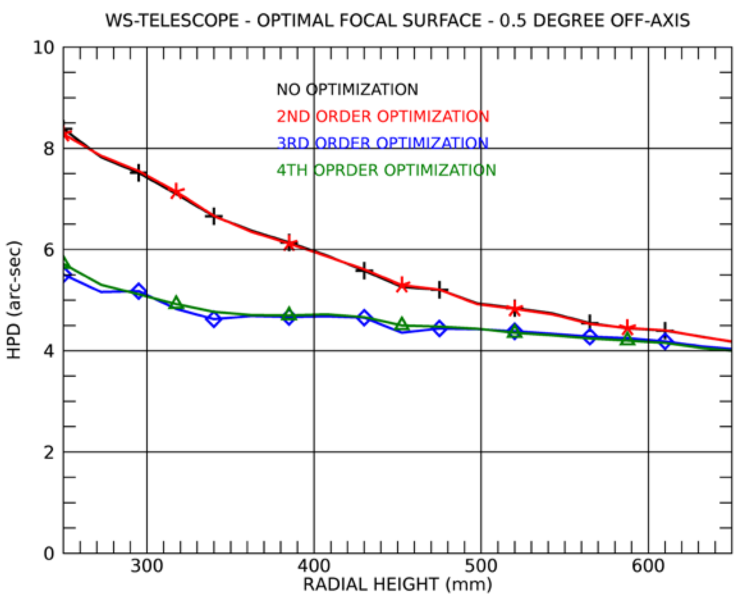
- Field curvature is dominating aberration
- Image quality
  - Minor improvements
  - 2nd order Legendre polynomial has no effect
  - 3rd order Legendre polynomial improves images of inner shells
  - 4th order Legendre polynomial improves images of middle shells

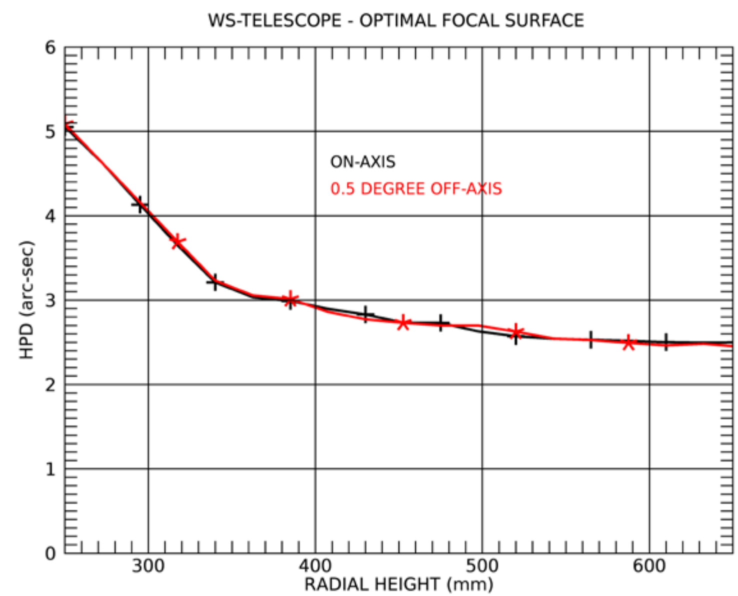




WS-telescopes – optimal focal surface

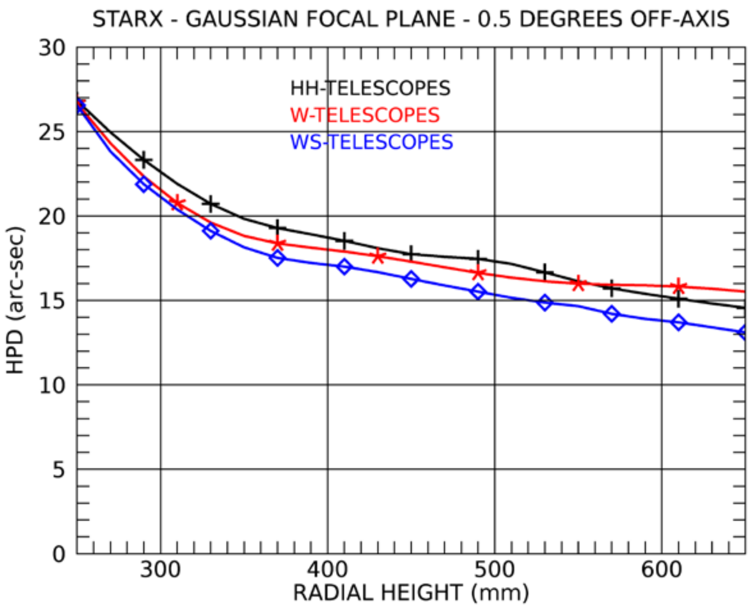
- Narrow FOV
- 2nd order polynomials have no effect
  - 3rd order polynomials improve HPD across the range
  - 4th order polynomials have no effect
- Wide FOV
  - On-axis image quality is balanced with off-axis image quality
  - Optimization provides improved imaging at the edge of the field of view
  - HPD of outer shells are ~2.5 arc-sec

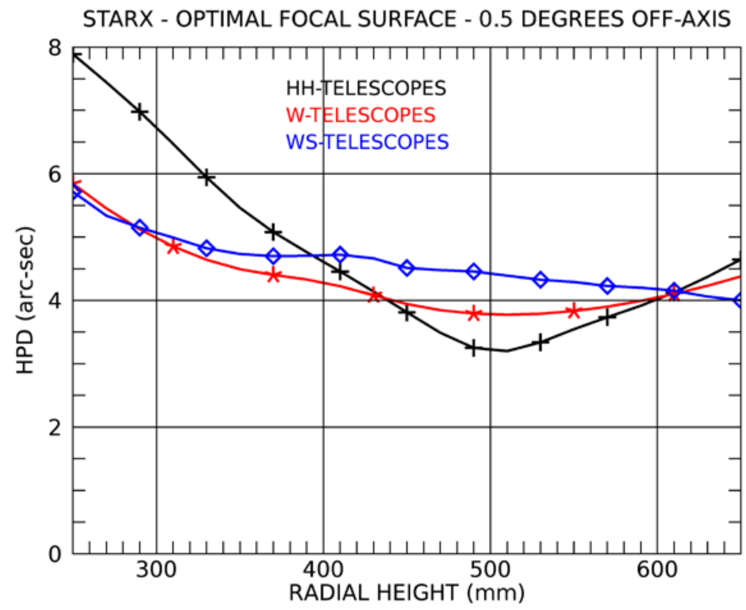




Comparison of optimized telescopes – narrow field of view

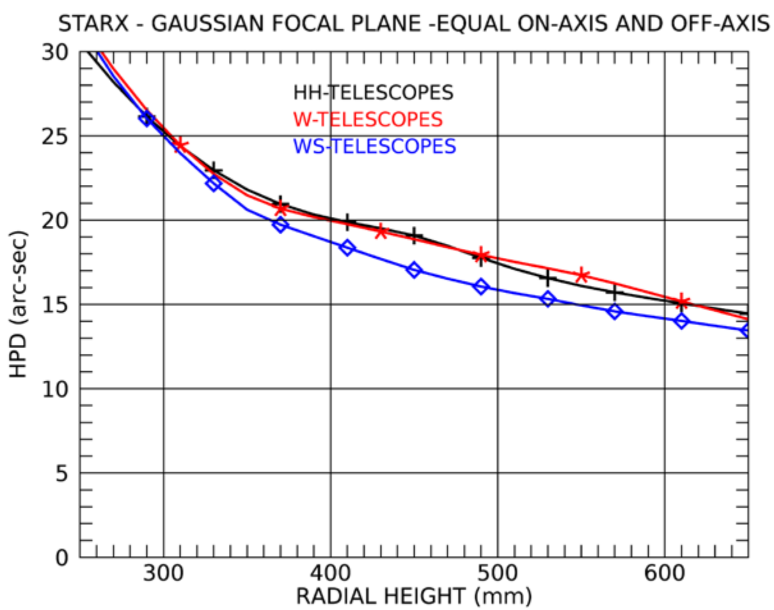
- Gaussian focal plane
  - Optimized WS-telescopes provide best image quality
- Optimal focal surface
  - Optimized W-telescopes offer best image quality across wide range of radial heights
  - Optimized HH-telescopes are surprisingly good in 450 mm to 600 mm radial height range

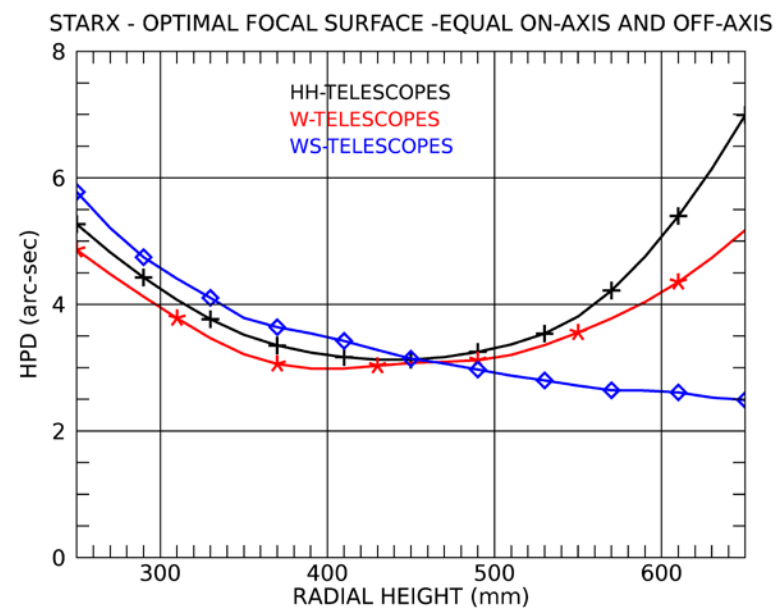




Comparison of telescopes – wide field of view

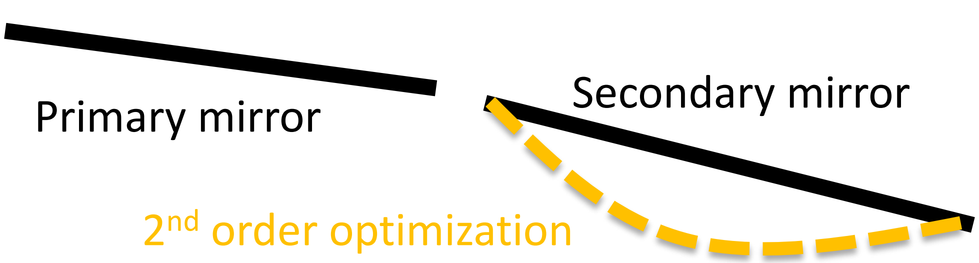
- Image quality at Gaussian focal plane
  - Optimized WS-telescopes provide best image quality
- Image quality at optimal focal surface
  - Outer shells of optimized WS-telescopes are superior
  - Inner shells of optimized W-telescopes are best

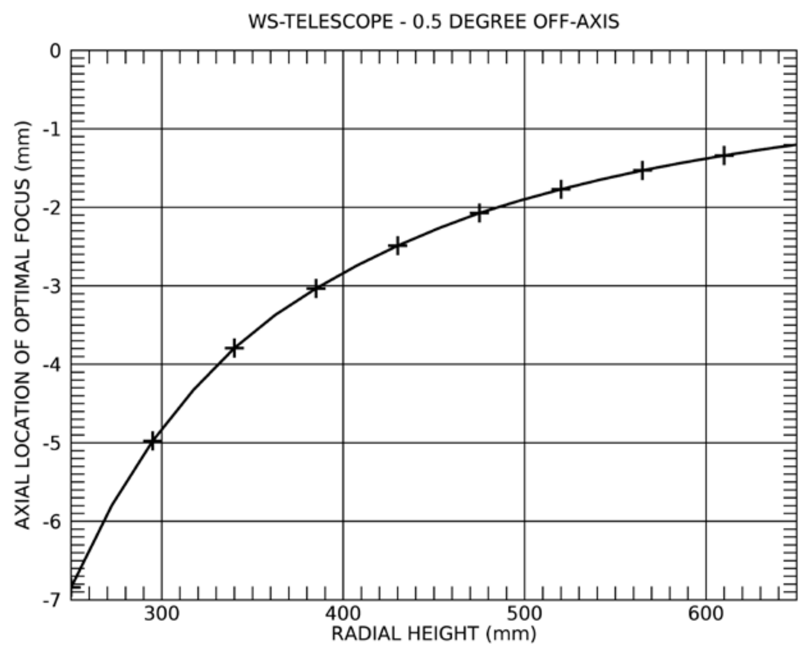




Optimization of nested WS-telescope

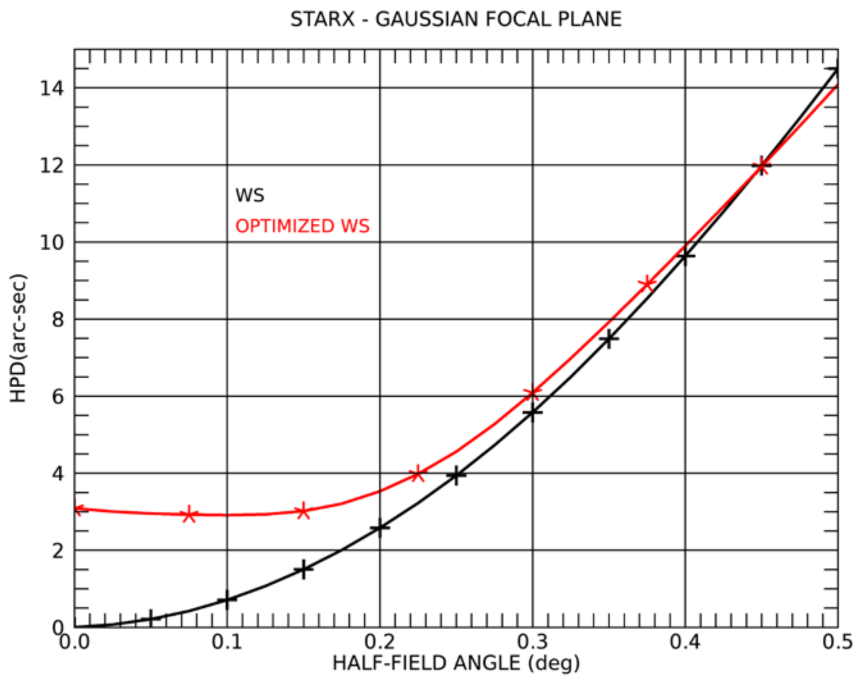
- Optimization of STARX wide field of view design
- Optimal focus strongly dependent on radial height of mirror pair
- Optimization performed at mean optimal focus location at the edge of 0.5-degree field of view
- Optimize 2nd order sag terms of secondary mirrors

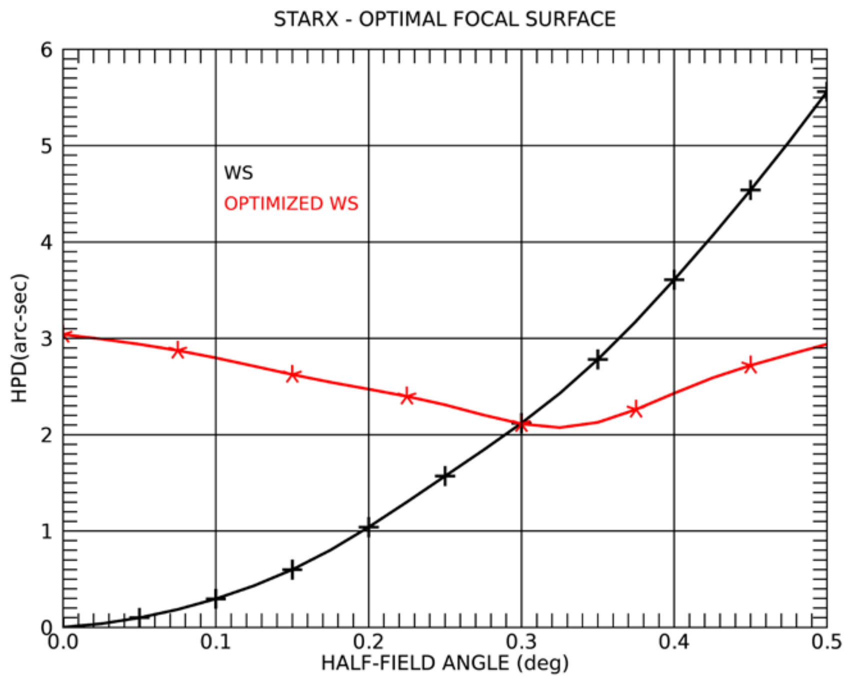




Optical performance of STARX telescope

- Optimization done at 1.0 keV energy
- Gaussian focal plane
  - HPD does not improve over WS-telescope
- Optimal focal surface
  - HPD is uniform across the FOV
  - Performance is below 3 arc-sec





Conclusions

- Low order Legendre polynomials provide simple platform to optimize on-axis and off-axis aberrations of x-ray telescopes
- Telescopes can be optimized for narrow FOV or for wide FOV
- Polynomial optimization removes low order image aberrations and performance of optimized W-telescopes and WS-telescopes can be improved significantly
- Optimization process can be used to design complex nested x-ray telescopes