# Engineering Specifications derived from Science Requirements

## Advanced Mirror Technology Development (AMTD) Project

# Introduction

# AMTD

Advanced Mirror Technology Development (AMTD) is a multi-year effort to systematically mature to TRL-6 the critical technologies needed to produce 4-m or larger flight-qualified UVOIR mirrors by 2018 so that a viable mission can be considered by the 2020 Decadal Review.

This technology must enable missions capable of both general astrophysics & ultra-high contrast observations of exoplanets.

To accomplish our objective,

- We use a science-driven systems engineering approach.
- We mature technologies required to enable the highest priority science AND result in a high-performance low-cost low-risk system.

# Multiple Technology Paths

Most future space telescope missions require mirror technology.

Just as JWST’s architecture was driven by launch vehicle, future mission’s architectures (mono, segment or interferometric) will depend on capacities of future launch vehicles (and budget).

Since we cannot predict future, we must prepare for all futures.

To provide science community with options, we must pursue multiple technology paths.

All potential UVOIR mission architectures (monolithic, segmented or interferometric) share similar mirror needs:

| | |
|---|---|
| • Very Smooth Surfaces | < 10 nm rms |
| • Thermal Stability | Low CTE Material |
| • Mechanical Stability | High Stiffness Mirror Substrates |

# Critical Technologies

Space telescopes require advances in 6 inter-linked technologies:

- *Large-Aperture, Low Areal Density, High Stiffness Mirrors:* 4 - 8 m monolithic & 8 - 16 m segmented primary mirrors require larger, thicker, stiffer substrates.
- *Support System:* Large-aperture mirrors require large support systems to ensure they survive launch and deploy on orbit in a stress-free and undistorted shape.
- *Mid/High Spatial Frequency Figure Error:* A very smooth mirror is critical for producing a high-quality point spread function (PSF) for high-contrast imaging.
- *Segment Edges:* Edges impact PSF for high-contrast imaging applications, contributes to stray light noise, and affects the total collecting aperture.
- *Segment-to-Segment Gap Phasing:* Segment phasing is critical for producing a high-quality temporally stable PSF.
- *Integrated Model Validation:* On-orbit performance determined by mechanical and thermal stability. Future systems require validated performance models.

# Simultaneous Maturation

Pursuing technology maturation in all 6 critical technologies simultaneously because all are required to make a primary mirror assembly (PMA); AND, it is the PMA's on-orbit performance which determines science return.

- PMA stiffness depends on substrate and support stiffness.
- Ability to cost-effectively eliminate mid/high spatial figure errors and polishing edges depends on substrate stiffness.
- On-orbit thermal and mechanical performance depends on substrate stiffness, the coefficient of thermal expansion (CTE) and thermal mass.
- Segment-to-segment phasing depends on substrate & structure stiffness.

# Engineering Specification

# Engineering Specification

To meet our goals, we need to derive engineering specifications for future monolithic or segmented space telescope based on science needs & implementation constraints.

We use a science-driven systems engineering approach:

Science Requirements → Engineering Specifications

To derive specifications, we assembled an outstanding team from academia, industry, & government with expertise in

- UVOIR astrophysics and exoplanet characterization,
- monolithic and segmented space telescopes, and
- optical manufacturing and testing.

# AMTD Project Technical Team

| | | | |
|---|---|---|---|
| **Principle Investigator** | | **Systems Engineering** | |
| Dr. H. Philip Stahl | MSFC | Dr W. Scott Smith | MSFC |
| | | | |
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- NASA ROSES SAT (10-SAT10-0048)
- Space Act Agreement (SAA8-1314052) with Ziva Corp
- NASA Graduate Student Research Program (NNX09AJ18H)

# AMTD Team

Science & Engineering work collaboratively to insure that we mature technologies required to enable highest priority science AND result in a high-performance low-cost low-risk system.

- derive engineering specifications for monolithic & segmented mirrors which provide on-orbit science performance needs AND satisfy implementation constraints
- identify technical challenges in meeting these specifications,
- iterate between science needs and engineering specifications to mitigate the challenges, and
- prioritize technology development which yields greatest on-orbit performance for lowest cost and risk.

STOP (structural, thermal, optical performance) models are used to help predict on-orbit performance & assist in trade studies.

# Disclaimer

The purpose of this effort is NOT to design a specific telescope for a specific mission or to work with a specific instrument.

We are <u>not</u> producing an optical design or prescription.

We <u>are</u> producing a set of primary mirror engineering specifications which will enable the on-orbit telescope performance required to enable the desired science.

Our philosophy is to define a set of specifications which 'envelop' the most demanding requirements of all potential science. If the PM meets these specifications, it should work with most potential science instrument.

Also, Coatings are out of scope.

# Science Requirements

# Summary

General Astrophysics & Exoplanet Requirements & Launch Vehicle Constraints define different Engineering Specifications

| Science Requirements → | Engineering Specifications |
|---|---|
| Exoplanet | |
| Habitable Zone Size | Telescope Diameter |
| Contrast | Mid/High Spatial Error |
| Contrast | WFE Stability |
| Star Size | Line of Sight Stability |
| General Astrophysics | |
| Diffraction Limit | Wavefront Error (Low/Mid) |
| Launch Vehicle | |
| Up-Mass Capacity | Mass Budget |
| Fairing Size | Architecture (monolithic/segmented) |

# Requirements for a large UVOIR space telescope are derived directly from fundamental Science Questions (2010)

**Table 2.1: Science Flow-down Requirements for a Large UVOIR Space Telescope**

| Science Question | Science Requirements | Measurements Needed | Requirements |
|---|---|---|---|
| Is there life elsewhere in Galaxy? | Detect at least 10 Earth-like Planets in HZ with 95% confidence. | High contrast (ΔMag > 25 mag) SNR=10 broadband (R = 5) imaging with IWA ~40 mas for ~100 stars out to ~20 parsecs. | ≥ 8 meter aperture<br>Stable $10^{-10}$ starlight suppression<br>~0.1 nm stable WFE per 2 hr<br>~1.3 to 1.6 mas pointing stability |
| | Detect presence of habitability and bio-signatures in the spectra of Earth-like HZ planets | High contrast (ΔMag > 25 mag) SNR=10 low-resolution (R=70-100) spectroscopy with an IWA ~ 40 mas; spectral range 0.3 – 2.5 microns; Exposure times <500 ksec | |
| What are star formation histories of galaxies? | Determine ages (~1 Gyr) and metallicities (~0.2 dex) of stellar populations over a broad range of galactic environments. | Color-magnitude diagrams of solar analog stars (Vmag~35 at 10 Mpc) in spiral, lenticular & elliptical galaxies using broadband imaging | ≥ 8 meter aperture<br>Symmetric PSF<br>500 nm diffraction limit<br>1.3 to 1.6 mas pointing stability |
| What are kinematic properties of Dark Matter | Determine mean mass density profile of high M/L dwarf Spheroidal Galaxies | 0.1 mas resolution for proper motion of ~200 stars per galaxy accurate to ~20 μas/yr at 50 kpc | |
| How do galaxies & IGM interact and affect galaxy evolution? | Map properties & kinematics of intergalactic medium over contiguous sky regions at high spatial sampling to ~10 Mpc. | SNR = 20 high resolution UV spectroscopy (R = 20,000) of quasars down to FUV mag = 24, survey wide areas in < 2 weeks | ≥ 4 meter aperture<br>500 nm diffraction limit<br>Sensitivity down to 100 nm wavelength. |
| How do stars & planets interact with interstellar medium? | Measure UV Ly-alpha absorption due to Hydrogen “walls” from our heliosphere and astrospheres of nearby stars | High dynamic range, very high spectral resolution (R = 100,000) UV spectroscopy with SNR = 100 for V = 14 mag stars | |
| How did outer solar system planets form & evolve? | UV spectroscopy of full disks of solar system bodies beyond 3 AU from Earth | SNR = 20 - 50 at spectral resolution of R ~10,000 in FUV for 20 AB mag | |

# Exoplanet Measurement Capability

Exoplanet characterization places the most challenging demands on a future UVOIR space telescope.

| Science Question | Science Requirements | Measurements Needed |
|---|---|---|
| **Is there life elsewhere in the Galaxy?** | Detect at least 10 Earth-like Planets in HZ with 95% confidence if $\eta_{\mathrm{EARTH}} = 0.15$ | High contrast ($\Delta$Mag>25 mag) SNR=10 broadband (R=5) imaging with IWA ~ 40 mas for ~100 target stars. |
| | Detect the presence of habitability and bio-signatures in the spectra of Earth-like HZ planets | High contrast ($\Delta$Mag>25 mag) SNR=10 low-resolution (R=70-100) spectroscopy with an IWA ~ 40 mas. Exposure times <500 ksec. |

# Aperture Size Specification

# Aperture Size

Telescope Aperture Size is driven by:

- Habitable Zone Resolution Requirement
- Signal to Noise Requirement
- $\eta_{EARTH}$
- Exo-Zodi Resolution Requirement

# Aperture Size vs Habitable Zone Requirement

Search for Exo-Earths (i.e. terrestrial mass planets with life) requires ability to resolve habitable zone (region around star with liquid water).

Different size stars (our Sun is G-type) have different diameter zones (ours extends from ~0.7 – 2 AU; Earth is at 1 AU).

Direct Detection requires angular resolution ~ 0.5x HZ radius at 760 nm (molecular oxygen line is key biomarker for life).

| Spectral Class on Main Sequence | Luminosity (Relative to Sun) | Habitable Zone Location (AU) | Angular radius of HZ at 10 pc (mas) | Telescope Diameter (meters) |
|---|---|---|---|---|
| M | 0.001 | 0.022 – 0.063 | 2.2 – 6.3 | 90 |
| K | 0.1 | 0.22 – 0.63 | 22 – 63 | 8.9 |
| G | 1.0 | 0.7 – 2.0 | 70 – 200 | 2.7 |
| F | 8.0 | 1.98 – 5.66 | 198 – 566 | 1.0 |

Mountain, M., van der Marel, R., Soummer, R., et al. Submission to NRC ASTRO2010 Decadal Survey, 2009

# Aperture Size vs Signal to Noise

Exo-Earth Characterization requires the ability to obtain a SN=10 R=70 spectrum in less than ~500 ksec.

| Telescope Diameter (meters) | Number of spec type F,G,K Stars Observed in a 5-year mission, yielding SNR=10 R=70 Spectrum of Earth-like Exoplanet |
|---|---|
| 2 | 3 |
| 4 | 13 |
| 8 | 93 |
| 16 | 688 |

Mountain, M., van der Marel, R., Soummer, R., et al. Submission to NRC ASTRO2010 Decadal Survey, 2009

# Aperture Size vs Habitable Zone and SNR

Lyon & Clampin looked at the number of stars in the TPF-C data base out to 30 parsecs whose Habitable Zone would be outside the Inner Working Angle for different diameter telescopes.

Δt is total time in days required to obtain SNR=5 R=5 (550 nm; FWHM 110) spectrum for N stars (assuming eta_Earth = 1)

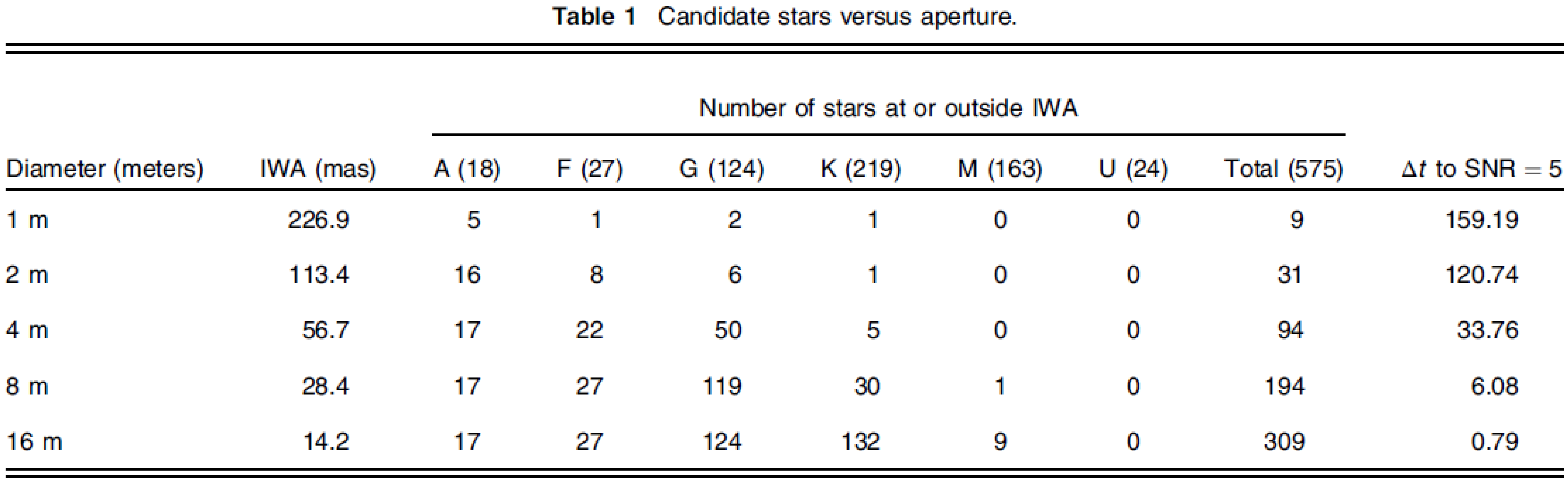


**Table 1** Candidate stars versus aperture.

| | | Number of stars at or outside IWA | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Diameter (meters) | IWA (mas) | A (18) | F (27) | G (124) | K (219) | M (163) | U (24) | Total (575) | $\Delta t$ to SNR $= 5$ |
| 1 m | 226.9 | 5 | 1 | 2 | 1 | 0 | 0 | 9 | 159.19 |
| 2 m | 113.4 | 16 | 8 | 6 | 1 | 0 | 0 | 31 | 120.74 |
| 4 m | 56.7 | 17 | 22 | 50 | 5 | 0 | 0 | 94 | 33.76 |
| 8 m | 28.4 | 17 | 27 | 119 | 30 | 1 | 0 | 194 | 6.08 |
| 16 m | 14.2 | 17 | 27 | 124 | 132 | 9 | 0 | 309 | 0.79 |

Lyon & Clampin, "Space telescope sensitivity and controls for exoplanet imaging", OE 011002-2, Jan 2012.

# Aperture Size vs $\eta_{EARTH}$

Number of stars needed to find Exo-Earths dependes on $\eta_{EARTH}$ (probability of an Exo-Earth in a given star system)

Kepler indicates $\eta_{EARTH}$ lies in the range [0.03,0.30]

Complete characterize requires multiple observations

| **Number of Earth-like Planets to Detect** | $\eta_{EARTH}$ | **Number of Stars one needs to Survey** | **Minimum Telescope Diameter** |
|---|---|---|---|
| 2 | 0.03 | 67 | 8 |
| 2 | 0.15 | 13 | 4 |
| 2 | 0.30 | 7 | 4 |
| 5 | 0.03 | 167 | 10 |
| 5 | 0.15 | 33 | 8 |
| 5 | 0.30 | 17 | 6 |
| 10 | 0.03 | 333 | 16 |
| 10 | 0.15 | 67 | 8 |
| 10 | 0.30 | 33 | 8 |

# Aperture Size vs Exo-Zodi Requirement

Detecting & Characterizing an Exo-Earth, requires ability to resolve an Exo-Earth in a planetary debris disc.

Planetary debris disc produces scattered or zodical light.

Being able to resolve an Exo-Earth in a system with up to 3X more zodical light than our own systems requires:

- Sharp (high resolution) PSF for increased contrast of planet relative to its zodi disk.

Thus, the larger the aperture the better.

Also, constrains mid-spatial frequency wavefront error

# Aperture Size Recommendation

Based on the analysis, the Science Advisory Team recommends a space telescope in the range of 4 meters to 8 meters.

| Telescope Diameter | Mirror Segmentation | Secondary Mirror Configuration |
|---|---|---|
| 4 | None – Monolithic | On-Axis or Off-Axis |
| 8 | Segmented | On-Axis or Partially Off-Axis |
| 8 | None - Monolithic | On-Axis or Off-Axis |

# Wavefront & Surface Figure Error Specification

# Wavefront Error

Total system wavefront error (WFE) is driven by:

- 500 nm Diffraction Limited Performance
- Dark Hole Speckle

Exoplanet science driven specifications include:

- Line of Sight Pointing Stability
- Total Wavefront Error Stability

# WFE vs 500 nm Diffraction Limit

Total system WFE is derived from PSF requirement using Diameter, Strehl ratio (S) & wavelength ($\lambda$):

$$\text{PSF FWHM (mas)} = (0.2063 / S) * (\lambda(\text{nm}) / D(\text{meters}))$$

$$S \sim \exp(-(2\pi * \text{WFE}/\lambda)^2)$$

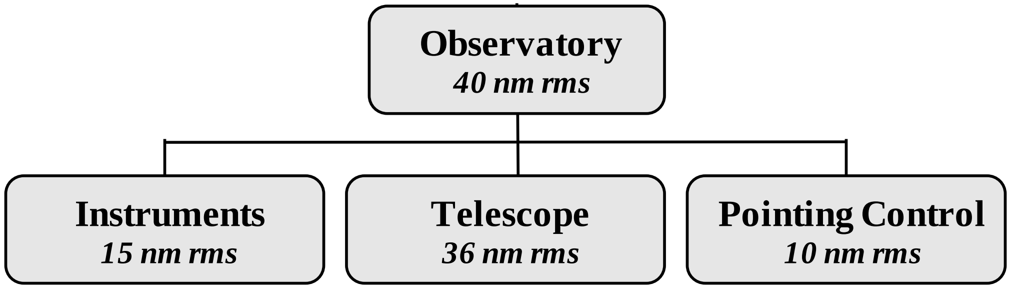
$$\text{WFE} = (\lambda/2\pi) * \text{sqrt}(-\ln S)$$

Diffraction limited performance requires S ~ 0.80.

At $\lambda$ = 500 nm, this requires total system WFE of ~38 nm.

# Primary Mirror Total Surface Figure Requirement

Primary Mirror requirements are derived by flowing System Level diffraction limited and pointing stability requirements to major observatory elements:



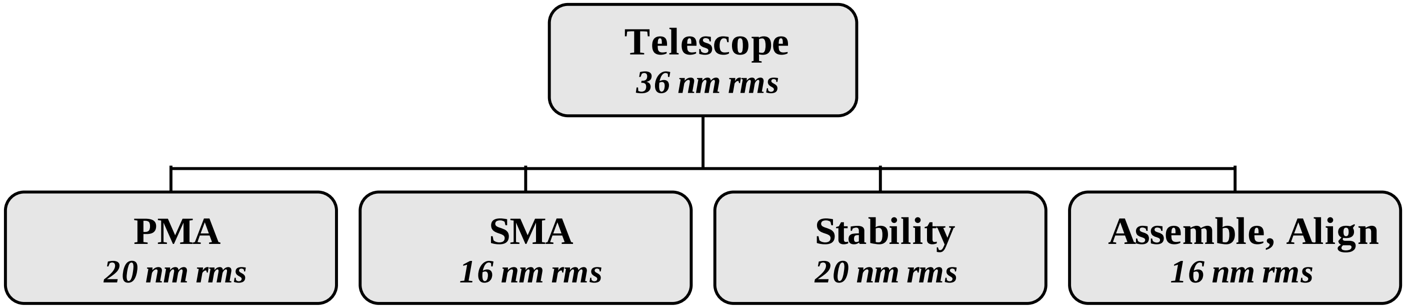
**Observatory**
*40 nm rms*

**Instruments**
*15 nm rms*

**Telescope**
*36 nm rms*

**Pointing Control**
*10 nm rms*

Then flowing Telescope Requirements to major Sub-Systems



**Telescope**
*36 nm rms*

**PMA**
*20 nm rms*

**SMA**
*16 nm rms*

**Stability**
*20 nm rms*

**Assemble, Align**
*16 nm rms*

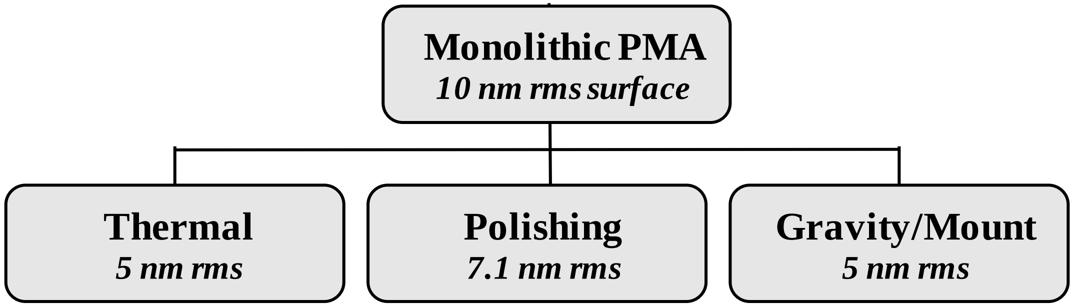
# Primary Mirror Total Surface Figure Requirement

Regardless whether monolithic or segmented,

PM must have < 10 nm rms surface.

And, if segmented, it must have a ‘phased’ wavefront which as same performance as a monolithic aperture.

PM Specification depends on thermal behavior & mounting uncertainty, leaving < ~8 nm rms for total manufactured SFE.



**Monolithic PMA**
*10 nm rms surface*

**Thermal**
*5 nm rms*

**Polishing**
*7.1 nm rms*

**Gravity/Mount**
*5 nm rms*

Next question is how to partition the PM SFE error.

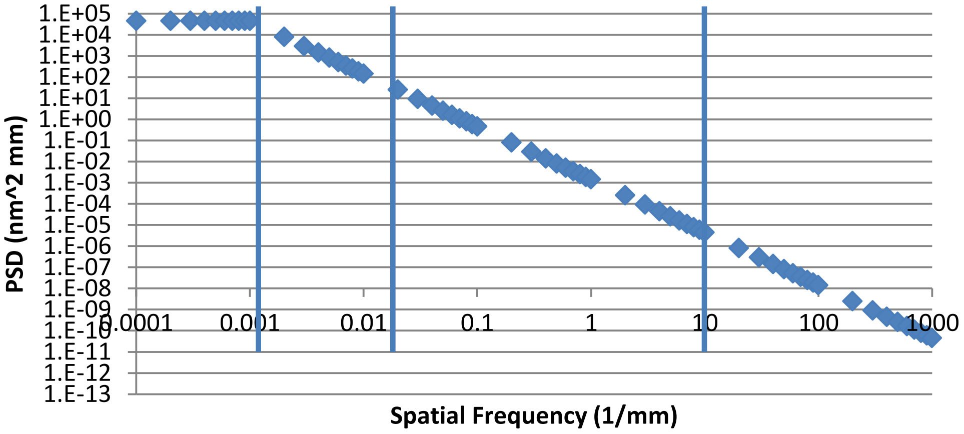
# PM Manufacturing Specification

Define band-limited or spatial frequency specifications

| | |
|---|---|
| Figure/Low | (1 to SF1 cycles/aperture) |
| Mid Spatial | (SF1 to SF2 cycles/aperture) |
| High Spatial | (SF2 cycles/aperture to 10 mm) |
| Roughness | (10 mm to < 1 micrometer) |

Assume that Figure/Low Frequency Error is Constant

Key questions is how to define SF1 and SF2



Also, what is proper PSD Slope

# Spatial Frequency Specification

There is no precise definition for the boundary between

- Figure/Low and Mid-Spatial Frequency
- Mid and High-Spatial Frequency

Harvey defines Figure/Low errors as removing energy from core without changing shape of core, and Mid errors as changing the shape of the core:

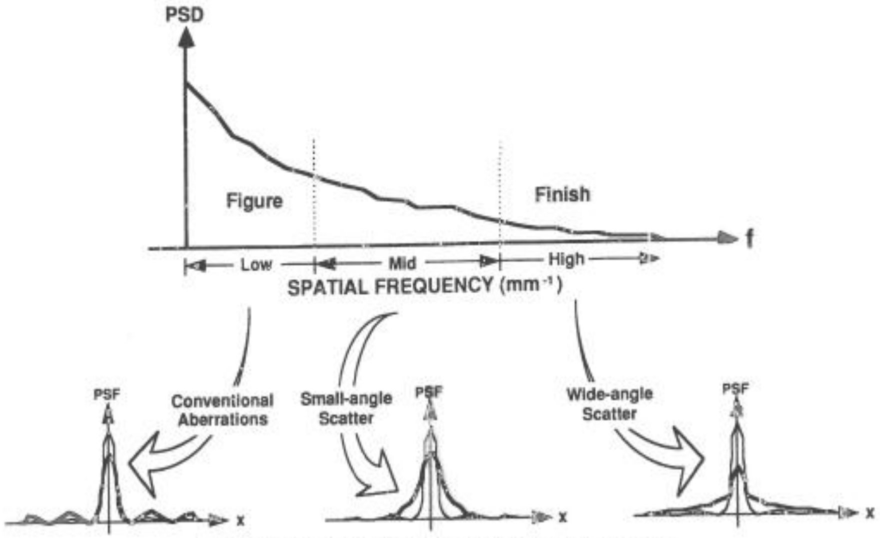
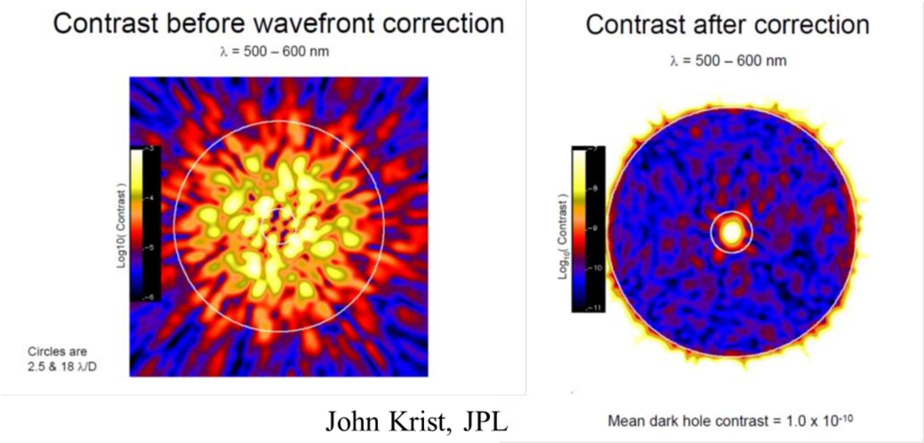


Fig. 11. Effect on image quality differs for each spatial-frequency regime.

Harvey, Lewotsky and Kotha, “Effects of surface scatter on the optical performance of x-ray synchrotron beam-line mirrors”, Applied Optics, Vol. 34, No. 16, pp.3024, 1995.

# Spatial Frequency vs Exoplant Science

Exoplanet Science requires a Deformable Mirror (DM) to correct wavefront errors and create a ‘Dark Hole’ for the coronagraph.



Contrast before wavefront correction

$\lambda$ = 500 – 600 nm

Contrast after correction

$\lambda$ = 500 – 600 nm

Mean dark hole contrast = 1.0 x $10^{-10}$

John Krist, JPL

To image an exoplanet, ‘dark hole’ needs to be below $10^{-10}$

Mid-spatial frequency errors move light from core into ‘hole’

- DM moves that light back into the core.

High-spatial errors (3X OWA) ‘fold’ or ‘scatter’ light into ‘hole’

- Errors above DM range produce speckles whose amplitude varies as $1/\lambda^2$

Krist, Trauger, Unwin and Traub, “End-to-end coronagraphic modeling including a low-order wavefront sensor”, SPIE Vol. 8422, 844253, 2012; doi: 10.1117/12.927143

Shaklan, Green and Palacios, “TPFC Optical Surface Requirements”, SPIE 626511-12, 2006.

# PM SFE Spatial Frequency Specification

Shaklan shows that a UVOIR mirror similar to Hubble (6.4 nm rms) or VLT (7.8 nm rms) can meet the requirements needed to provide a $< 10^{-10}$ contrast 'dark hole'.

- If PM is conjugate with the DM, then PM low-order errors are compensated by DM.
- Recommends < 4 nm rms above 40 cycles
- Both HST & VLT surface figure error is so small enough that there is negligible Contrast reduction from frequency folding
- Because VLT is larger, stiffer and not light-weighted, it is actually smoother at frequencies of concern

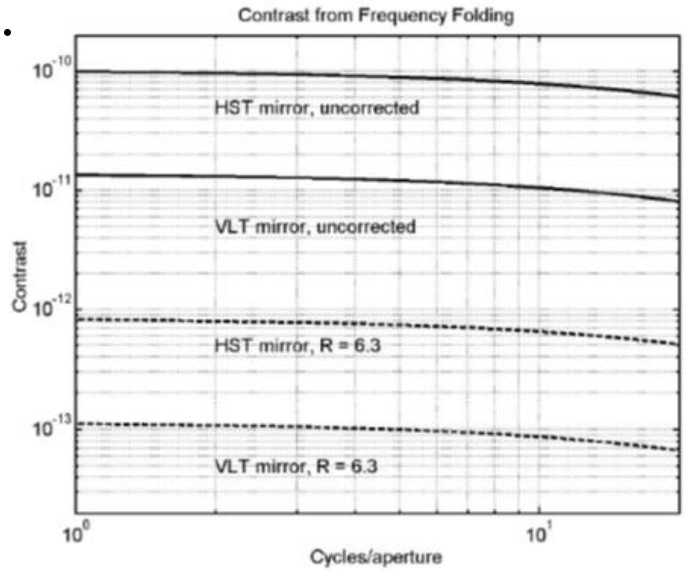


Figure 7. Contrast from frequency folding for spatial frequencies above 48 cycles per aperture, for an 8-m VLT primary and the 2.4 m HST primary. The uncompensated effect is above the required level of $10^{-12}$ for both mirrors. The sequential DM configuration provides about ~100x reduction of the contrast when it compensates the center of a 100 nm bandpass centered at 633 nm. Both mirrors are acceptable after compensation. The frequency folding effect can be perfectly compensated by the Michelson configuration and is not present in the Visible Nuller.

Shaklan, Green and Palacios, "TPFC Optical Surface Requirements", SPIE 626511-12, 2006.
Shaklan & Green, "Reflectivity and optical surface height requirements in a coronagraph", Applied Optics, 2006

# Spatial Frequency vs Science

Low spatial frequency specification is driven by General Astrophysics (not Exoplanet) science.

Exoplanet instruments have deformable mirrors to correct low-spatial errors and General Astrophysics instruments typically do not.

Mid/High spatial frequency specification is driven by Exoplanet because of ‘leakage’ or ‘frequency folding’.

For exoplanet, the spatial band is from the inner working angle (IWA) to approximately 3X the outer working angle (OWA).

Theoretically, a 64 x 64 DM can correct spatial frequencies up to 32 cycles per diameter (N/2), therefore, the maximum mid-spatial frequency of interest is ~ 90 cycles.

Since mirrors are smooth & DM controllability rolls-off near N/2 limit, a conservative lower limit is ~N/3 or ~20 cycles.

# Mid-Spatial Frequency Considerations

Mid-Spatial Frequency Error has many different sources:

- Different substrate architectures have different mid-spatial errors

  e.g. lightweighted vs solid; active vs passive
- Different polishing processes have different mid-spatial signatures

  e.g. large vs small tool

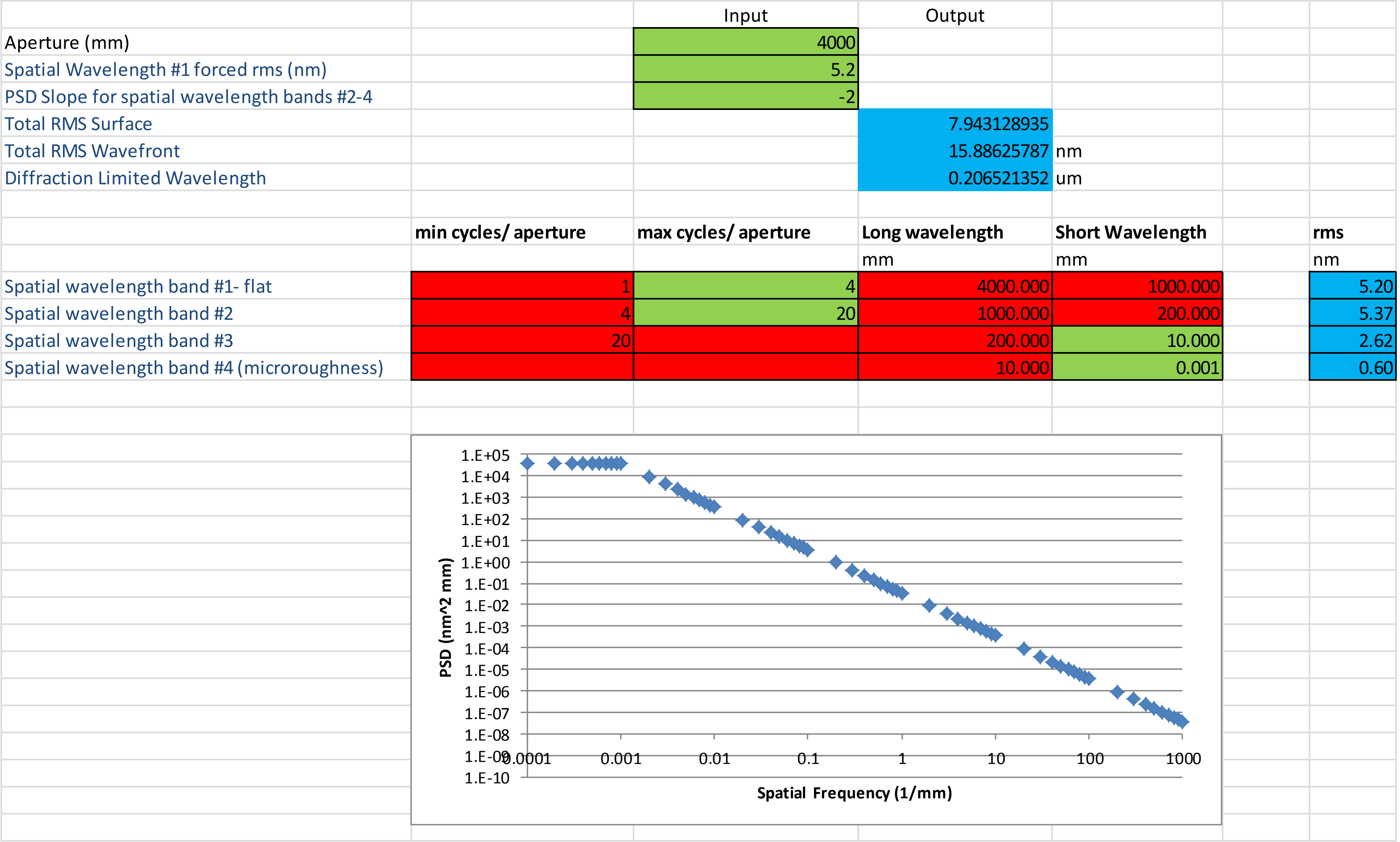
The upper limit for the exoplanet mid-spatial band is important because the physical dimension varies with Aperture Diameter

| Aperture Diameter | 100 cycles Length |
|---|---|
| 4 m | 40 mm |
| 8 m | 80 mm |

In general, the longer the spatial frequency, the easier it is to make the surface smooth.

# PSD Tool

Developed a PSD tool for defining spatial frequency band limited surface figure error specification.



| | | Input | Output | | | |
|---|---|---|---|---|---|---|
| Aperture (mm) | | 4000 | | | | |
| Spatial Wavelength #1 forced rms (nm) | | 5.2 | | | | |
| PSD Slope for spatial wavelength bands #2-4 | | -2 | | | | |
| Total RMS Surface | | | 7.943128935 | | | |
| Total RMS Wavefront | | | 15.88625787 | nm | | |
| Diffraction Limited Wavelength | | | 0.206521352 | um | | |
| | | | | | | |
| | **min cycles/ aperture** | **max cycles/ aperture** | **Long wavelength** | **Short Wavelength** | | **rms** |
| | | | mm | mm | | nm |
| Spatial wavelength band #1- flat | 1 | 4 | 4000.000 | 1000.000 | | 5.20 |
| Spatial wavelength band #2 | 4 | 20 | 1000.000 | 200.000 | | 5.37 |
| Spatial wavelength band #3 | 20 | | 200.000 | 10.000 | | 2.62 |
| Spatial wavelength band #4 (microroughness) | | | 10.000 | 0.001 | | 0.60 |

# Primary Mirror Spatial Frequency Specification

Manufacturing processes typically range from -2.0 to -2.5 (in special cases to -3.0). Different slopes result in different allocations of PM spatial frequency surface figure error.

| Spatial Frequency Band Limited Primary Mirror Surface Specification | | | |
|---|---|---|---|
| PSD Slope | - 2.0 | - 2.25 | - 2.5 |
| Total Surface Error | 8.0 nm rms | 8.0 nm rms | 8.0 nm rms |
| Figure/Low Spatial<br>(1 to 4 cycles per diameter) | 5.2 nm rms | 5.5 nm rms | 5.8 nm rms |
| Mid Spatial<br>(4 to 60 cycles per diameter) | 5.8 nm rms | 5.6 nm rms | 5.4 nm rms |
| High Spatial<br>(60 cycles per diameter to 10 mm) | 1.4 nm rms | 1.0 nm rms | 0.7 nm rms |
| Roughness<br>(10 mm to < 0.001 mm) | 0.6 nm rms | 0.3 nm rms | 0.2 nm rms |

# Wavefront Error Stability Specification

# Primary Mirror Surface Figure Error Stability

Per Krist, once a $10^{-10}$ contrast dark hole has been created, the corrected wavefront phase must be kept stable to within a few picometers rms between science exposures to maintain the instantaneous (not averaged over integration time) speckle intensity to within $10^{-11}$ contrast.

Any drift in WFE can result in speckles which can produce a false exoplanet measurement or mask a true signal.

WFE can vary with time due to the response of optics, structure and mounts to mechanical and thermal stimuli.

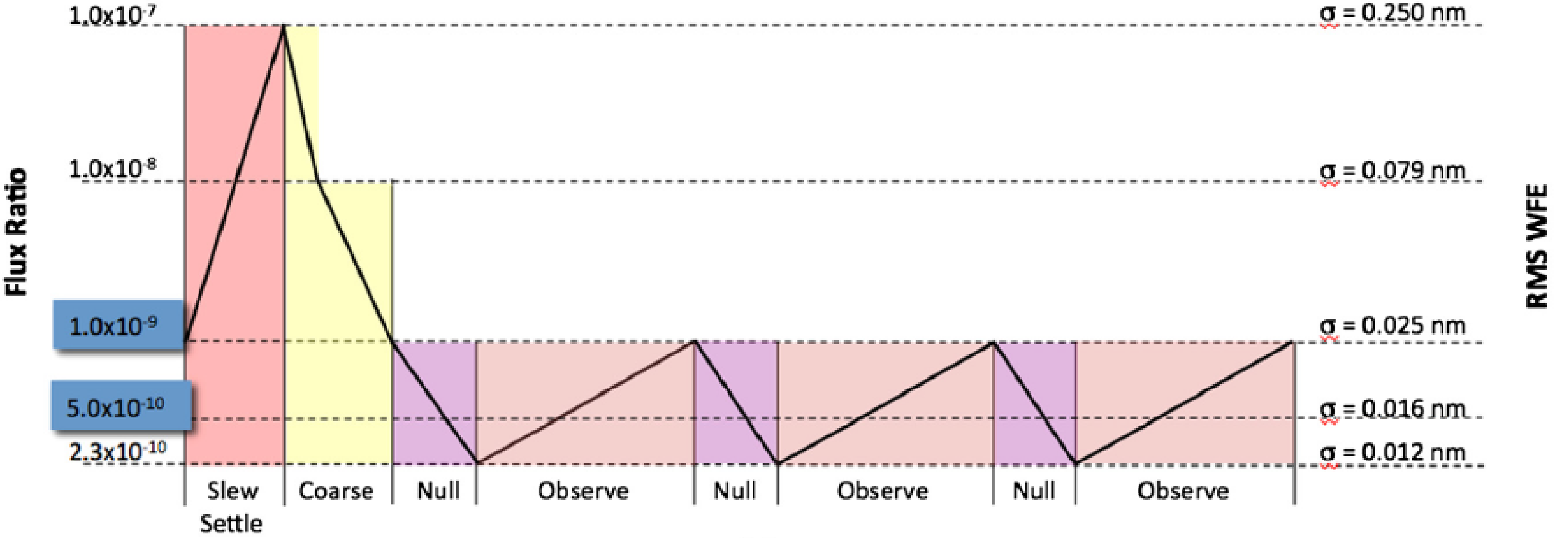
- Vibrations can be excited from reaction wheels, gyros, etc.
- Thermal drift can occur from slew changes relative to Sun

Krist, Trauger, Unwin and Traub, "End-to-end coronagraphic modeling including a low-order wavefront sensor", SPIE Vol. 8422, 844253, 2012; doi: 10.1117/12.927143
Lyon & Clampin, "Space telescope sensitivity and controls for exoplanet imaging", Optical Engineering, Vol 51, 2012; 011002-2

# Primary Mirror Surface Figure Error Stability

If the telescope system cannot be designed with sufficient stability, then the WFE must be controlled actively.

If one assumes that DMs can ‘perfectly’ correct WFE drift, then the Telescope must have a WFE drift less than the required ‘few’ picometers over the active control period.



Lyon and Clampin, “Space telescope sensitivity and controls for exoplanet imaging”, Optical Engineering, Vol 51, 2012; 011002-2

# PM SFE Stability vs Control Frequency

The magnitude of allowable WFE drift depends upon the rate of drift and the correction system’s control frequency.

The maximum amount of allowable drift is when the drift period is equal to or longer than the control period.

But, if the drift rate is faster than the control period, then the amount of allowable drift error becomes smaller.

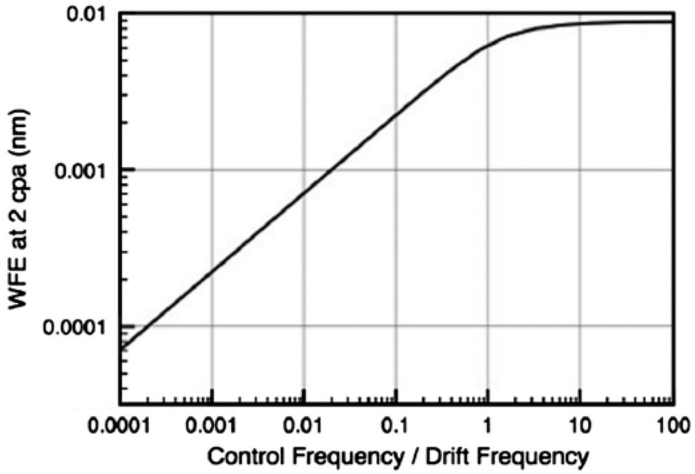


**Fig. 11** WFE at 2 cpa versus control. Full-control effectiveness is not reached until the control frequency exceeds the drift frequency.

Lyon and Clampin, “Space telescope sensitivity and controls for exoplanet imaging”, Optical Engineering, Vol 51, 2012; 011002-2

# Controllability Period

Krist (Private Communication, 2013): wavefront changes can be measured with accuracy of 5 – 8 pm rms for first 11 Zernikes in 60 – 120 sec on a 5th magnitude star in a 4 m telescope over a 500 – 600 nm pass band (reflection off the occulter). This accuracy scales proportional to square root of exposure time or telescope area.

Lyon (Private Communication, 2013): 8 pm control takes ~64 sec for a Vega 0th mag star and 500 – 600 nm pass band [$10^8$ photons/$m^2$-sec-nm produce 4.7 x $10^5$ electrons/DOF and sensing error ~ 0.00073 radians = 64 pm at $\lambda$= 550 nm]

Guyon (Private Communication, 2012): measuring a single sine wave to 0.8 pm amplitude on a Magnitude V=5 star with an 8-m diameter telescope and a 100 nm effective bandwidth takes 20 seconds. [Measurement needs $10^{11}$ photons and V=5 star has $10^6$ photons/m2-sec-nm.] BUT, Controllability needs 3 to 10 Measurements, thus stability period requirement is 10X measurement period.

# Primary Mirror SFE Stability Specification

Bottom Line: Telescope and PM must be stable < 10 pm for periods longer (1x to 10x?) than the control loop period.

Ignoring the issue of what magnitude star is used for the control loop, a conservative specification for the primary mirror surface figure error stability might be:

< 10 picometers rms per 800 seconds for 4-m telescope

< 10 picometers rms per 200 seconds for 8-m telescope

If PM SFE changes less than this rate, then coronagraph control system should be able to maintain $10^{-11}$ contrast.

This specifies how the PM SFE can change as a function of:

- Thermal environment from slews or rolls relative to the sun, etc.
- Mechanical stimuli such as reaction wheels, solar wind, etc.

# QUESTION about Stability

Should there be a difference between how we specify ‘random’ or ‘random-walk’ motion versus predictable discrete or periodic motion?

What is the difference in the effect of repetitive errors whose period is:  slower, equal to, or longer than the measurement exposure?

How sensitive is SFE to thermal environment changes from slews and rotations?

How slowly or rapidly does the SFE change?

Is it better to have a rapid equalization or a very long time constant?

Thermal inertia.

Same with sensitivity to mechanical disturbances.

# Line of Sight Pointing Stability Specification

# Telescope Pointing Stability

For General Astrophysics, Pointing Stability is usually

< 1/8th PSF FWHM per exposure

| Telescope Diameter | PSF FWHM | Pointing Stability |
|---|---|---|
| 4-meter | 32 mas | 4 mas |
| 8-meter | 16 mas | 2 mas |

For Exoplanet, Pointing Stability needs to be ~ 0.5 mas in order for coronagraph to block the star. (Guyon, Private Communication) This can be accomplished via a fine steering mirror.

Pointing is primarily a telescope requirement. But it does have implications on the structural stiffness of the primary mirror.

# Segmented Aperture

# Monolithic vs Segmented Aperture

Engineering Specifications derived apply to Monolithic & Segmented – Segmented must meet all specifications.

But segmented apertures have additional challenges:

- Segmentation Pattern results in secondary peaks
- Segmentation Gaps redistribute energy
- Rolled Edges redistribute energy
- Segment Co-Phasing Absolute Accuracy
- Segment Co-Phasing Stability

There are many different potential segmentation schemes, ranging from hexagonal segments to pie segments to large circular mirrors. The selection and analysis of potential segmentation patterns is beyond the scope of this effort.

For this analysis, we assume hexagonal.

# Hexagonally Segmented Aperture

Point Spread Function for Hexagonal Segmented Aperture:

$$PSF_{tel}(\rho) = \left(\frac{A\,N}{\lambda\,z}\right)^2 * PSF_{seg}(\rho) * Grid(\rho)$$

where:

$\mathrm{PSF}_{\mathrm{seg}}$ size $\sim {}^{\lambda}/_{d_{seg}}$

Grid space $\sim {}^{\lambda}/_{d_{seg}}$

and Phased Telescope has:

$\mathrm{PSF}_{\mathrm{tel}}$ size $\sim {}^{\lambda}/_{D_{tel}}$

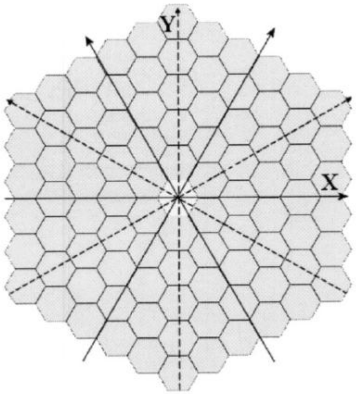
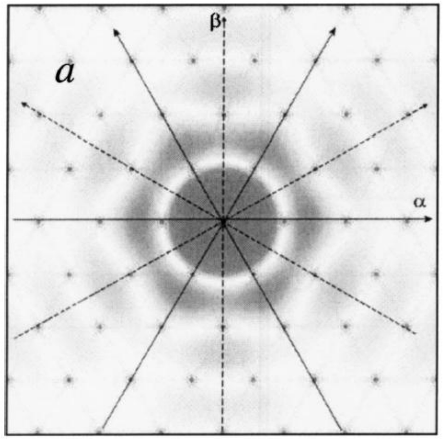


Fig. 1. Segmented mirror with segmentation order $M = 5$ consisting of $N = 90$ segments. Solid and dashed arrows illustrate the double $\pi/3$ symmetry of the system.

Yaitskova *et al.* J. Opt. Soc. Am. A/Vol. 20, No. 8/August 2003

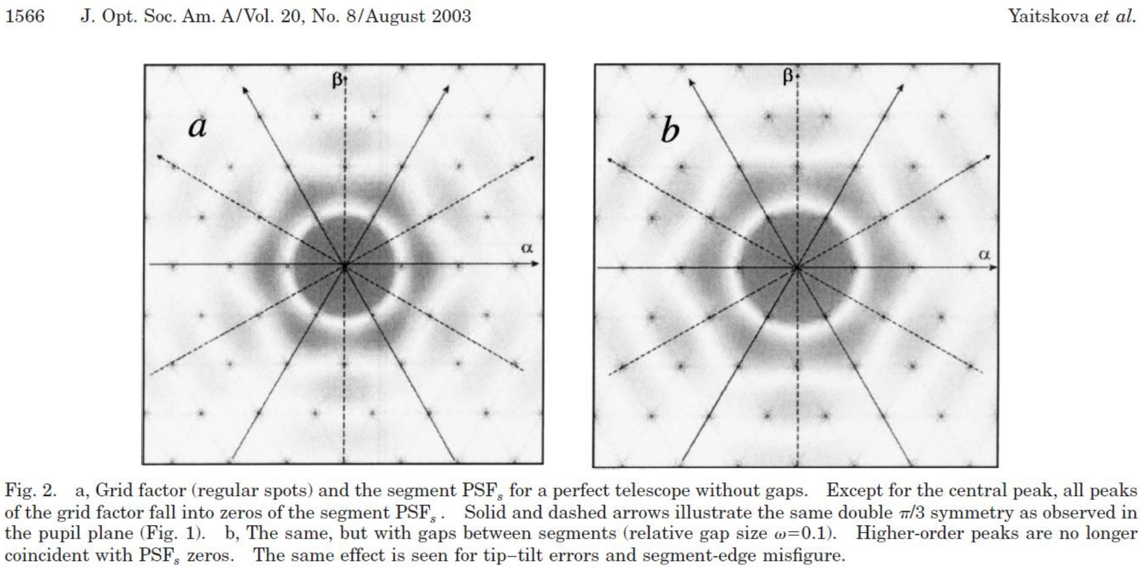


Yaitskova, Dohlen and Dierickx, "Analytical study of diffraction effects in extremely large segmented telescopes", JOSA, Vol.20, No.8, Aug 2003.

# Segmented Aperture Point Spread Function

For perfectly phased telescope with no gaps & optically perfect segments, zeros of $\mathrm{PSF}_{\mathrm{seg}}$ coincide with peaks of Grid function resulting in $\mathrm{PSF}_{\mathrm{tel}}$ with a single central peak size $\sim \lambda / D_{tel}$

In a real telescope: gaps, tip/tilt errors, piston errors, rolled edges & figure errors move energy from central peak to higher-order peaks and into speckle pattern.



1566 J. Opt. Soc. Am. A/Vol. 20, No. 8/August 2003 Yaitskova *et al.*

Fig. 2. a, Grid factor (regular spots) and the segment $\mathrm{PSF}_s$ for a perfect telescope without gaps. Except for the central peak, all peaks of the grid factor fall into zeros of the segment $\mathrm{PSF}_s$. Solid and dashed arrows illustrate the same double $\pi/3$ symmetry as observed in the pupil plane (Fig. 1). b, The same, but with gaps between segments (relative gap size $\omega$=0.1). Higher-order peaks are no longer coincident with $\mathrm{PSF}_s$ zeros. The same effect is seen for tip–tilt errors and segment-edge misfigure.

Yaitskova, Dohlen and Dierickx, “Analytical study of diffraction effects in extremely large segmented telescopes”, JOSA, Vol.20, No.8, Aug 2003.

# Segmentation Pattern vs. Dark Hole

Question: Is fewer large segments better or is many small better?

If segment relative position errors are static and correctable via a segmented DM, then it should be possible to remove effects of higher-order peaks.

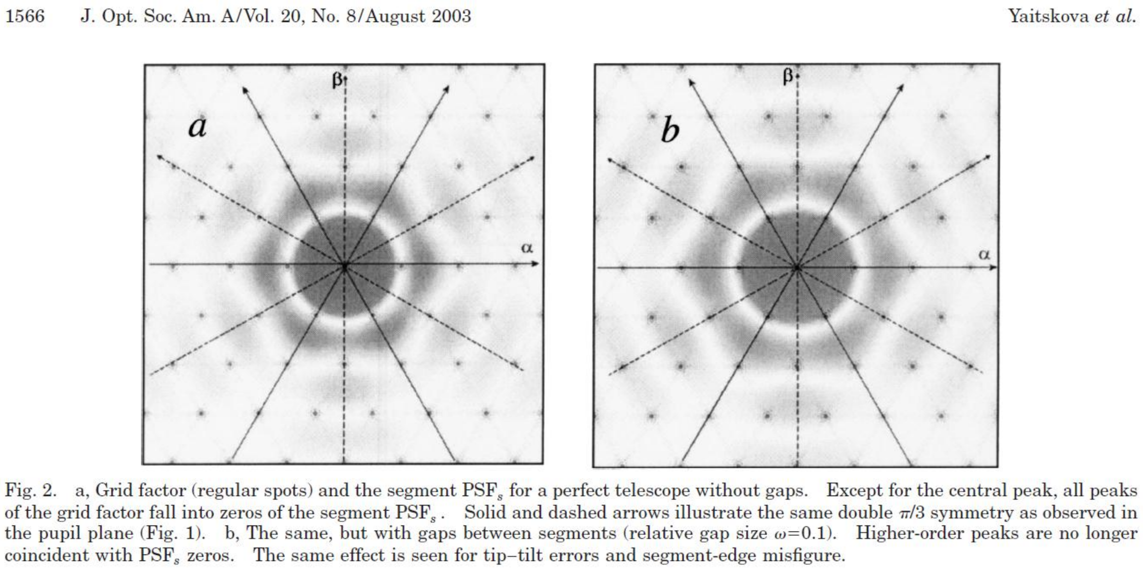
If the goal is to produce a ‘dark hole’, should the segmentation pattern be selected to keep higher-order peaks beyond the outer working angle (OWA)?

For example, an aperture composed of many small segments (e.g. 32 segments per diameter in 16 rings) will have higher-order peaks that are beyond the outer working angle (16λ/D).

# Segmented Aperture Point Spread Function

In a real telescope:

- gaps, tip/tilt errors, rolled edges & figure errors change $\mathrm{PSF}_{\mathrm{seg}}$ but leave Grid function unchanged, resulting in a $\mathrm{PSF}_{\mathrm{tel}}$ with higher-order peaks.
- piston errors change Grid function but leaves $\mathrm{PSF}_{\mathrm{seg}}$ unchanged, resulting in a $\mathrm{PSF}_{\mathrm{tel}}$ with speckles.



1566 J. Opt. Soc. Am. A/Vol. 20, No. 8/August 2003 Yaitskova *et al.*

Fig. 2. a, Grid factor (regular spots) and the segment $\mathrm{PSF}_s$ for a perfect telescope without gaps. Except for the central peak, all peaks of the grid factor fall into zeros of the segment $\mathrm{PSF}_s$. Solid and dashed arrows illustrate the same double $\pi/3$ symmetry as observed in the pupil plane (Fig. 1). b, The same, but with gaps between segments (relative gap size $\omega$=0.1). Higher-order peaks are no longer coincident with $\mathrm{PSF}_s$ zeros. The same effect is seen for tip–tilt errors and segment-edge misfigure.

Yaitskova, Dohlen and Dierickx, "Analytical study of diffraction effects in extremely large segmented telescopes", JOSA, Vol.20, No.8, Aug 2003.

# Co-Phasing Errors

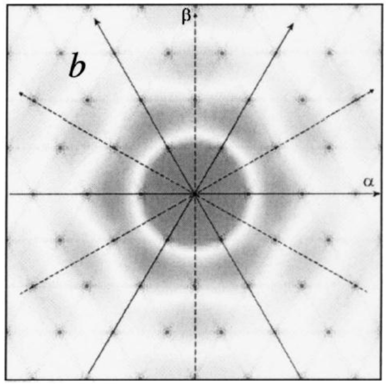
Co-Phasing errors introduce speckles.

If the error is ‘static’ then a segmented piston deformable mirror should be able to ‘correct’ the error and any residual error should be ‘fixed-pattern’ and thus removable from the image.

But, if error is ‘dynamic’, then speckles will move.

Question: If piston error is composed of repeating and non-repeating dynamic components:

- is it possible to remove a time-averaged steady-state pattern of the repeating motion such that only non-repeating must be < 10 pm?
- or, must all error be < 10 pm?



Yaitskova, Dohlen and Dierickx, “Analytical study of diffraction effects in extremely large segmented telescopes”, JOSA, Vol.20, No.8, Aug 2003.

# Co-Phasing Stability vs Segmentation

Per Guyon:

- Co-Phasing required to meet given contrast level depends on number of segments; is independent of telescope diameter.
- Time required to control co-phasing depends on telescope diameter; is independent of number of segments.
  - To measure a segment's co-phase error takes longer if the segment is smaller because there are fewer photons.
  - But, allowable co-phase error is larger for more segments.

TABLE 1: Segment cophasing requirements for space-based telescopes
(wavefront sensing done at λ=550nm with an effective spectral bandwidth δλ= 100 nm)

| Telescope diameter (D) & λ | Number of Segments (N) | Contrast | Target | Cophasing requirement | Stability timescale |
|---|---|---|---|---|---|
| 4 m, 0.55 μm | 10 | 1e-10 | $m_V$=8 | 2.8 pm | 22 mn |
| 8 m, 0.55 μm | 10 | 1e-10 | $m_V$=8 | 2.8 pm | 5.4 mn |
| 8 m, 0.55 μm | 100 | 1e-10 | $m_V$=8 | 8.7 pm | 5.4 mn |

Guyon, "Coronagraphic performance with segmented apertures: effect of cophasing errors and stability requirements", Private Communication, 2012.

# Tip/Tilt Errors

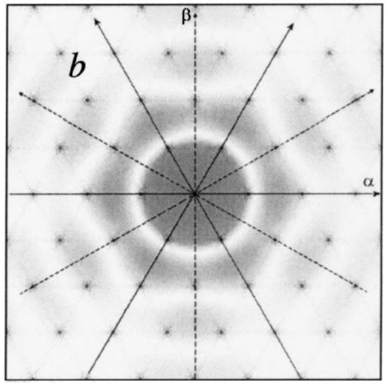
A segmented aperture with tip/tilt errors is like a blazed grating removes energy from central core to higher-order peaks.

If the error is ‘static’ then a segmented tip/tilt deformable mirror should be able to ‘correct’ the error and any residual error should be ‘fixed-pattern’ and thus removable from the image.

But, if error is ‘dynamic’, then higher-order peaks will ‘wink’.

Question: If tip/tilt error is composed of repeating and non-repeating dynamic components:

- is it possible to remove a time-averaged steady-state pattern of the repeating motion such that only non-repeating must be < 10 pm?
- or, must all error be < 10 pm?

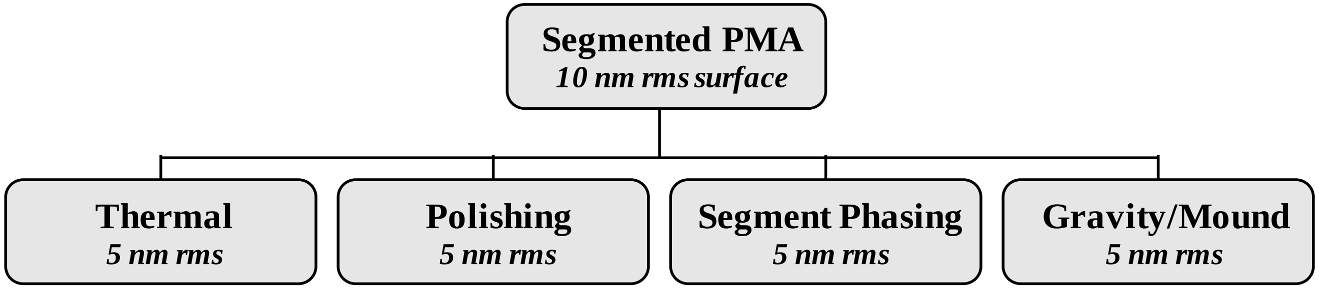


Yaitskova, Dohlen and Dierickx, “Analytical study of diffraction effects in extremely large segmented telescopes”, JOSA, Vol.20, No.8, Aug 2003.

# Primary Mirror Total Surface Figure Error

Regardless whether monolithic or phased, PM must have < 10 nm rms surface.

Segmenting increases complexity and redistributes the error allocations.



- **Segmented PMA** *10 nm rms surface*
  - **Thermal** *5 nm rms*
  - **Polishing** *5 nm rms*
  - **Segment Phasing** *5 nm rms*
  - **Gravity/Mound** *5 nm rms*

Polishing specification is for individual segments.

Segment phasing specification is how well individual segments can be aligned before correction by a segmented deformable mirror.

# Segment Gaps and Edges

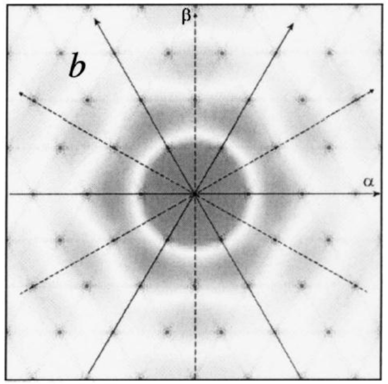
Gaps between segments and segment edge roll-off both effect the segment point spread function and redistributes energy from the central core to the to higher-order peaks.

Effect is complicated by variations in gap spacing & edge roll-off

These errors cannot be corrected via a deformable mirror.

But, they are 'static' and their effect can be removed from image.

Segment to Segment Gap distance is determined by geometry and 'non-interference' issues.



Segment Edge Roll-Off effects collecting aperture & Strehl. A good specification is < 5 mm

(JWST is < 7 mm; QED & Zeeko SOA is ~ 2 mm).

Yaitskova, Dohlen and Dierickx, "Analytical study of diffraction effects in extremely large segmented telescopes", JOSA, Vol.20, No.8, Aug 2003.
QED - NASA SBIR 03-S2.05-7100; Zeeko - NASA SBIR 04-S2.04-9574

# Summary Science Driven Specifications

# Telescope Performance Requirements

Science is enabled by the performance of the entire Observatory: Telescope and Science Instruments.

Telescope Specifications depend upon the Science Instrument.

Telescope Specifications have been defined for 3 cases:

- 4 meter Telescope with an Internal Masking Coronagraph
- 8 meter Telescope with an Internal Masking Coronagraph
- 8 meter Telescope with an External Occulter

WFE Specification is before correction by a Deformable Mirror

WFE/EE Stability and MSF WFE are the stressing specifications

AMTD has not studied the specifications for a Visible Nulling Coronagraph or phase type coronagraph.

# 4m Telescope Requirements for use with Coronagraph

| On-axis Monolithic 4-m Telescope with Coronagraph | | |
|---|---|---|
| Performance Parameter | Specification | Comments |
| Maximum total system rms WFE | 38 nm | Diffraction limit (80% Strehl at 500 nm) |
| Encircled Energy Fraction (EEF) | 80% within 32 mas at 500 nm | HST spec, modified to larger aperture and slightly bluer wavelength<br>Vary < 5% across 8 arcmin FOV |
| EEF stability | <2% | JWST |
| Telescope WFE stability | < 10 pm per 800 sec | |
| PM rms surface error | 5 - 10 nm | |
| Pointing stability (jitter) | ~4 mas | scaled from HST<br>Guyon: ~ 0.5 mas determined by stellar angular diameter. |
| Mid-frequency WFE | < 4 nm | |

# 8m Telescope Requirements for use with Coronagraph

| **On-axis Monolithic 8-m Telescope with Coronagraph** | | |
|---|---|---|
| Performance Parameter | Specification | Comments |
| Maximum total system rms WFE | 38 nm | Diffraction limit (80% Strehl at 500 nm) |
| Encircled Energy Fraction (EEF) | 80% within 16 mas at 500 nm | HST spec, modified to larger aperture and slightly bluer wavelength<br>Vary < 5% across 4 arcmin FOV |
| EEF stability | <2% | JWST |
| Telescope WFE stability | < 10 pm per 200 sec | |
| PM rms surface error | 5 - 10 nm | |
| Pointing stability (jitter) | ~2 mas | scaled from HST<br>Guyon: ~ 0.5 mas determined by stellar angular diameter. |
| Mid-frequency WFE | < 4 nm | |

# 8m Telescope Requirements for use with Coronagraph

| On-axis Segmented 8-m Telescope with Coronagraph | | |
|---|---|---|
| Performance Parameter | Specification | Comments |
| Maximum total system rms WFE | 38 nm | Diffraction limit (80% Strehl at 500 nm) |
| Encircled Energy Fraction (EEF) | 80% within 16 mas at 500 nm | HST spec, modified to larger aperture & bluer wavelength<br>Vary < 5% across 4 arcmin FOV |
| EEF stability | <2% | JWST |
| WFE stability | < 10 pm per 200 sec | |
| Segment gap stability | TBD | Soummer, McIntosh 2013 |
| Number and Size of Segments | TBD<br>(1 – 2m, 36 max) | Soummer 2013 |
| Segment edge roll-off stability | TBD | Sivaramakrishnan 2013 |
| Segment co-phasing stability | 4 to 6 pm per 300 secs | Depends on number of segments |
| Pointing stability (jitter) | ~2 mas | scaled from HST<br>Guyon, ~ 0.5 mas floor determined by stellar angular diameter. |

# 8m Telescope Requirements for use with Occulter

| **On-axis Segmented 8-m Telescope with External Occulter** | | |
|---|---|---|
| Performance Parameter | Specification | Comments |
| Maximum total system rms WFE | 38 nm | Diffraction limit (80% Strehl at 500 nm) |
| Encircled Energy Fraction (EEF) | 80% within 16 mas at 500 nm | HST spec, modified to larger aperture & bluer wavelength<br>Vary < 5% across 4 arcmin FOV |
| EEF stability | <2% | JWST |
| WFE stability | ~ 35 nm | Depends on number of segments |
| Segment gap stability | TBD | Soummer, McIntosh 2013 |
| Number and Size of Segments | TBD<br>(1 – 2m, 36 max) | Soummer 2013 |
| Segment edge roll-off stability | TBD | Sivaramakrishnan 2013 |
| Segment co-phasing stability | TBD | Soummer, McIntosh 2013 |
| Pointing stability (jitter) | ~2 mas | scaled from HST<br>Guyon, ~ 0.5 mas floor determined by stellar angular diameter. |

# Implementation Constraints

# Representative Missions

Four 'representative' mission architectures achieve Science:

- 4-m monolith launched on an EELV,
- 8-m monolith on a HLLV,
- 8-m segmented on an EELV
- 16-m segmented on a HLLV.

The key difference between launch vehicles is up-mass

EELV can place 6.5 mt to Sun-Earth L2

HLLV is projected to place 40 to 60 mt to Sun-Earth L2

The other difference is launch fairing diameter

EELV has 5 meter fairing

HLLV is projected to have a 8 to 10 meter fairing

# Technology Challenges derived from Science & Mission Requirements, and Implementation Constraints (2010)

**Table 3.1: Science Requirement to Technology Need Flow Down**

| Science | Mission | Constraint | Capability | Technology Challenge |
|---|---|---|---|---|
| Sensitivity | Aperture | EELV<br>5 m Fairing,<br>6.5 mt to SEL2 | 4 m Monolith | 4 m, 200 Hz, 60 kg/m$^2$ |
| | | | | 4 m support system |
| | | | 8 m Segmented | 2 m, 200 Hz, 15 kg/m$^2$ |
| | | | | 8 m deployed support |
| | | HLLV-Medium<br>10 m Fairing,<br>40 mt to SEL2 | 8 m Monolith | 8 m, <100Hz, 200kg/m$^2$ |
| | | | | 8 m, 10 mt support |
| | | | 16 m Segmented | 2-4m, 200Hz, 50kg/m2 |
| | | | | 16 m deployed support |
| | | HLLV-Heavy<br>10 m Fairing,<br>60 mt to SEL2 | 8 m Monolith | 8m, <100Hz, 480kg/m2 |
| | | | | 8 m, 20 mt support |
| | | | 16 m Segmented | 2-4m, 200Hz, 120kg/m$^2$ |
| | | | | 16 m deployed support |
| | 2 hr Exposure | Thermal<br>280K ± 0.5K<br>0.1K per 10min | < 5 nm rms per K | low CTE material |
| | | | > 20 hr thermal time constant | thermal mass |
| | | Dynamics<br>TBD micro-*g* | < 5 nm rms figure | passive isolation |
| | | | | active isolation |
| | Reflectance | Substrate Size | > 98% 100-2500 nm | Beyond Scope |
| High Contrast | Diffraction Limit | Monolithic | < 10 nm rms figure | mid/high spatial error fabrication & test |
| | | Segmented | < 5 nm rms figure | |
| | | | < 2 mm edges | edge fabrication & test |
| | | | < 1 nm rms phasing | passive edge constraint |
| | | | | active align & control |

# Space Launch System (SLS)

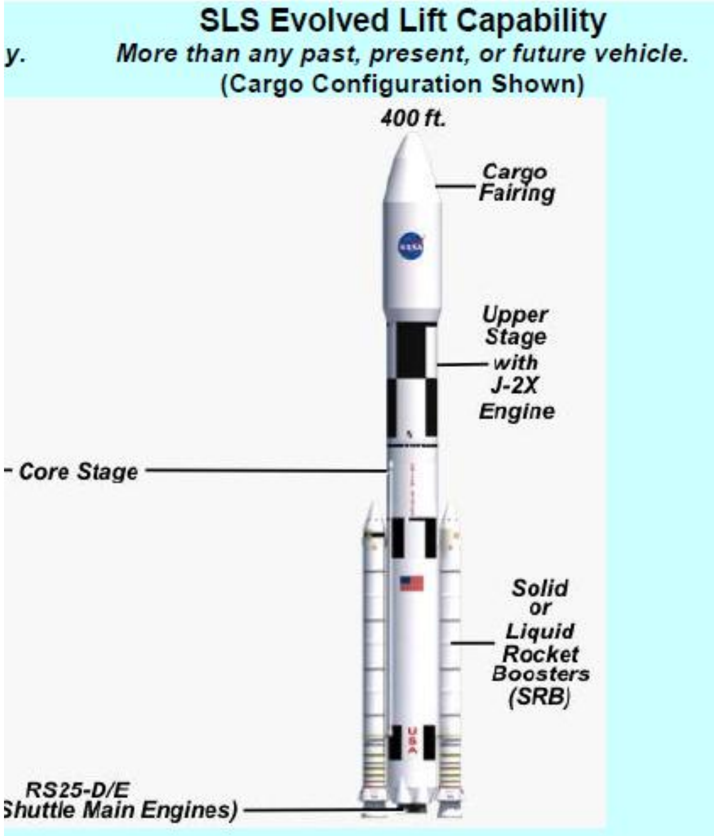
## Space Launch System (SLS) Cargo Launch Vehicle specifications

Preliminary Design Concept

- 8.3 m dia x 18 m tall fairing
- 70 to 100 mt to LEO
- consistent with HLLV Medium

Enhanced Design Concept

- 10.0 m dia x 30 m tall fairing
- 130 mt to LEO
- consistent with HLLV Heavy



HLLV Medium could launch an 8-m segmented telescope whose mirror segments have an areal density of 60 kg/m2.

Stahl, H. Philip, Phil Sumrall, and Randall Hopkins, "Ares V launch vehicle: an enabling capability for future space science missions", Acta Astronautica, Elsevier Ltd., 2009, doi:10.1016/j.actaastro.2008.12.017

# Mass

Mass is the most important factor in the ability of a mirror to survive launch and meet its required on-orbit performance.

More massive mirrors are

stiffer and thus easier and less expensive to fabricate;

more mechanically and thermally stable.

# Primary Mirror Mass Allocation

Given that JWST is being designed to a 6500 kg mass budget, we are using JWST to define the EELV telescope mass budget:

| | |
|---|---|
| Optical Telescope Assembly | < 2500 kg |
| Primary Mirror Assembly | < 1750 kg |
| Primary Mirror Substrate | < 750 kg |

This places areal density constraints of:

| Aperture | PMA | PM |
|---|---|---|
| 4 meter | 145 kg | 62.5 kg |
| 8 meter | 35 kg | 15 kg |

An HLLV would allow a much larger mass budget

| | |
|---|---|
| Optical Telescope Assembly | < 20,000 to 30,000 kg |
| Primary Mirror Assembly | < 15,000 to 25,000 kg |
| Primary Mirror Substrate | < 10,000 to 20,000 kg |

# Launch Loads

Primary mirror assembly for any potential mission must survive launch without degrading its on-orbit performance.

Launch environment for SLS is unknown.

We are specifying to a representative EELV (Delta-IV Heavy)

- Launch Loads & Coupled Loads
- Vibro-Acoustic

# Combined Steady and Dynamic Acceleration

Delta-IV Heavy axial and lateral G loads applied to spacecraft model (mass at center of gravity) envelops spacecraft/launch vehicle interface loads.

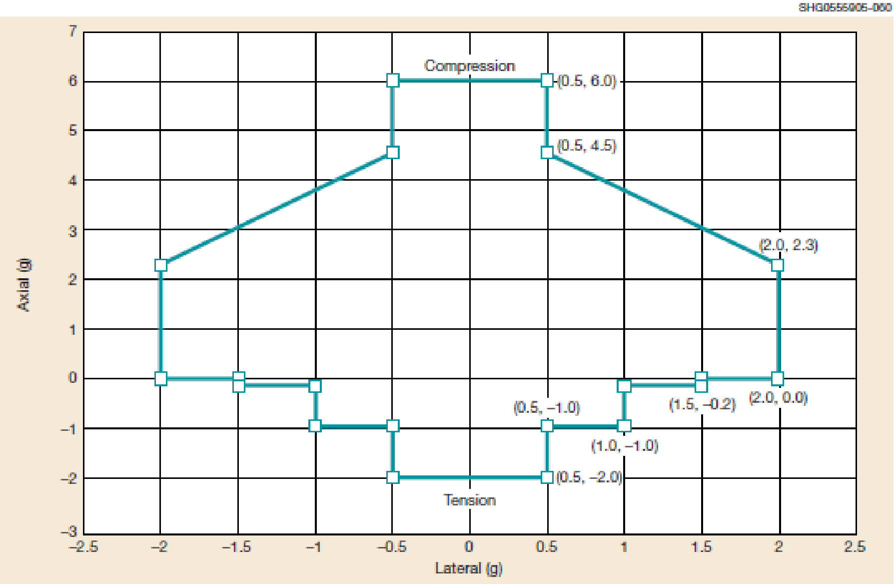


Figure 4-30. Delta IV Heavy Design Load Factors

For a minimum payload mass of 6577 kg, (from Coupled Mode Analysis), payload minimum:

axial frequency = 30 Hz; lateral frequency = 8 Hz

Delta IV Payload Planners Guide, United Launch Alliance, Sept 2007

# Vibro-Acoustic Environment

Environment depends on mechanical transmission of vibration from engines and acoustic fields.

Maximum acoustic environment is fluctuation of pressure on all surfaces of the launch vehicle and spacecraft.

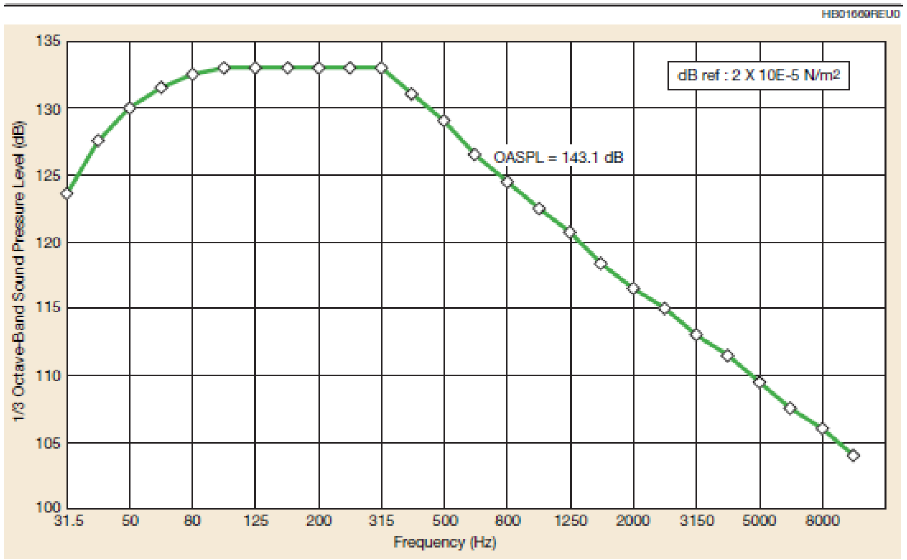


Figure 4-33. Delta IV Heavy (5-m Composite Fairing) Internal Payload Acoustics Typical 95th Percentile, 50% Confidence Predictions, 60% Fill Effect Included

Maximum Shock typically occurs at separation but depends upon the Payload Attachment Fitting (PAF)

Delta IV Payload Planners Guide, United Launch Alliance, Sept 2007

# Conclusions

# Conclusion

AMTD is using a Science Driven Systems Engineering approach to develop Engineering Specifications based on Science Measurement Requirements and Implementation Constraints.

Science requirements meet the needs of both Exoplanet and General Astrophysics science.

Engineering Specifications are guiding our effort to mature to TRL-6 the critical technologies needed to produce 4-m or larger flight-qualified UVOIR mirrors by 2018 so that a viable mission can be considered by the 2020 Decadal Review.

Engineering Specification is a ‘living’ document.

# Bibliography

Delta IV Payload Planners Guide, United Launch Alliance, Sept 2007

Harvey, Lewotsky and Kotha, "Effects of surface scatter on the optical performance of x-ray synchrotron beam-line mirrors", Applied Optics, Vol. 34, No. 16, pp.3024, 1995.

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Yaitskova, Dohlen and Dierickx, "Analytical study of diffraction effects in extremely large segmented telescopes", JOSA, Vol.20, No.8, Aug 2003.

Zeeko - NASA SBIR 04-S2.04-9574.

# BACKUP

# Low/Mid Spatial Frequency Specification

There is no precise definition for the boundary between Figure/Low and Mid-Spatial Frequency.

- Value ranging from 4 cycles to 10 cycle.
- Many assert that Zernike Polynomial Set defines Figure/Low

Harvey defines Figure/Low errors as removing energy from core without changing shape of core, and Mid errors as changing the shape of the core:

We choose 4 cycles

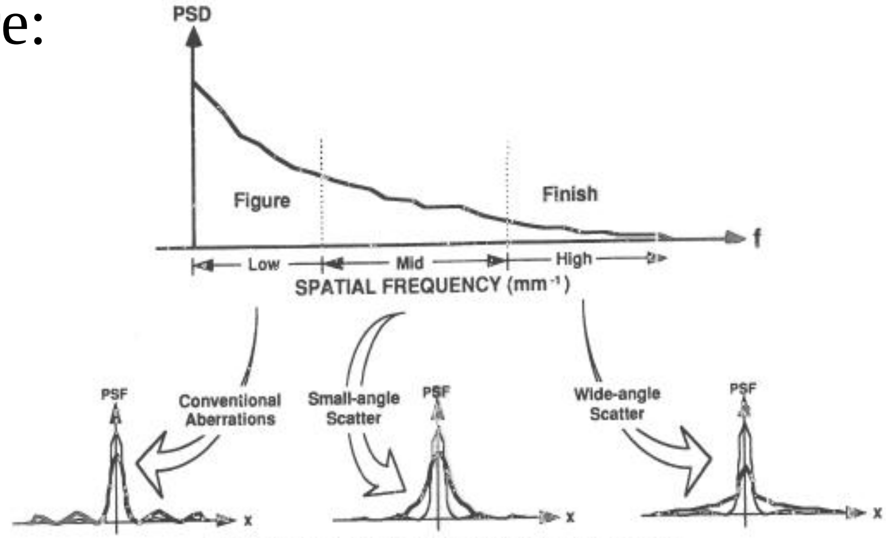


Fig. 11. Effect on image quality differs for each spatial-frequency regime.

Harvey, Lewotsky and Kotha, “Effects of surface scatter on the optical performance of x-ray synchrotron beam-line mirrors”, Applied Optics, Vol. 34, No. 16, pp.3024, 1995.

# Mid/High Spatial Frequency Specification

Just as there is no definitive Low/Mid, there is no definitive Mid/High Spatial Frequency Boundary.

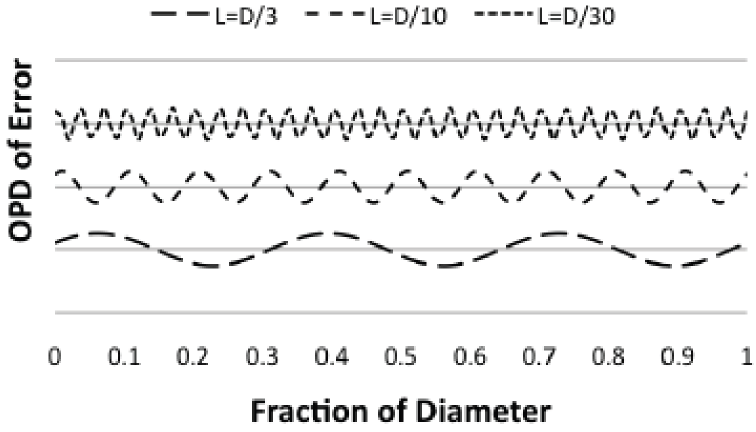
Harvey would define it as the spatial frequency at which energy starts being distributed broadly across the image.

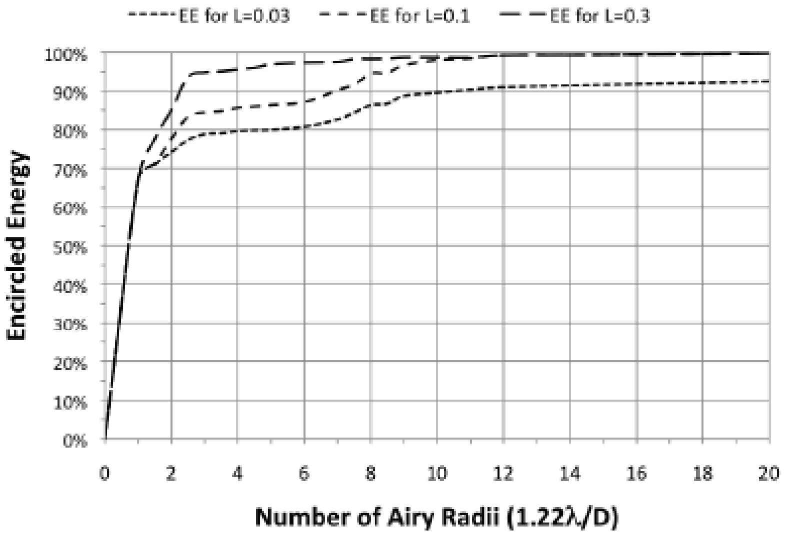
Noll ("Effect ofMid- and High-Spatial Frequencies on Optical Performance", Optical Engineering, Vol. 18, No. 2, pp.137, 1979) defines it as the spatial frequency which scatters energy beyond 16 Airy Rings.

Wetherell ("The Calculation of Image Quality", Applied Optics and Optical Engineering, Vol. VIII, Academic Press, 1980) defines it as the spatial frequency which scatters energy beyond 10 Airy Rings.

# Mid/High Spatial Frequency Specification

Following Wetherell, Hull ("Mid-spatial frequency matters: exmaples of the control of the power spectral density and what that means to the performance of imaging systems", SPIE DSS, 2012) showed that a 30 cycle per aperture error requires 5 Airy Rings to achieve 80% EE and 10 Airy rings to achieve 90% EE.





Noll states that if an optical system has λ/8 rms of mid-frequency WFE, it requires 16 Airy rings to achieve 80% EE

# Ultraviolet Capability

Science Applications are somewhat wavelength dependent:

| | |
|---|---|
| 90 to 120 nm | High Resolution Spectroscopy |
| 120 to 150 nm | Imaging and Spectroscopy |
| > 150 nm | Imaging |

Far-UV high resolution spectroscopy PSF FWHM Specification

| | |
|---|---|
| Requirement | 200 mas at 150 nm |
| Goal | 100 mas at 100 nm |

This, as well as Exo-planet requirement for a compact PSF, places constraints on Telescope Mid-Spatial Frequency error.

# Mid/High Spatial Frequency Specification

Far-UV High-Resolution Spectroscopy desires 50% to 80% EE for 100 to 200 mas.

4 m Telescope can achieve this in 4 to 5 Airy rings.

Diffraction limited at 500 nm results in an Airy Disc

| Airy Disc | λ/D | 4 m | 8 m |
|---|---|---|---|
| 1st min | 1.22 | 32 mas | 16 mas |
| 2nd min | 2.23 | 58 mas | 29 mas |
| 3rd min | 3.24 | 85 mas | 42 mas |
| 4th min | 4.24 | 111 mas | 56 mas |
| 5th min | 5.24 | 137 mas | 69 mas |
| 6th min | 6.24 | 164 mas | 82 mas |
| 7th min | 7.25 | 190 mas | 95 mas |
| 8th min | 8.25 | 216 mas | 108 mas |
| 9th min | 9.25 | 243 mas | 121 mas |
| 10th min | 10.25 | 269 mas | 134 mas |

From Wetherell, this implies Mid/High boundary of 30 cycles