AMTD: update of engineering specifications derived from science requirements for future UVOIR space telescopes

Mirror Technology Days in the Government 2014
Albuquerque
18-20 Nov 2014

H. Philip Stahl

Summary

In AMTD-1 2013 SPIE paper we:

- Discussed the flow down to Telescope Aperture Diameter from Science Requirements, including:
  - Habitable Zone Resolution Requirement
  - Signal to Noise Requirement
  - η_{EARTH}
  - Exo-Zodi Resolution Requirement
- Developed a PSD tool for flowing the Diffraction Limit Requirement to a Surface Wavefront Error Specification.
- Proposed a Wavefront Error Stability Specification.
- Considered Wavefront Stability issues of a Segmented Mirror
- And, reviewed Launch Vehicle and Environmental Constraints

Stahl, H. Philip, Marc Postman and W. Scott Smith, "Engineering specifications for large aperture UVO space telescopes derived from science requirements", Proc. SPIE 8860, 2013, DOI: 10.1117/12.2024480

Summary

In AMTD-2 2014 SPIE Astronomy Paper, we updated and refined our findings:

- Refine the Telescope Aperture Diameter flow down from Science Requirements based on a new paper by Stark et. al.
- Discuss the impact of Launch Vehicle Constraints on implementing the desired aperture diameter.
- Review the Surface Wavefront Error Specification.
- Define a Wavefront Error Stability Specification.
- Discuss the scaling of Aperture Size and Stiffness

H. Philip Stahl, Marc Postman, Gary Mosier, W. Scott Smith, Carl Blaurock, Kong Ha and Christopher C. Stark, "AMTD: update of engineering specifications derived from science requirements for future UVOIR space telescopes"

Maximizing the ExoEarth Candidate Yield from a Future Direct Imaging Mission, Stark, C. C., Roberge, A., Mandell, A., & Robinson, T. 2014, ApJ, submitted

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

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.

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

Requirements Flowdown

Science Requirements, Launch Vehicle & Programmatic Constraints define different Engineering Specifications

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

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 not producing an optical design or prescription.

We are 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.

Future is to integrate these PM specifications into a telescope.

Also, right now, Coatings are out of scope.

And, this presentation is a sub-set of our work.

Science Requirements

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 Stable 10^{-10} starlight suppression ~0.1 nm stable WFE per 2 hr ~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 Symmetric PSF 500 nm diffraction limit 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 500 nm diffraction limit 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	

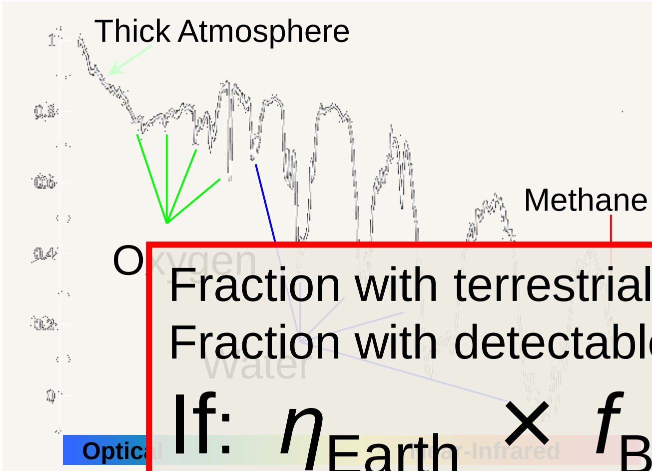
Exoplanet Measurement Capability

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 $\eta_{EARTH} = 0.15$	High contrast (ΔMag>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 (ΔMag>25 mag) SNR=10 low-resolution (R=70-100) spectroscopy with an IWA ~ 40 mas. Exposure times <500 ksec.

Must be able to resolved a sufficient number of planets in their star's habitable zone AND obtain an R = 70 spectra at 760 nm (molecular oxygen line is key biomarker for life).

“Is there another Earth out there?”



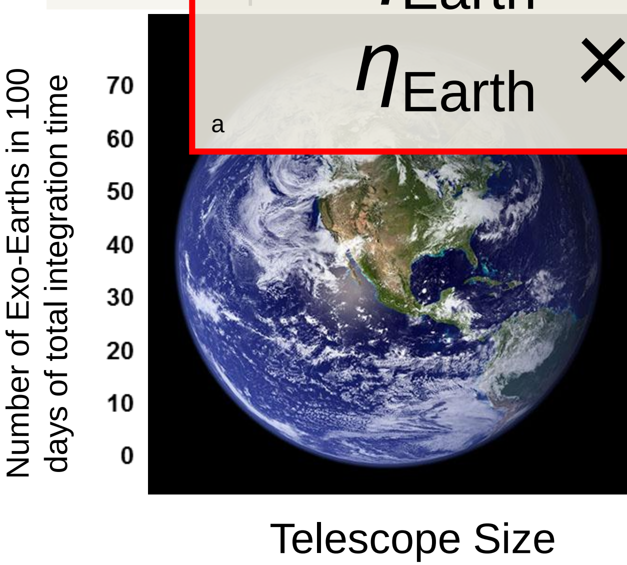
Fraction with terrestrial planets = η_{Earth}

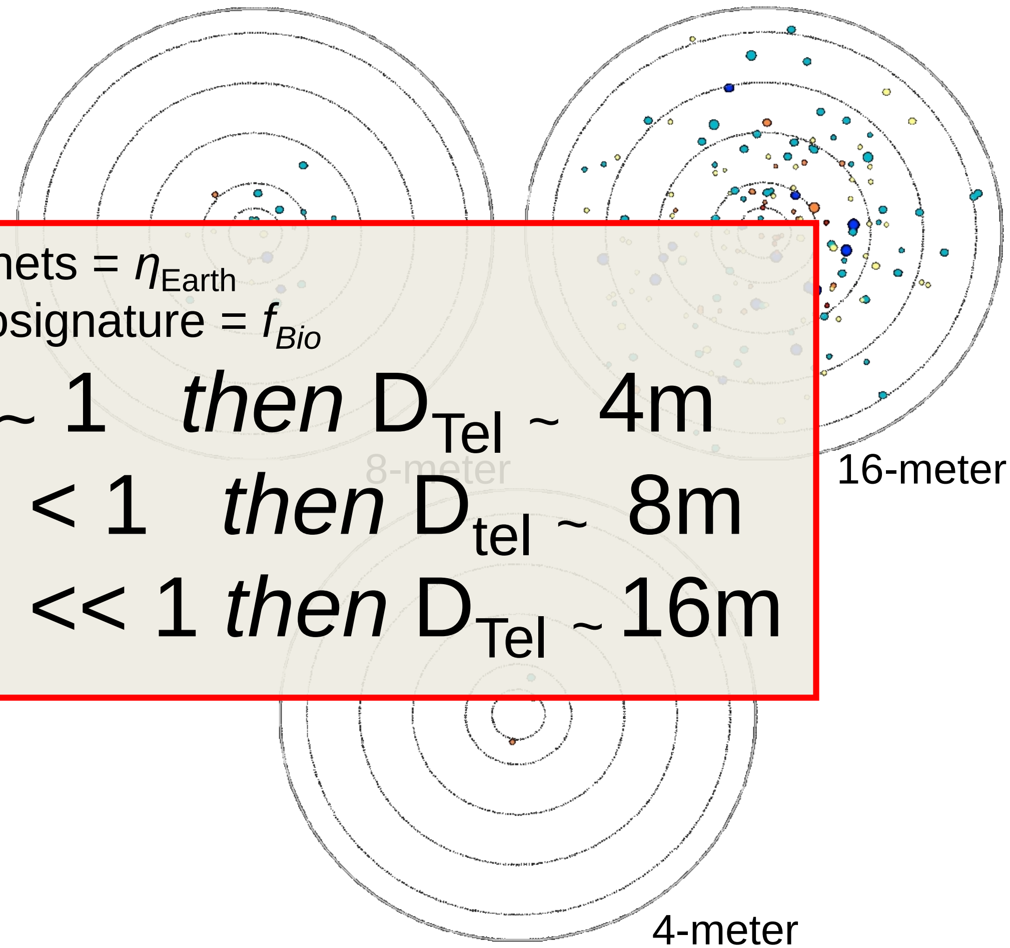
Fraction with detectable biosignature = f_{Bio}

If: $\eta_{Earth} \times f_{Bio} \sim 1$ *then* $D_{Tel} \sim$ 4m

$\eta_{Earth} \times f_{Bio} < 1$ *then* $D_{tel} \sim$ 8m

$\eta_{Earth} \times f_{Bio} << 1$ *then* $D_{Tel} \sim$ 16m





Above: Distribution of all FGK stars within 45 pc of the Sun where a R=70 spectrum of an Earth-twin could be acquired in <500 ksec *shown as a function of telescope aperture*. Assumes eta_Earth = 0.1 and IWA = 2λ/D.

Beyond HST: The Universe in High-Definition – UVOIR Space Astronomy in 2030, Marc Postman & Julianne Dalcanton, Science with HST IV Meeting, Rome, Italy, March 18, 2014

Importance of Spectral Resolution

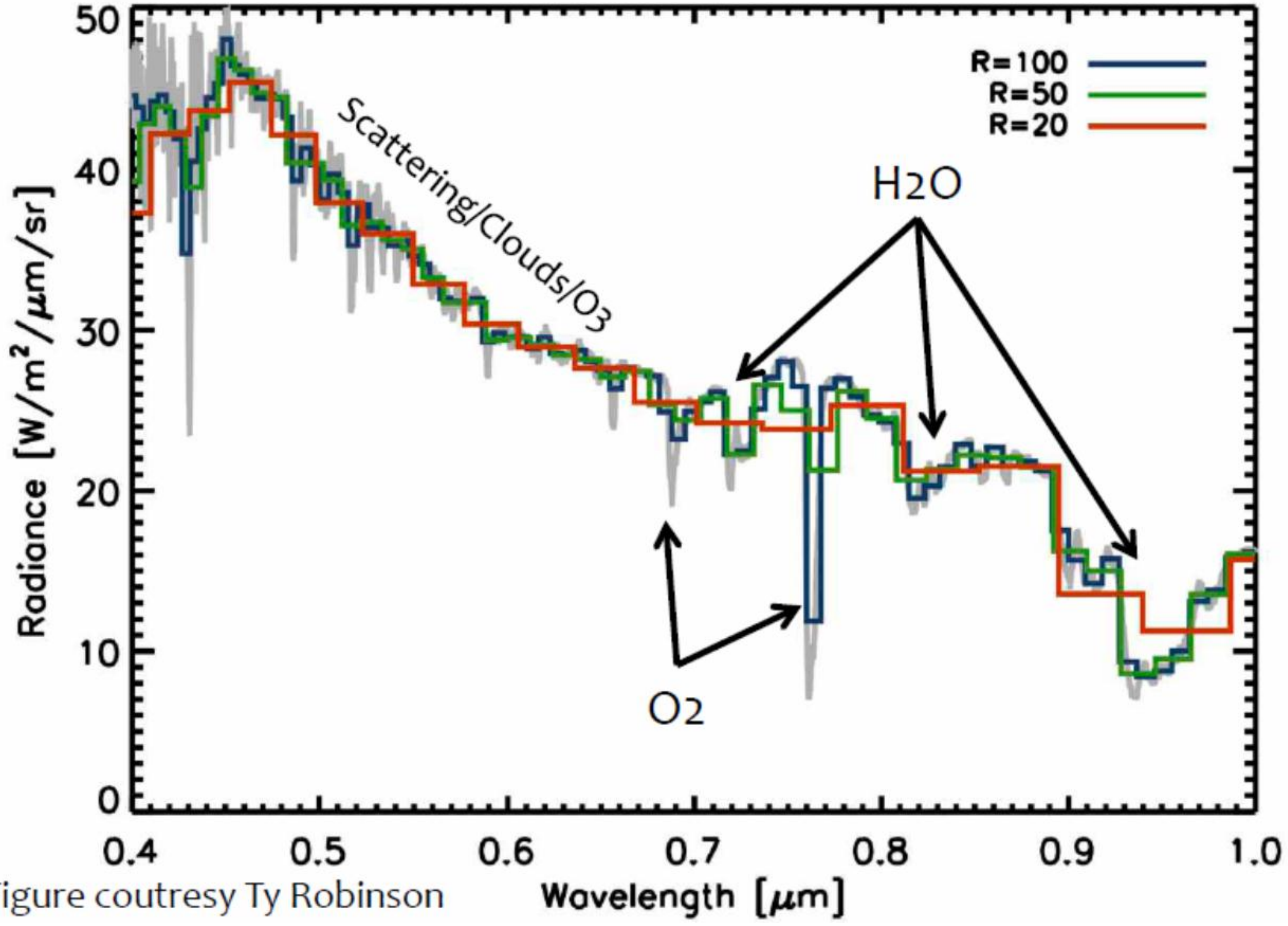
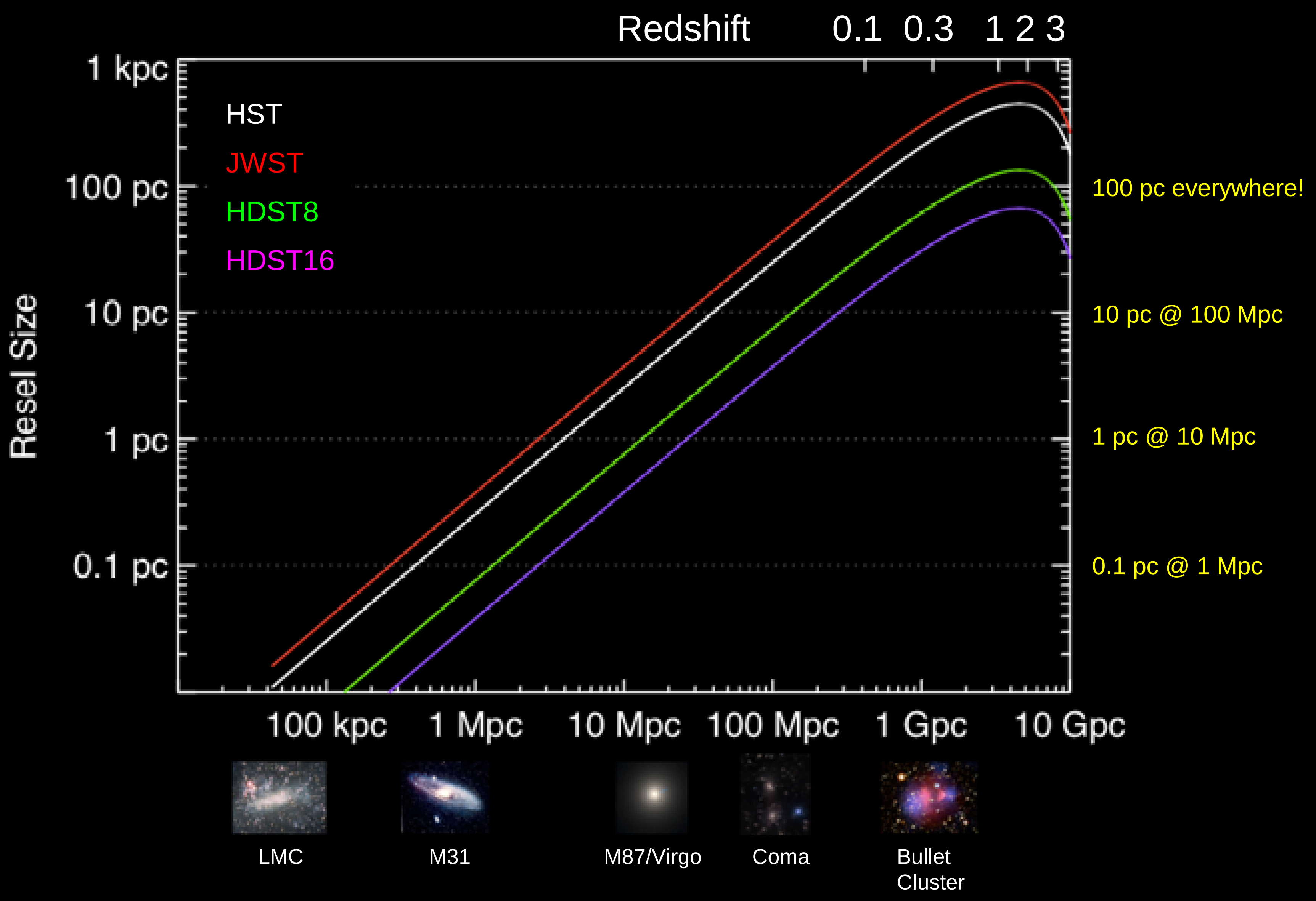


Figure coutresy Ty Robinson

Aperture Size Specification

HDST: Breaking Resolution Barriers



Beyond HST: The Universe in High-Definition – UVOIR Space Astronomy in 2030, Marc Postman & Julianne Dalcanton, Science with HST IV Meeting, Rome, Italy, March 18, 2014

Aperture Size

Based on Stark, Telescope Aperture Size is driven by:

- Number of Earth Candidates required for Characterization
- Characterization Spectral Resolution Signal to Noise
- Angular Resolution

Maximizing Exo-Earth Candidates

Per Stark et al., # of candidates depends on Aperture Diameter, IWA, Contrast, ΔMagnitude, Eta_Earth and Exo-Zodi

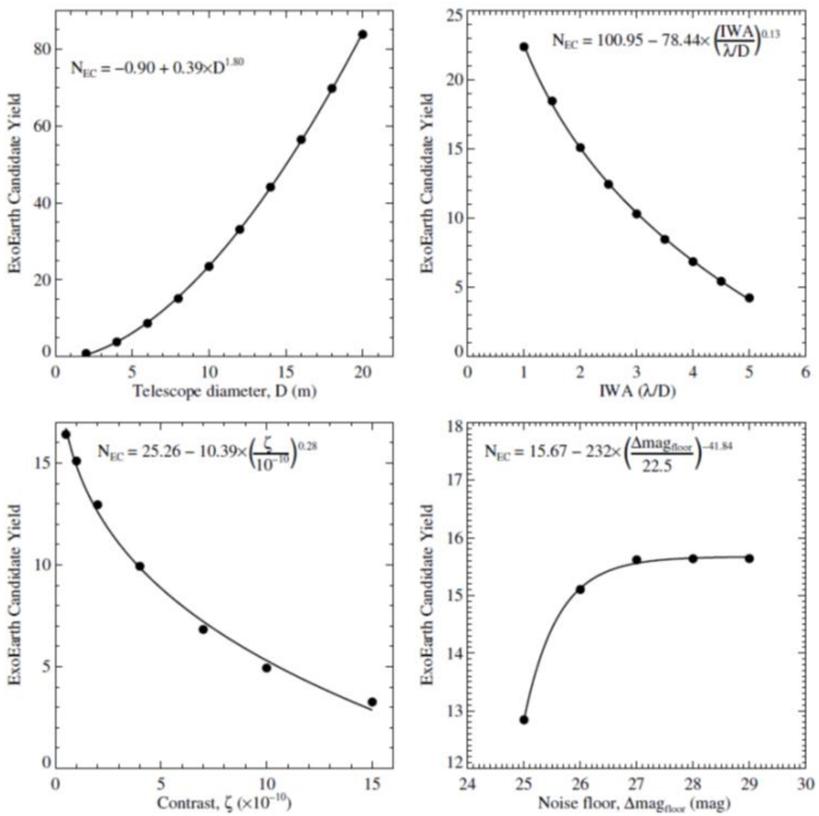


Fig. 6.— Variations in exoEarth candidate yield from our baseline mission as we vary on telescope/instrument parameter at a time. Calculated yields are shown as points and fit are shown as solid lines. ExoEarth candidate yield is roughly $\propto D^{1.8}$ and plateaus at larg values of systematic noise floor.

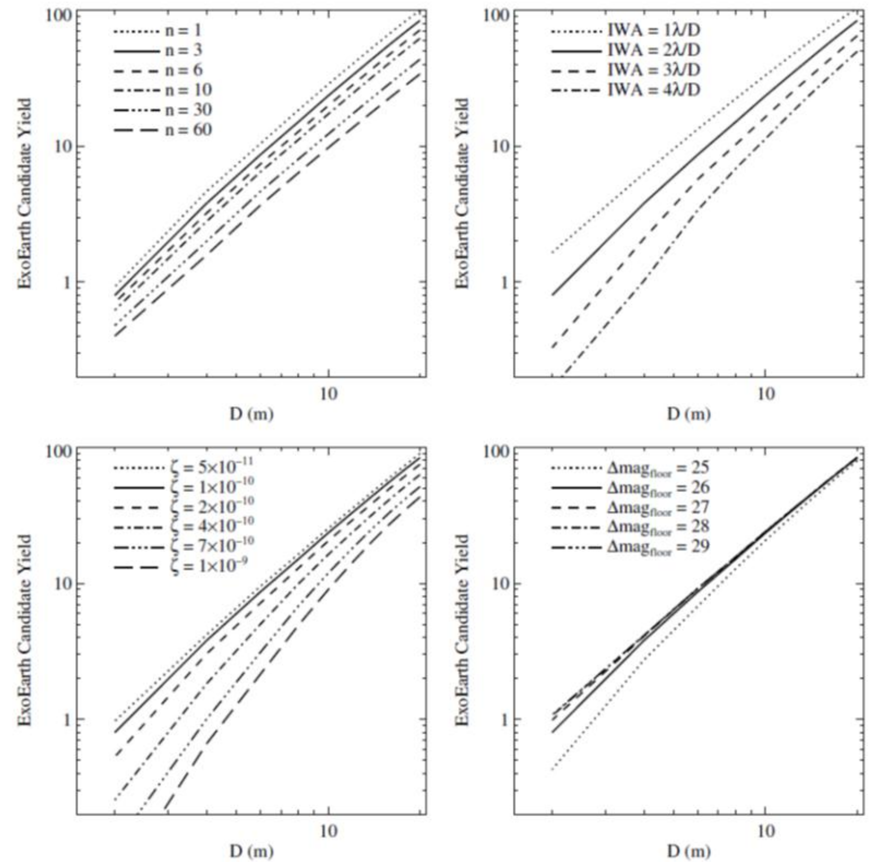


Fig. 8.— ExoEarth candidate yield for our baseline mission as a function of several mission parameters.

Maximizing the ExoEarth Candidate Yield from a Future Direct Imaging Mission, Stark, C. C., Roberge, A., Mandell, A., & Robinson, T. 2014, ApJ, submitted

Detect & Characterize versus Aperture Size

Number of Candidate Exo-Earths that can be Detected and Characterized to R = 70 with SNR = 10 in approx 1.5 years of mission observation time as a function of Aperture.

Aperture Diameter	IWA = 2 λ/D	IWA = 1 λ/D
4 meter	4	6
8 meter	15	22
12 meter	33	44
16 meter	56	77

Assuming:

Eta_Earth = 10% (increasing to 20% would double #)

Exo-Zodi = 3 (increasing to 30 would halve #)

Maximizing the ExoEarth Candidate Yield from a Future Direct Imaging Mission, Stark, C. C., Roberge, A., Mandell, A., & Robinson, T. 2014, ApJ, submitted

Aperture Size

Others researchers derive Telescope Aperture Size based on:

- Habitable Zone Resolution Requirement
- Signal to Noise Requirement
- η_{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 η_{EARTH}

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

Kepler indicates η_{EARTH} lies in the range [0.03,0.30]

Complete characterization requires multiple observations

Number of Earth-like Planets to Detect	η_{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 Recommendation

Based on the analysis, the Science Advisory Team recommends a space telescope in the range of 8 meters to 16 meters.

Telescope Diameter	Architecture
8 meter	Monolithic
8 meter	Segmented
> 8 meter	Segmented

An SLS with a 10-meter fairing can launch an 8-meter class monolithic mirror.

A segmented aperture is required for:

any launch vehicle with a 5 m fairing (EELV or SLS Block 1)

any telescope aperture larger than 8-meters

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)	Δt 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 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

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 (λ):

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

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

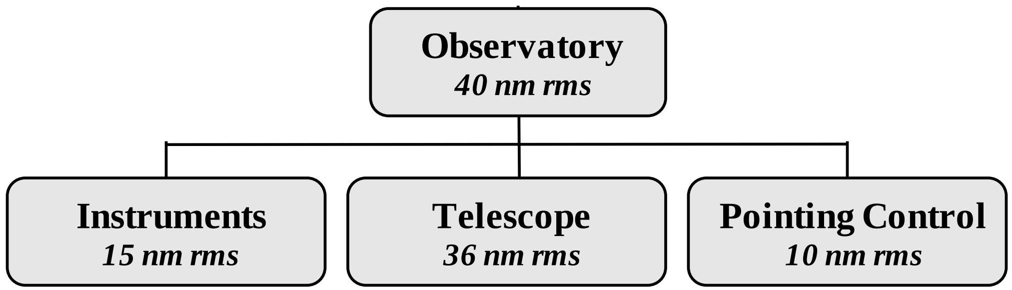
$$\text{WFE} = (\lambda/2\pi) * \text{sqrt}(-\ln S)$$

Diffraction limited performance requires S ~ 0.80.

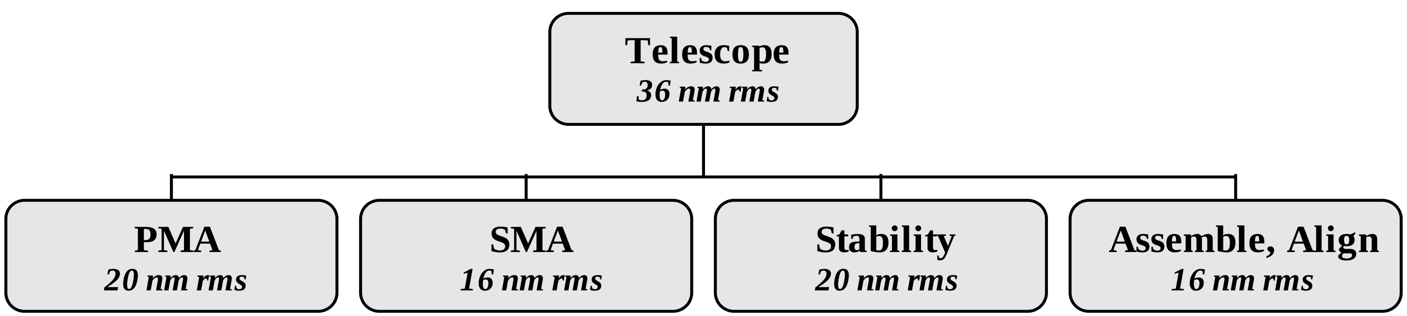
At λ = 500 nm, this <u>requires total system WFE of ~38 nm</u>.

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:



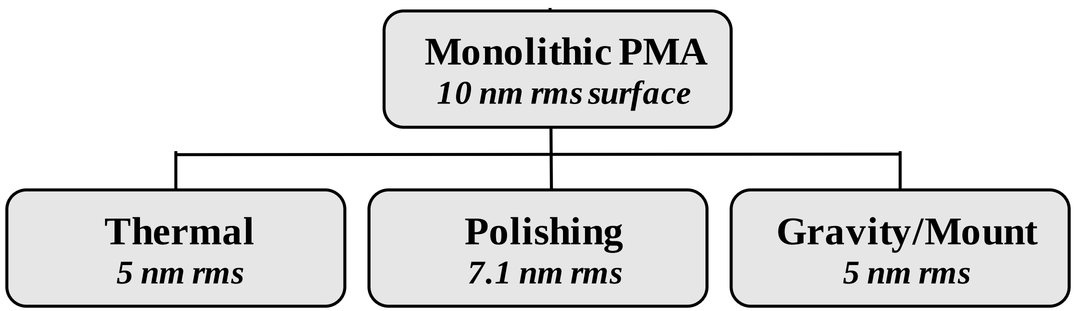
Then flowing Telescope Requirements to major Sub-Systems



Primary Mirror Total Surface Figure Requirement

Then flowing major Sub-Systems Requirements into Manufacturing Processes

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

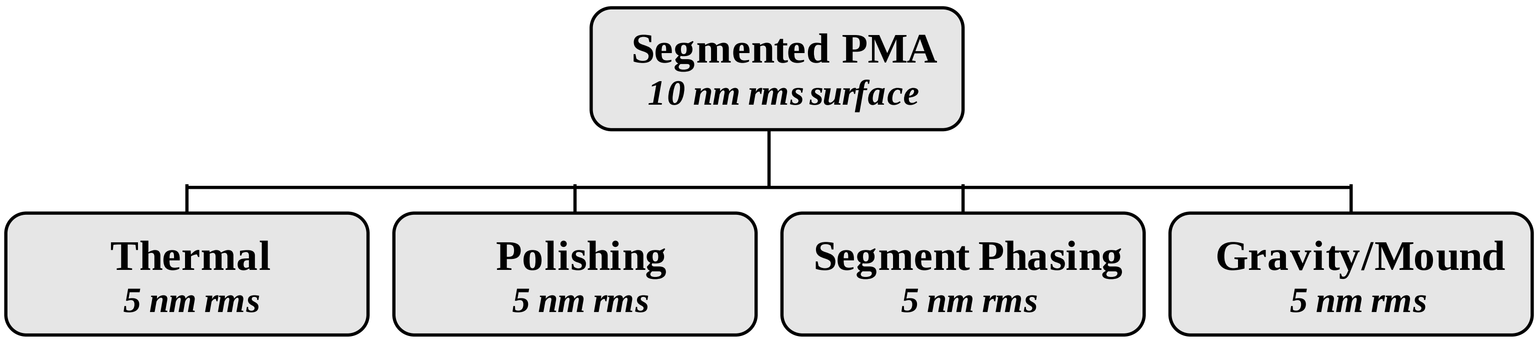


Note: Divide by 2 to convert from Wavefront to Surface Error

Primary Mirror Total Surface Figure Requirement

If the PM is segmented, it still must have < 10 nm rms surface.

Segmenting increases complexity and redistributes errors.



Notes:

Polishing specification is for individual segments.

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

Primary Mirror Total Surface Figure Requirement

Regardless whether monolithic or segmented,

PM must have < 8 nm rms surface figure error (SFE)

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

Next question is how to partition the PM SFE error.

Wavefront Error Spatial Frequency Allocation

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, Mid errors as changing the shape of the core, and High errors scattering light.

Mid & High errors are important for Exoplanet Science.

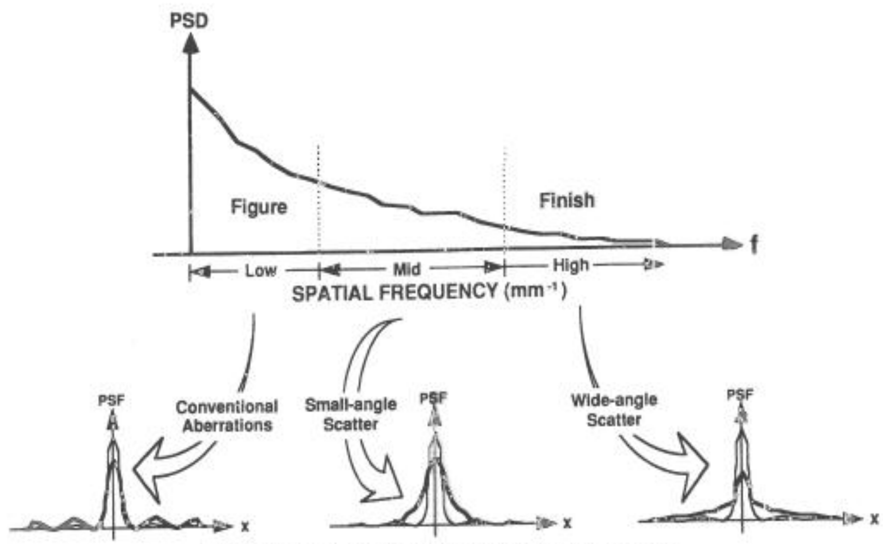


Fig. 11. Effect on image quality differs for each spatial-frequency regime.

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 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’.

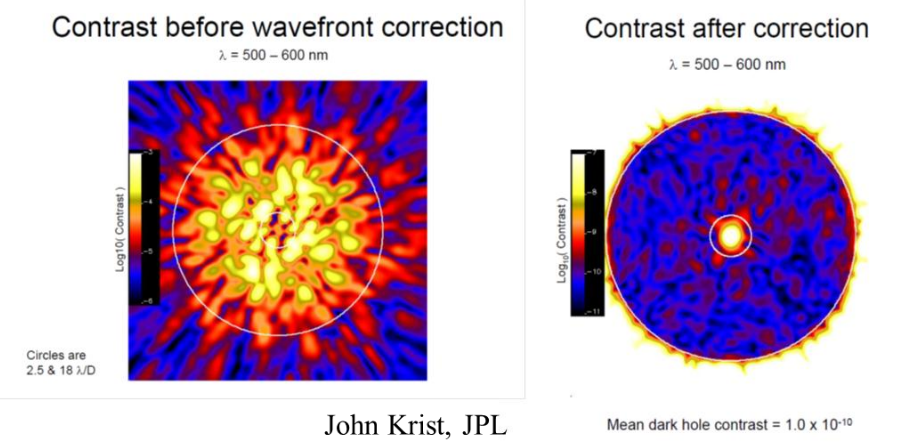
For exoplanet, the spatial band is from the inner working angle (IWA) to approximately 3X the outer working angle (OWA).

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.

Spatial Frequency vs Exoplant Science

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



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.

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 the Zernike Polynomial Set defines Figure/Low. But some say it is the first 8 terms and other say it is 36 terms.
- Some assert that low-order should be those errors which can be controlled via deformable mirrors

Traditionally, low-order errors are those which can be controlled during the fabrication process via passive (large) tools

And, mid-spatial are controlled via small (computerized) tools.

We arbitrarily choose 4 cycles.

Mid/High Spatial Frequency Specification

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

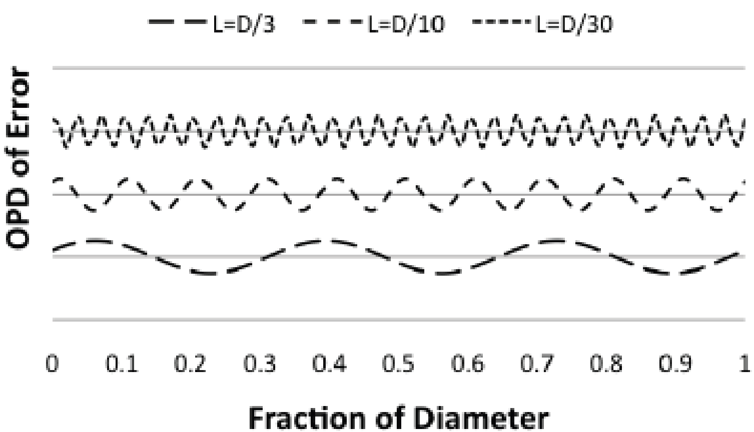
Harvey would define it as the spatial frequency at which energy starts being distributed broadly across the image.

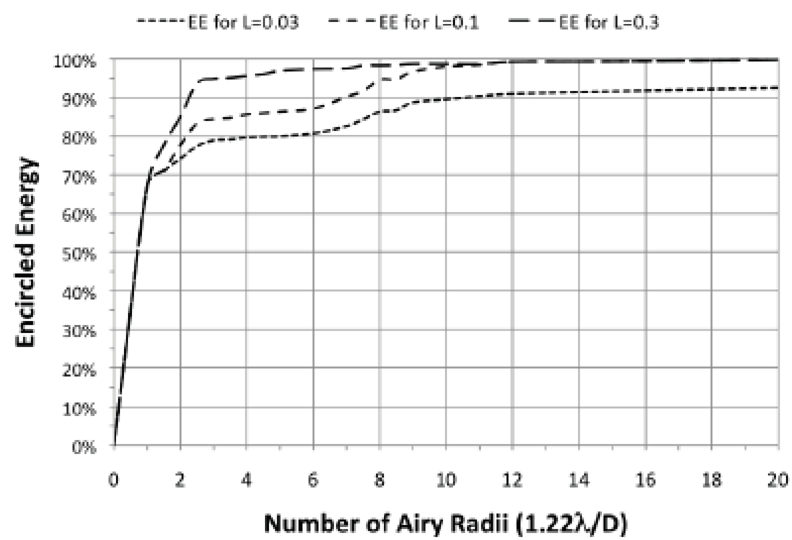
Noll ("Effect ofMid- and High-Spatial Frequencies on Optical Performance", Optical Engineering, Vol. 18, No. 2, pp.137, 1979) defines it as the spatial frequency which scatters energy beyond 16 Airy Rings.

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

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.

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

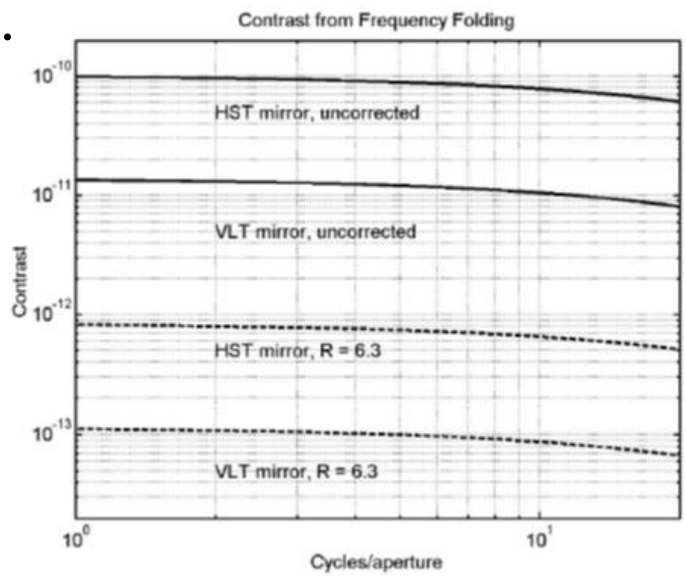


Figure 7. Contrast from frequency folding for spatial frequencies above 48 cycles per aperture, for an 8-m VLT primary and the 2.4 m HST primary. The uncompensated effect is above the required level of 10^{-12} for both mirrors. The sequential DM configuration provides about ~100x reduction of the contrast 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

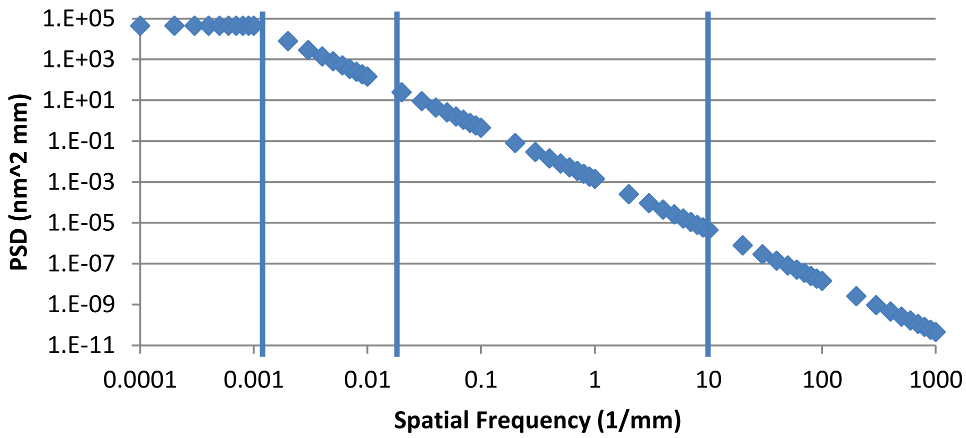
PM Manufacturing Specification

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

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 (1 to 4 cycles per diameter)	5.2 nm rms	5.5 nm rms	5.8 nm rms
Mid Spatial (4 to 60 cycles per diameter)	5.8 nm rms	5.6 nm rms	5.4 nm rms
High Spatial (60 cycles per diameter to 10 mm)	1.4 nm rms	1.0 nm rms	0.7 nm rms
Roughness (10 mm to < 0.001 mm)	0.6 nm rms	0.3 nm rms	0.2 nm rms

Ultraviolet Capability vs Mid-Spatial Error

UV science also requires a compact PSF. This places constraints on Telescope Mid-Spatial Frequency error.

UV Science Applications are 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

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

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

Wavefront Error Stability Specification

Primary Mirror Surface Figure Error Stability

Independent of Architecture (Monolithic or Segmented), any drift in WFE may result in speckles which can produce a false exoplanet measurement or mask a true signal.

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.

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

REQUIREMENT: ΔWFE < 10 picometers rms

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

Wavefront Stability Specification
Contrast vs. Number of Segments for 1nm RMS WFE

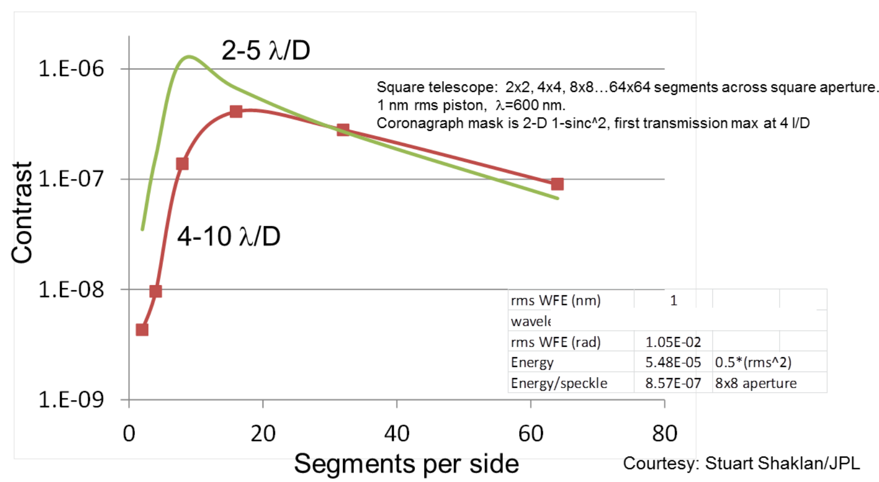
Per Shaklan:

- For any given Inner Working Angle (IWA) in units of λ/D, ‘best’ contrast is obtained for the fewest # of segments or very many segments.

- The smaller the IWA, the smaller the random segment to segment rms WFE stability needed

    IWA of 2-5 λ/D requires Piston of 0.1 to 1 pm rms

    IWA of 4-10 λ/D requires Piston of 1 to 10 pm rms



Monolithic Aperture

Wavefront Stability

For a monolithic aperture primary mirror, the primary source of wavefront stability error will be thermal drift and primary mirror bending modes.

Segmented Aperture

Segmented Aperture

Segmented apertures have many 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 segmentation schemes, ranging from hexagonal segments to pie segments to large circular mirrors.

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:

PSF_{seg} size $\sim \lambda / d_{seg}$

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

and Phased Telescope has:

PSF_{tel} size $\sim \lambda / D_{tel}$

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

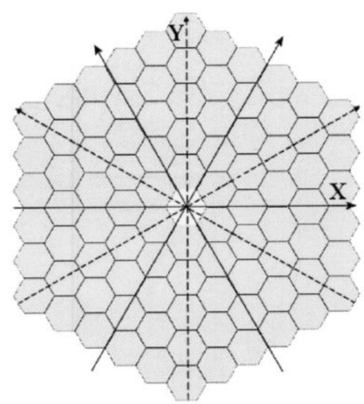
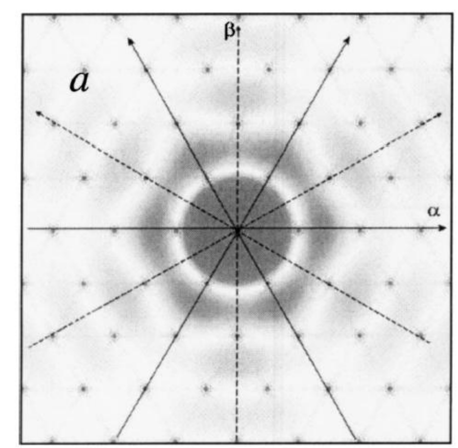


Fig. 1. Segmented mirror with segmentation order $M = 5$ consisting of $N = 90$ segments. Solid and dashed arrows illustrate the double $\pi/3$ symmetry of the system.



Yaitskova, 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 (PSF)

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

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

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

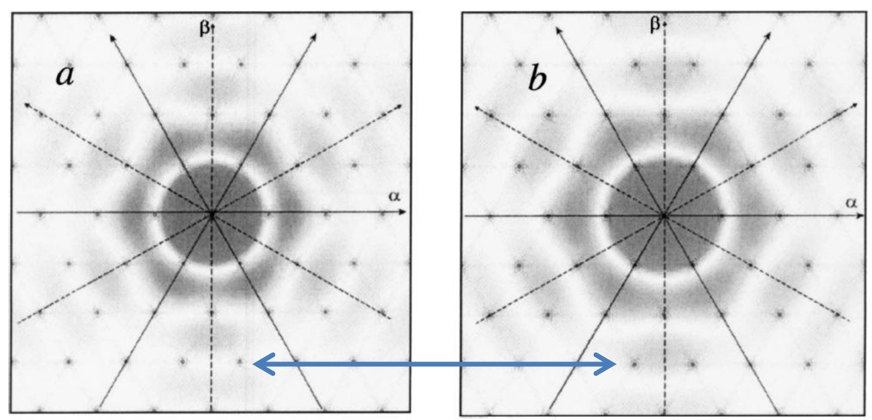


Fig. 2. a, Grid factor (regular spots) and the segment PSF_s for a perfect telescope without gaps. Except for the central peak, all peaks of the grid factor fall into zeros of the segment PSF_s. Solid and dashed arrows illustrate the same double $\pi/3$ symmetry as observed in the pupil plane (Fig. 1). b, The same, but with gaps between segments (relative gap size ω=0.1). Higher-order peaks are no longer coincident with 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.

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’.

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

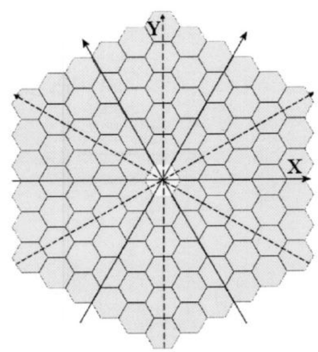
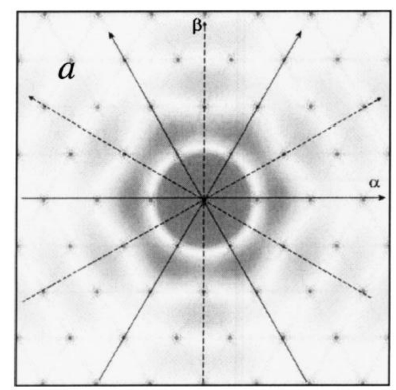


Fig. 1. Segmented mirror with segmentation order $M = 5$ consisting of $N = 90$ segments. Solid and dashed arrows illustrate the double $\pi/3$ symmetry of the system.



Yaitskova, 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.

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

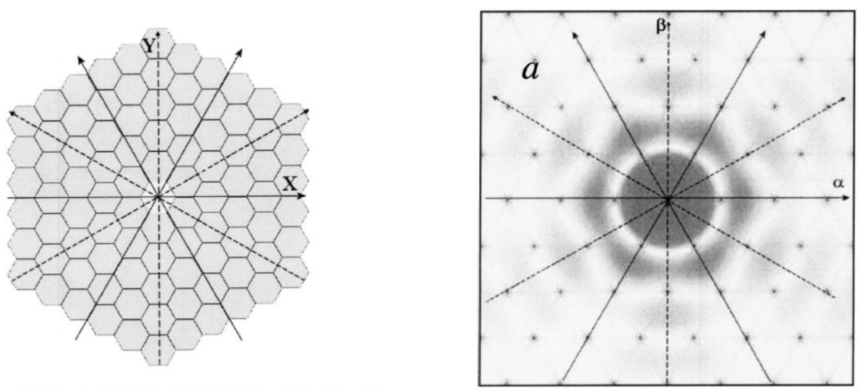


Fig. 1. Segmented mirror with segmentation order $M = 5$ consisting of $N = 90$ segments. Solid and dashed arrows illustrate the double $\pi/3$ symmetry of the system.

Yaitskova, 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)

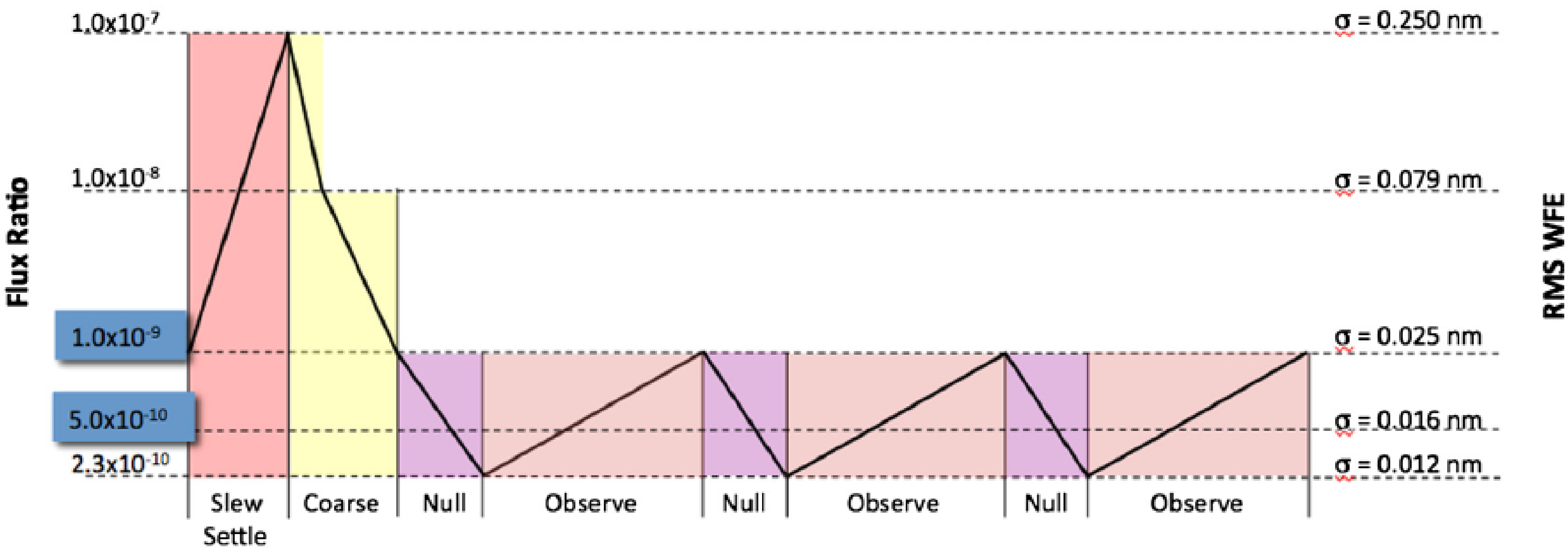
Telescope diameter (D) & λ	**Number of Segments (N)**	**Contrast**	**Target**	**Cophasing requirement**	**Stability timescale**
4 m, 0.55 μm	10	1e-10	$m_V=8$	2.8 pm	22 mn
8 m, 0.55 μm	10	1e-10	$m_V=8$	2.8 pm	5.4 mn
8 m, 0.55 μm	100	1e-10	$m_V=8$	8.7 pm	5.4 mn

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

Primary Mirror Surface Figure Error Stability

If the telescope system cannot be designed near zero stability, then the WFE must be actively controlled.

Assuming that DMs can perfectly 'correct' WFE error once every 'control period', then the Telescope must have a WFE change less than the required 'few' picometers between corrections.



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

Controllability Period

Key issue is how long does it take to sense and correct the temporal wavefront error.

Constraining factors include:

- Aperture Diameter of Telescope
- ‘Brightness’ of Star used to sense WFE
- Spectral Bandwidth of Sensing
- Spatial Frequency Degrees of Freedom being Sensed
- Wavefront Control ‘Overhead’ and ‘Efficacy’

Another factor is the difference between systematic, harmonic and random temporal WFE.

Primary Mirror SFE Stability Specification

Telescope and PM must be stable < 10 pm for periods longer 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.

REQUIREMENT: ΔWFE < 10 pico-meters per 10 min

Controllability Period

Krist (Private Communication, 2013): wavefront changes of the first 11 Zernikes can be measured with accuracy of 5 – 8 pm rms 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 λ= 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.

Wavefront Stability

There are 2 primary source of Temporal Wavefront Error:

Thermal Environment

Mechanical Environment

Wavefront Stability - Thermal

Changes in orientation relative to the Sun changes the system thermal load. These changes can increase (or decrease) the average temperature and introduce thermal gradients.

In response to the 'steady-state' temperature change, variations in the Coefficient of Thermal Expansion (CTE) distribution cause static wavefront errors.

Stability errors depend on the temporal response of the mirror system to the thermal change.

Requirement is for WFE to change by < 10 pm per 10 minutes

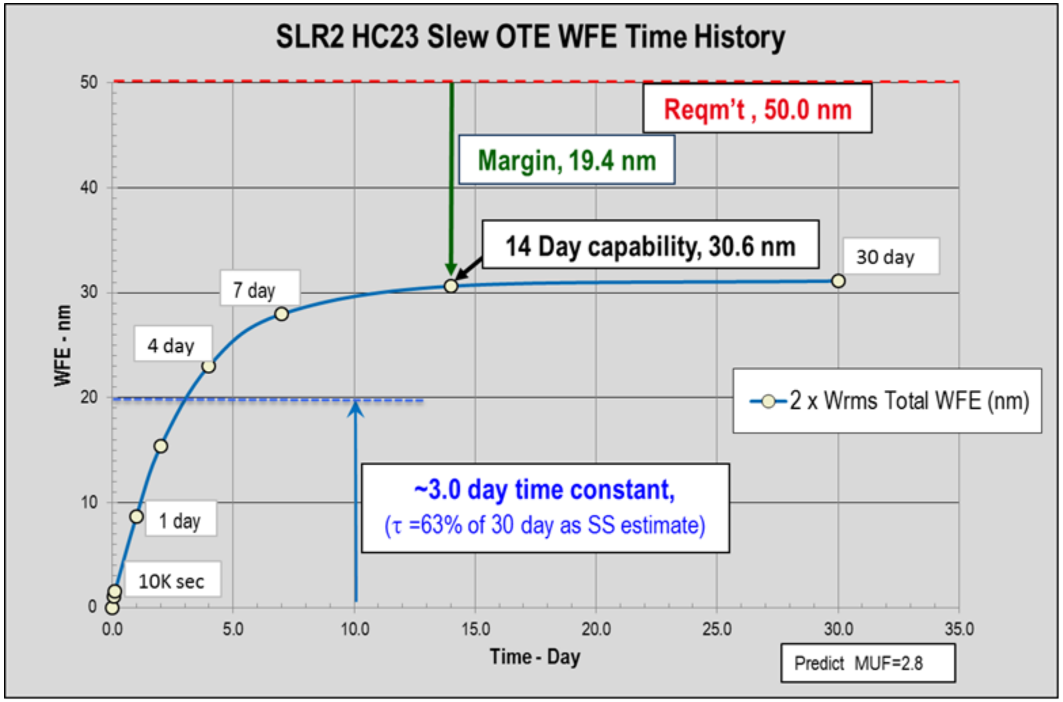
For a low CTE material (< 10 ppb) such as ULE or Zerodur, this requires a thermal drift of < 0.001K per 10 minutes.

For a high CTE material (< 10 ppm) such as SiC, this requires a thermal drive of < 0.000001K per 10 minutes.

Wavefront Stability - Thermal

For example, (while not designed for a UVOIR Exoplanet Science Mission) JWST experiences a worst-case thermal slew of 0.22K which results in a 31 nm rms WFE response.

It takes 14 days to 'passively' achieve < 10 pm per 10 min



13-JWST-0207 F, 2013

Wavefront Stability - Mechanical

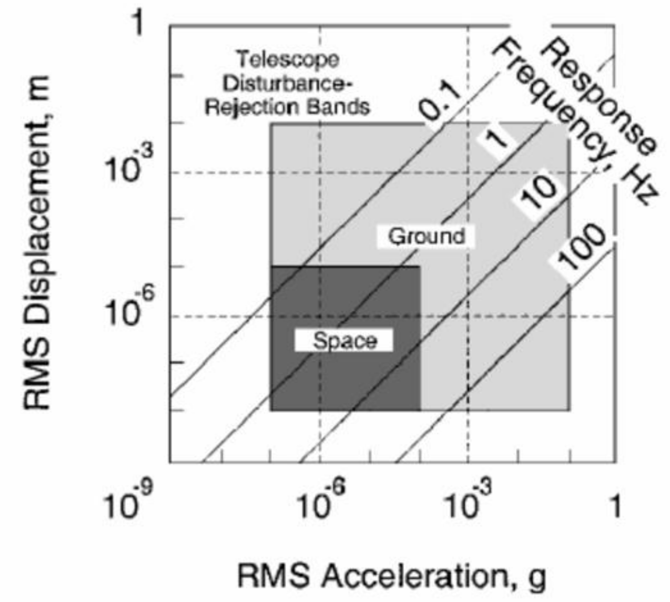
Mechanical disturbances

- from spacecraft such as reaction wheels or mechanisms, or
- from the solar wind

can excite modal vibration modes.

Per Lake, rms wavefront error is proportional to rms magnitude of the applied inertial acceleration (a_{rms}) divided by square of the structure's first mode frequency (f_0)

$$WFE_{rms} \sim a_{rms}/f_0^2$$



To achieve < 10 pm rms requires

First Mode Frequency	RMS Acceleration
10 HZ	< 10^-9 g
100 HZ	< 10^-7 g

Lake, Peterson and Levine, "Rationale for defining Structural Requirements for Large Space Telescopes", AIAA Journal of Spacecraft and Rockets, Vol. 39, No. 5, 2002.

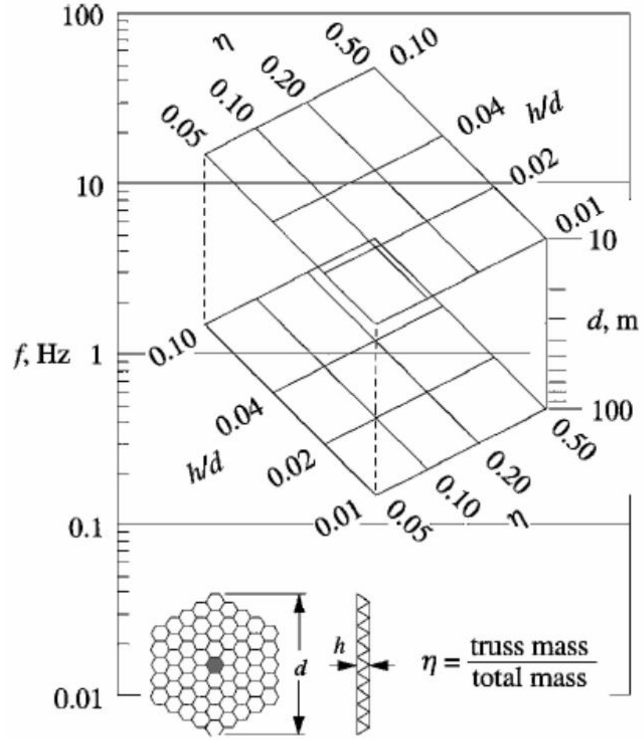
Wavefront Stability - Mechanical

One way to gain mechanical wavefront stability is to make the system stiffer. A 2X increase has a 4X benefit.

For a Truss Mirror support

where Truss Mass = PM Substrate Mass.

Diameter	Depth	f_0
10 m	0.2 m	10 Hz
10 m	2.0 m	100 Hz
20 m	0.4 m	10 Hz
20 m	4.0 m	100 Hz



Note: Adding Stiffness requires MASS.

Another way is to increase isolation.

A final way is active control.

Lake, Peterson and Levine, "Rationale for defining Structural Requirements for Large Space Telescopes", AIAA Journal of Spacecraft and Rockets, Vol. 39, No. 5, 2002.

Wavefront Stability - Mechanical

For example, (while not designed for a UVOIR Exoplanet Science Mission) JWST has several mechanical modes:

- PMA Structure has a ~ 40 nm rms 'wing-flap' mode at ~15 HZ
- Individual PMSAs have a ~ 20 nm rms 'rocking' mode at ~ 40 Hz

Because of the frequency of these modes, to perform Exoplanet Science, their amplitude needs to be reduced to < 10 pm rms.

JWST engineers (private conversation) believe that they could reduce both of these modes to the required < 10 pm rms via the combination of 3 design elements:

1. Operating at 280K instead of < 50K adds dampening
2. Returning Structural Mass removed for 50K operation
3. 120 db of Active Vibration Isolation

Transfer Functions

AMTD is working to define two design tools (similar to MTF):

- Thermal Modulation Transfer Function (T-MTF)
- Dynamic Modulation Transfer Function (D-MTF)

T-MTF is the RMS WFE response of a mirror system to a sinusoidal amplitude thermal variation of a given period.

D-MTF is the RMS WFE response of a mirror system to a sinusoidal amplitude mechanical vibration of a given period.

These tools allow us to place constraints on the operating environment for the mirror system to achieve the dynamic WFE requirement.

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 2 cases:

- 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.

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 Vary < 5% across 4 arcmin FOV
EEF stability	<2%	JWST
Telescope WFE stability	< 10 pm per 600 sec	
PM rms surface error	5 - 10 nm	
Pointing stability (jitter)	~2 mas	scaled from HST 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 Vary < 5% across 4 arcmin FOV
EEF stability	<2%	JWST
WFE stability	< 10 pm per 600 sec	
Segment gap stability	TBD	Soummer, McIntosh 2013
Number and Size of Segments	TBD (1 – 2m, 36 max)	Soummer 2013
Segment edge roll-off stability	TBD	Sivaramakrishnan 2013
Segment co-phasing stability	4 to 6 pm per 600 secs	Depends on number of segments
Pointing stability (jitter)	~2 mas	scaled from HST 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 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 (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

Line of Sight Pointing Stability Specification:

Telescope Assembly

Telescope Pointing Stability

Pointing is a telescope requirement which depends on stiffness of the structure and primary mirror.

For General Astrophysics, Pointing Stability is usually:

< 1/8th PSF FWHM per exposure

Alternatively, Jitter can be allocated to an equivalent rms wavefront error. For our study, we allocate 10 nm rms

Diameter	PSF	PSF/10	$\sigma_{eq\ WFE}$
4-meter	32 mas	3.2 mas	±1.5 mas
8-meter	16 mas	1.6 mas	±0.75 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.

Telescope Pointing Stability

Pointing Jitter smears PSF and reduces system Strehl ratio.

Total system Strehl ratio is a product of two Strehl ratios:

$$S_{\text{total}} = S_{(\text{wavefront error})} * S_{(\text{line of sight pointing jitter})}$$

where:

$$S_{WFE} = e^{-\left(2\pi\frac{\sigma_{WFE}}{\lambda}\right)^2}$$

$$S_{LOS} = \left[1 + \frac{1}{2}\left(\pi\sigma_{LOS}\frac{D}{\lambda}\right)^2\right]^{-1}$$

Equating the two Strehls, one can solve for the allowed rms jitter based on an rms wavefront error budget allocation. :

$$\sigma_{LOS} = \frac{\sqrt{2}}{\pi}\frac{\lambda}{D}\sqrt{\frac{1}{e^{-\left(2\pi\frac{\sigma_{WFE}}{\lambda}\right)^2}} - 1}$$

Gary Mosier, Private Communication, 2013.

Telescope Pointing Stability

$$\sigma_{LOS} = \frac{\sqrt{2}}{\pi}\frac{\lambda}{D}\sqrt{\frac{1}{e^{-\left(2\pi\frac{\sigma_{WFE}}{\lambda}\right)^2}} - 1}$$

$$\sigma_{Eq\,WFE} = \frac{\lambda}{2\pi}\sqrt{\ln\left[1 + \frac{1}{2}\left(\pi\sigma_{LOS}\frac{D}{\lambda}\right)^2\right]^2}$$

Gary Mosier, Private Communication, 2013.

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

Space Launch System (SLS)

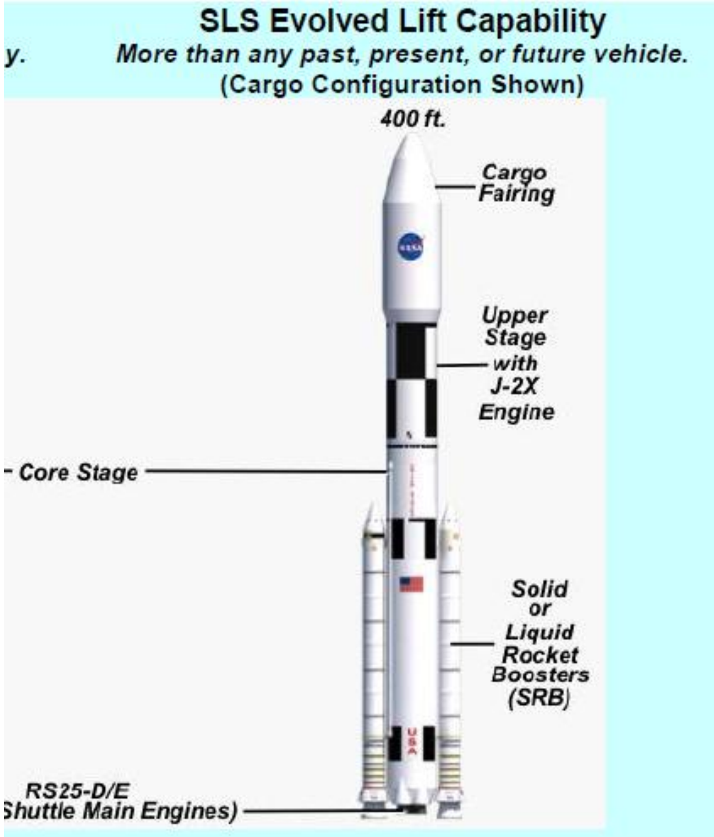
Space Launch System (SLS) Cargo Launch Vehicle specifications

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.

Areal Density

Independent of Architecture, Areal Density is constrained by launch vehicle up-mass capacity (single launch only).

Launch Vehicle	SE-L2 Payload Mass [kg]	Primary Mirror Assembly [kg]	Aperture [m]	Areal Density [kg/m2]
JWST	6600	1600	6.5	64
Delta IVH	10,000	2500	8	50
			12	23
			14	16
			16	12
Falcon 9H	15,000	5000	8	100
			12	45
			14	32
			16	25
SLS Block 1	30,000	15,000	8	300
			12	135
			14	100
			16	75
SLS Block 2	60,000	30,000	8	600
			12	270
			14	200
			16	150

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.

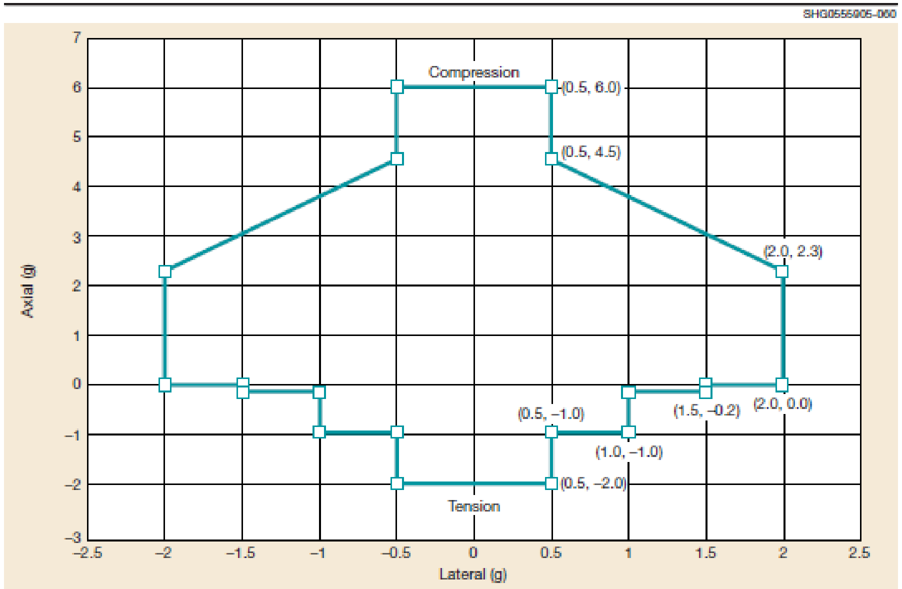


Figure 4-30. Delta IV Heavy Design Load Factors

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

axial frequency = 30 Hz; lateral frequency = 8 Hz

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.

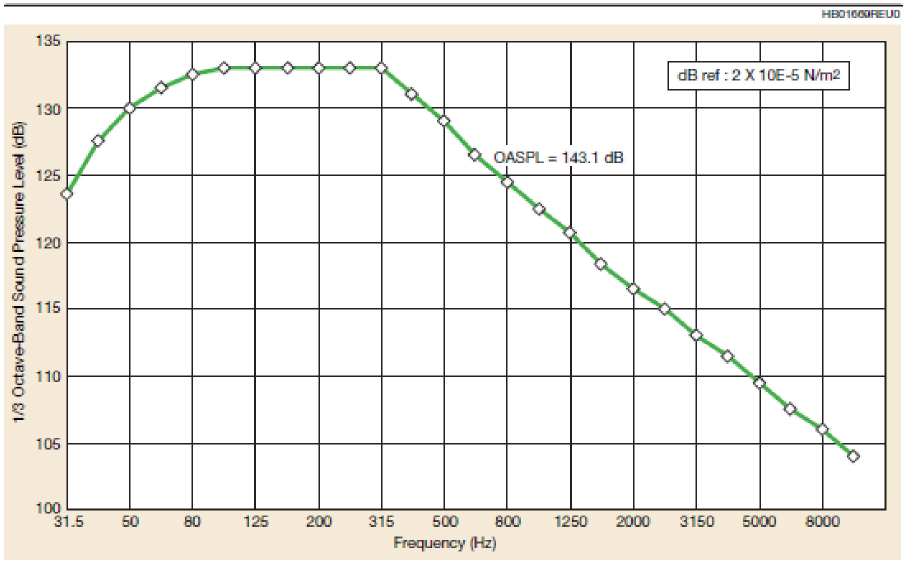


Figure 4-33. Delta IV Heavy (5-m Composite Fairing) Internal Payload Acoustics Typical 95th Percentile, 50% Confidence Predictions, 60% Fill Effect Included

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.

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