Engineering Specifications derived from Science Requirements

for the
Advanced Mirror Technology Development (AMTD) Project

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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.

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.

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

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 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.

Aperture Size Specification

Aperture Size

Telescope Aperture Size is driven by:

- 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 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 (λ):

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

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

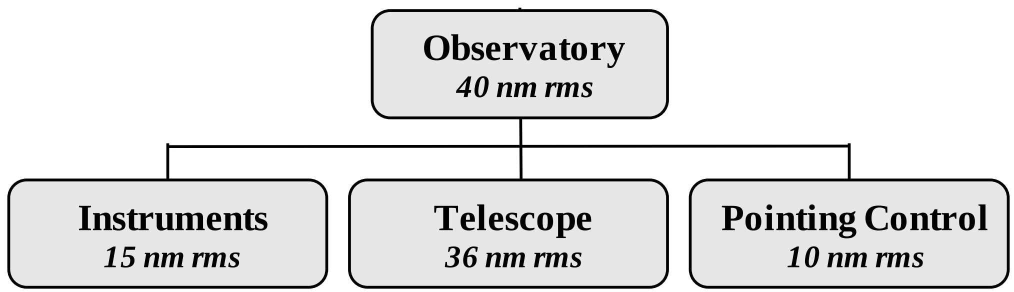
$$\text{WFE} = (\lambda/2\pi) * \text{sqrt}(-\ln S)$$

Diffraction limited performance requires S ~ 0.80.

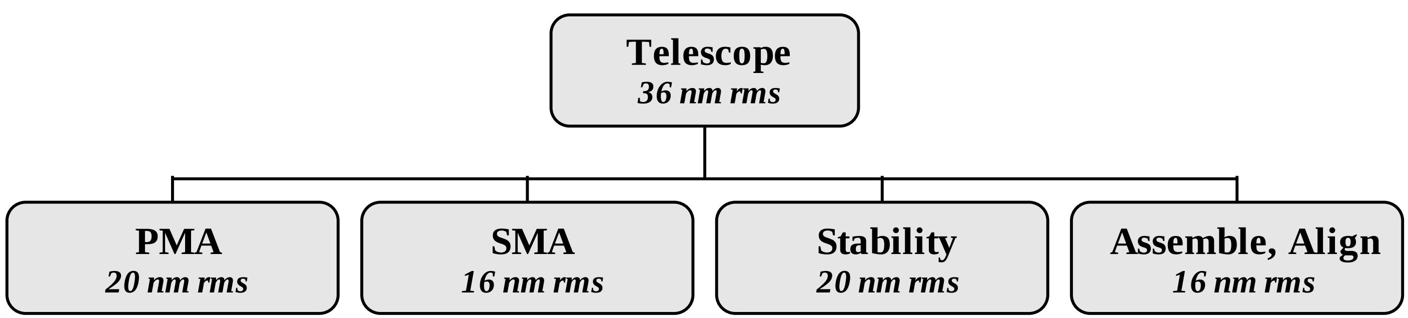
At λ = 500 nm, this <u>requires total system WFE of ~38 nm</u>.

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



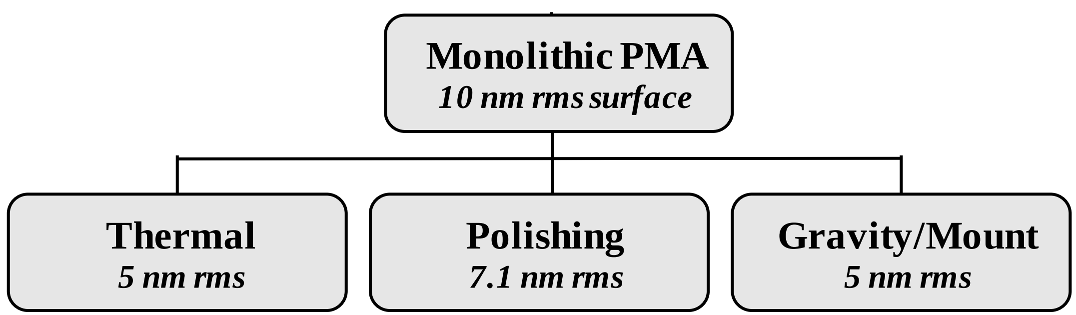
Primary Mirror Total Surface Figure Requirement

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.



Next question is how to partition the PM SFE error.

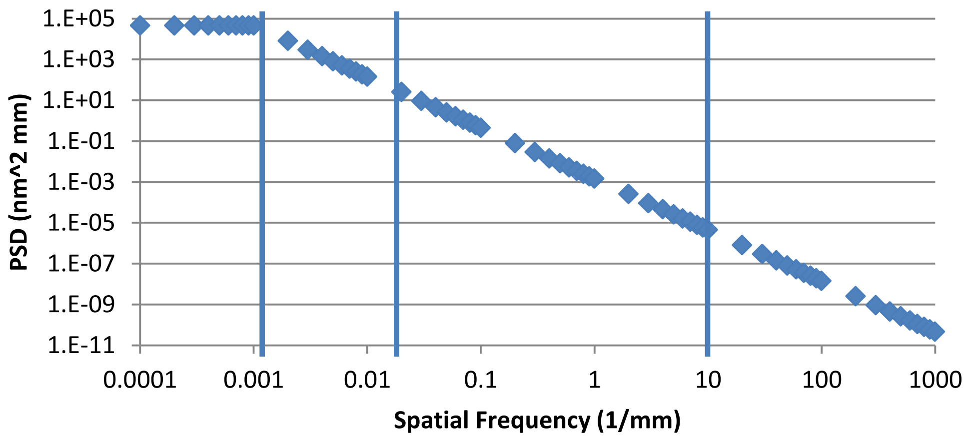
PM Manufacturing Specification

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

Mid & High errors are important for Exoplanet Science.

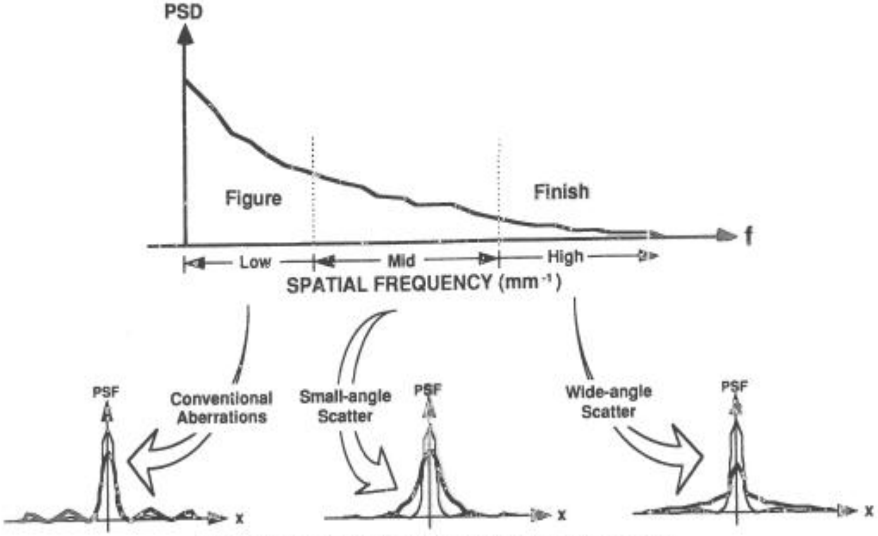
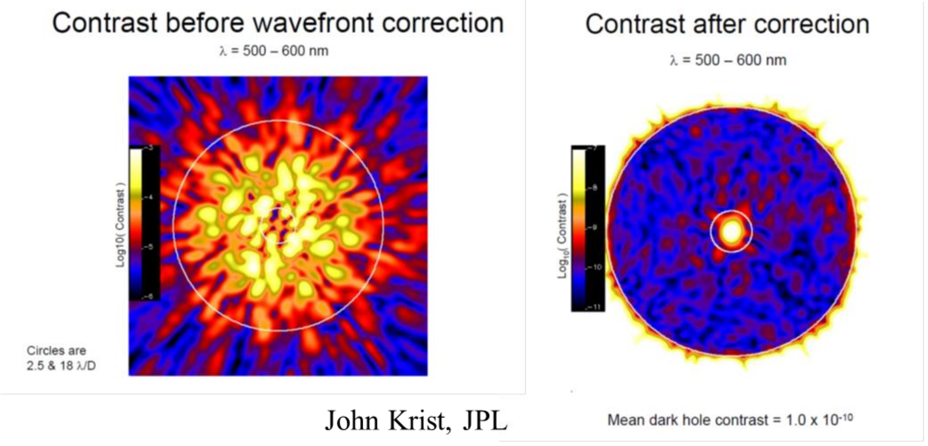


Fig. 11. Effect on image quality differs for each spatial-frequency regime.

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 Exoplant Science

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



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

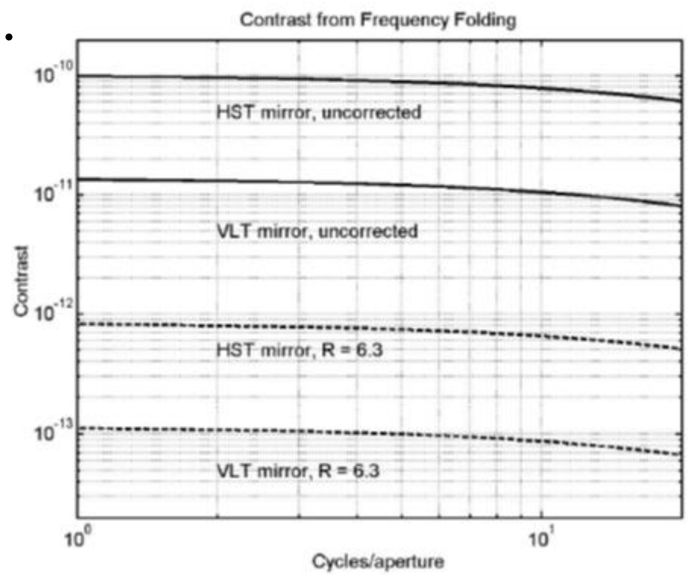


Figure 7. Contrast from frequency folding for spatial frequencies above 48 cycles per aperture, for an 8-m VLT primary and the 2.4 m HST primary. The uncompensated effect is above the required level of 10^{-12} for both mirrors. The sequential DM configuration provides about ~100x reduction of the contrast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

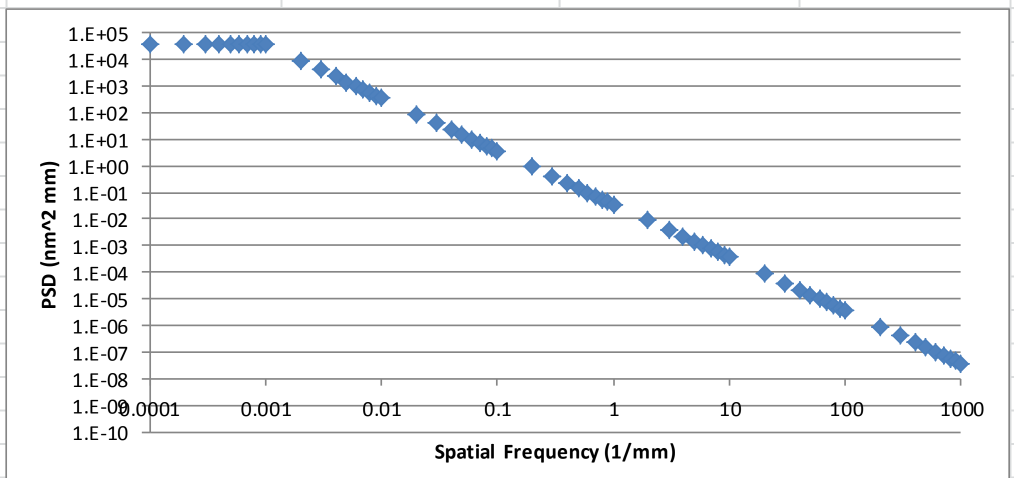
Theoretically, a 64 x 64 DM can correct spatial frequencies up to 32 cycles per diameter (N/2), therefore, the maximum mid-spatial frequency of interest is ~ 90 cycles.

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

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 (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

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

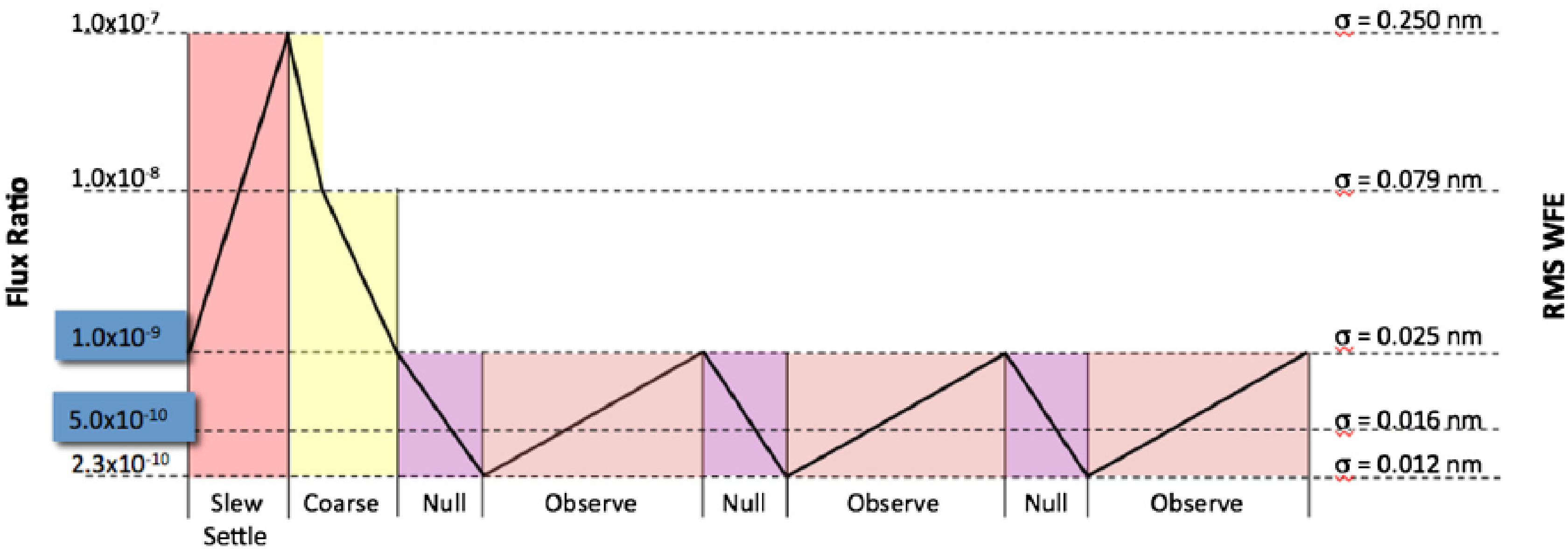
Krist, Trauger, Unwin and Traub, "End-to-end coronagraphic modeling including a low-order wavefront sensor", SPIE Vol. 8422, 844253, 2012; doi: 10.1117/12.927143

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 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.

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.

Segmented Aperture

Primary Mirror Total Surface Figure Error

Regardless of whether PM is monolithic or segmented, it must have < 10 nm rms surface.

Segmenting increases complexity and redistributes errors.

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.

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

Monolithic vs 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

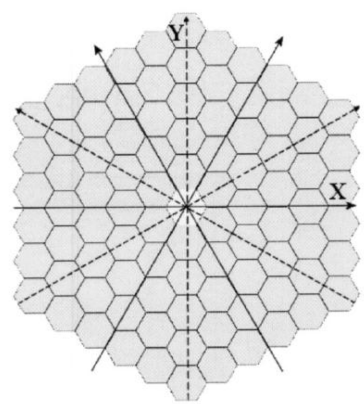
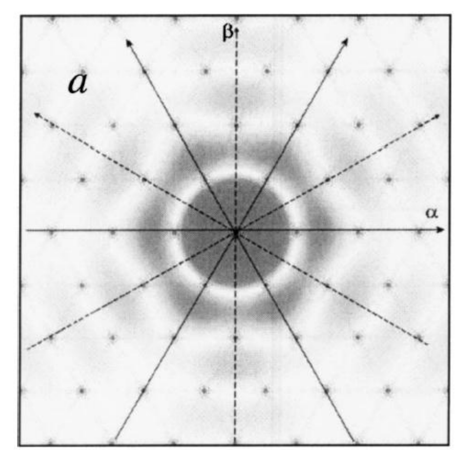


Fig. 1. Segmented mirror with segmentation order $M = 5$ consisting of $N = 90$ segments. Solid and dashed arrows illustrate the double $\pi/3$ symmetry of the system.



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.*

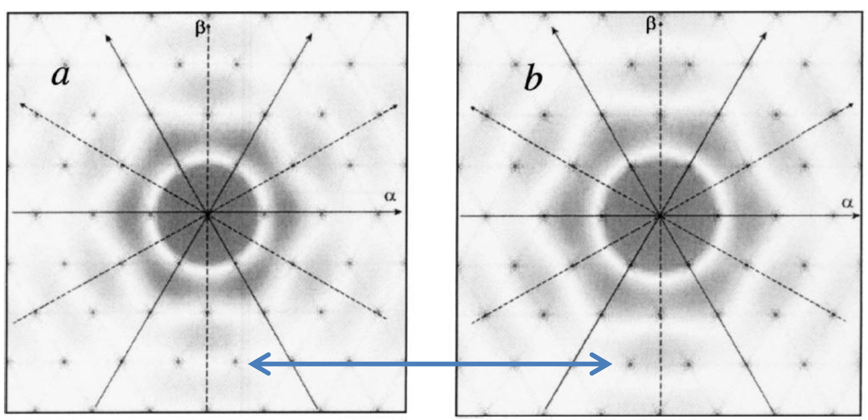


Fig. 2. a, Grid factor (regular spots) and the segment PSF_s for a perfect telescope without gaps. Except for the central peak, all peaks of the grid factor fall into zeros of the segment PSF_s. Solid and dashed arrows illustrate the same double $\pi/3$ symmetry as observed in the pupil plane (Fig. 1). 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.

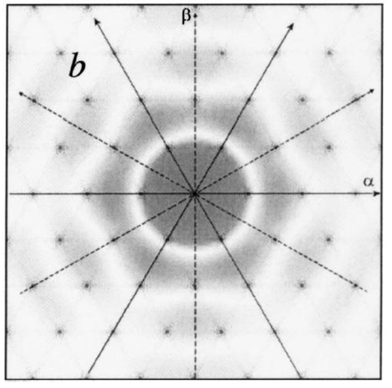
Yaitskova, Dohlen and Dierickx, "Analytical study of diffraction effects in extremely large segmented telescopes", JOSA, Vol.20, No.8, Aug 2003.

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’.



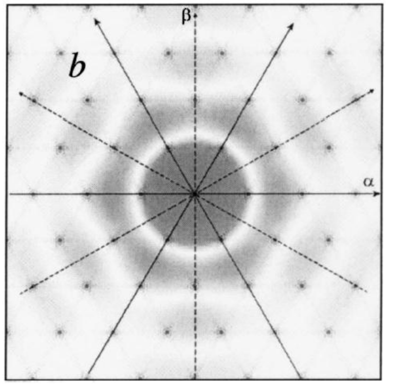
Yaitskova, Dohlen and Dierickx, “Analytical study of diffraction effects in extremely large segmented telescopes”, JOSA, Vol.20, No.8, Aug 2003.

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, 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.

Segmentation 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 ($16\lambda/D$).

And, the more segments, the larger the co-phasing specification.

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 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 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 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 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 200 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 300 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

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 5 m Fairing, 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 10 m Fairing, 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 10 m Fairing, 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 280K ± 0.5K 0.1K per 10min	< 5 nm rms per K	low CTE material
			> 20 hr thermal time constant	thermal mass
		Dynamics 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

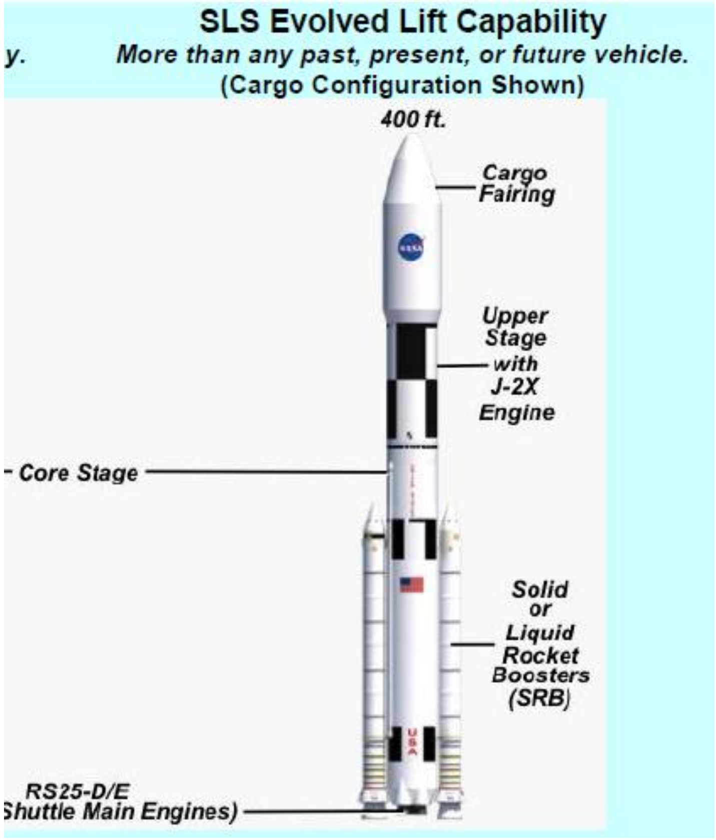
consistent with HLLV Medium

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.

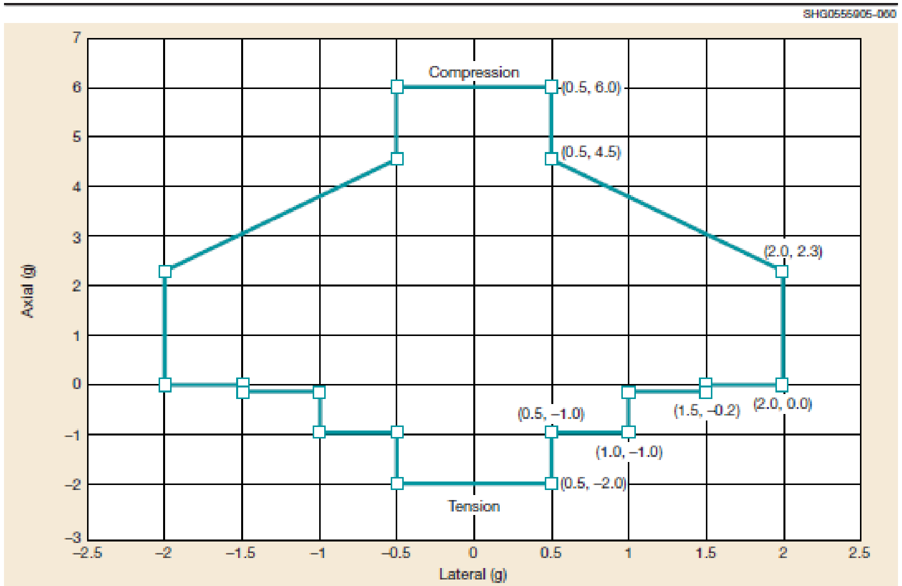


Figure 4-30. Delta IV Heavy Design Load Factors

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.

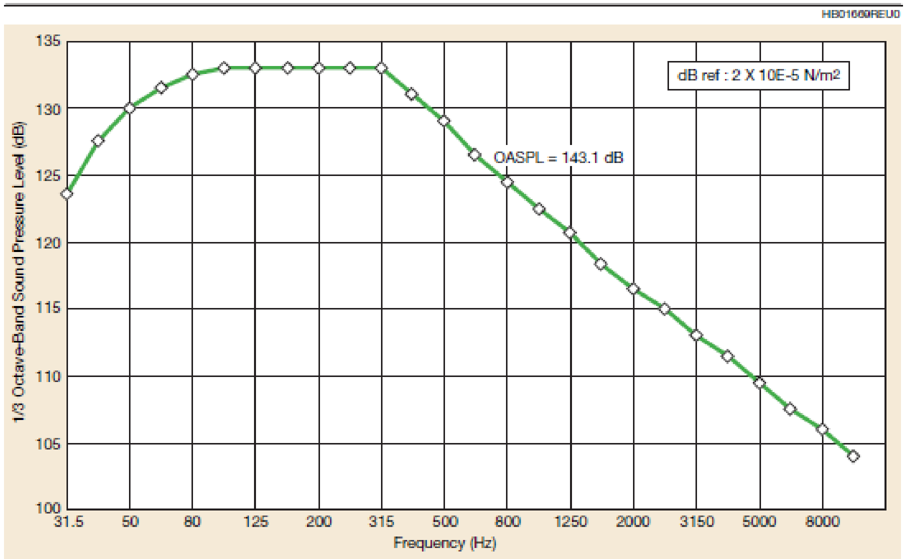


Figure 4-33. Delta IV Heavy (5-m Composite Fairing) Internal Payload Acoustics Typical 95th Percentile, 50% Confidence Predictions, 60% Fill Effect Included

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

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.