AMTD: Science Derived Engineering Specifications

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Approach

A fundamental strategy of our long term objective:

> To provide the science community with TRL6 technologies to enable either a future monolithic or segmented UVOIR space telescope by 2018 so that a viable flight mission can be proposed to the 2020 Decadal Review.

Is to fully integrate Science and Engineering.

- Engineering Specifications must be traceable to Required Science Measurement Capabilities
- Engineering Specifications must be compatible with implementation constraints, i.e. launch vehicles
- Developed Technology must enable mission capable of doing both general astrophysics and ultra-high contrast observations of exoplanets.

Science Team

Science Advisory Team:

Dr. Marc Postman, Space Telescope Science Institute

Dr. Remi Soummer, Space Telescope Science Institute

Dr. Annand Sivramakrishnan, Space Telescope Institute

Dr. Bruce Macintosh, Lawrence Livermore National Lab

Dr. Olivier Guyon University of Arizona

Dr. John Krist Jet Propulsion Laboratory

Systems Engineering Team

Dr. H. Philip Stahl, NASA, Principle Investigator

Dr. W. Scott Smith, NASA, Systems Engineer

Dr. Gary Mosier, NASA, Modeling Lead

Required Science Measurement Capabilities

In 2012, the Science Advisory Team has met:

- Once face-to-face
- Four times on telescons, and
- Exchanged numerous emails

To develop a draft Science Requirements document.

Document defines on-orbit performance capabilities required to accomplish the most stressing science observations:

- Imaging Earth like exoplanets
- Far Ultraviolet Spectroscopy

Systems Engineering is converting these Requirements into Specifications for Monolithic and Segmented Telescopes.

Exoplanet Measurement Capability

Exoplanet characterization requirements may place 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

Telescope Aperture Size is driven by:

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

Aperture Size vs Habitable Zone Requirement

The search for Exo-Earths (i.e. terrestrial mass planets with life) requires the ability to resolve the habitable zone (the 'Goldie Locks' region around a 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

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:

A 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 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

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 characterize 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

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.

Telescope Performance Requirements

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 requires total system WFE of ~38 nm.

For 4-meter telescope, PSF FWHM is 32 mas

For 8-meter telesocpe, PSF FWHM is 16 mas

Pointing stability is usually < 1/8th PSF FWHM per exposure

Telescope Performance Requirements

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

Therefore, Telescope (and Primary Mirror) 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

Specifications have not been defined for a Visible Nulling Coronagraph or phase type coronagraph.

Telescope Performance Requirements

These are Telescope not Primary Mirror Specifications

WFE Specification is before correction by a Deformable Mirror

WFE/EE Stability and MSF WFE are the stressing specifications

Segmented Mirror Specifications are a FY13 Task

4m Telescope Requirements for use with Coronagraph

On-axis Monolithic 4-m Telescope with 3λ/D Coronagraph			
Performance Parameter	Specification	Source	Comments
Maximum total system rms WFE	38 nm	Diffraction limit (80% Strehl ratio 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 over 20 minutes	~1.5 nm	Lambda/500 at 760 nm, prior to any coronagraph WFS&C system.	The precise timescale may be anywhere from 20 minutes to 1 hour.
PM rms surface error	5 - 10 nm	HST / ATLAST studies	
Pointing stability (jitter)	~4 mas	Guyon, scaled from HST	~ 0.5 mas floor determined by stellar angular diameter.
Mid-frequency WFE	< 20 nm	HST	

8m Telescope Requirements for use with Coronagraph

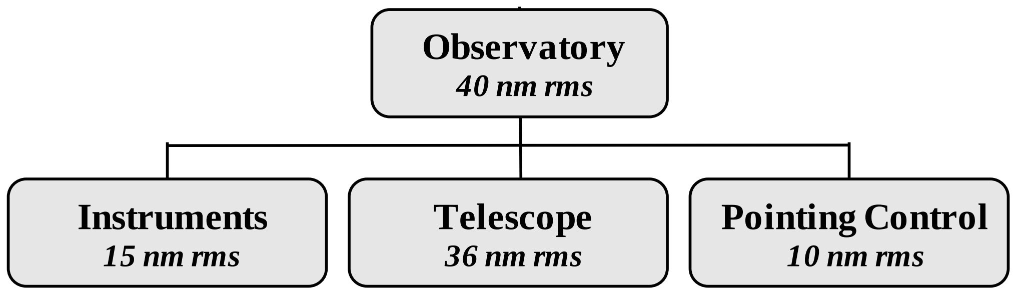
On-axis Monolithic 8-m Telescope with 3λ/D Coronagraph			
Performance Parameter	Specification	Source	Comments
Maximum total system rms WFE	38 nm	Diffraction limit (80% Strehl ratio at 500 nm)	
Encircled Energy Fraction (EEF)	80% within 16 mas at 500 nm	HST spec, modified to larger aperture and slightly bluer wavelength	Vary < 5% across 4 arcmin FOV
EEF stability	<2%	JWST	
Telescope WFE stability over 20 minutes	~1.5 nm	Lambda/500 at 760 nm, prior to any coronagraph WFS&C system.	The precise timescale may be anywhere from 20 minutes to 1 hour.
PM rms surface error	5 - 10 nm	HST / ATLAST studies	
Pointing stability (jitter)	~2 mas	Guyon, scaled from HST	~ 0.5 mas floor determined by stellar angular diameter.
Mid-frequency WFE	< 20 nm	HST	

8m Telescope Requirements for use with Occulter

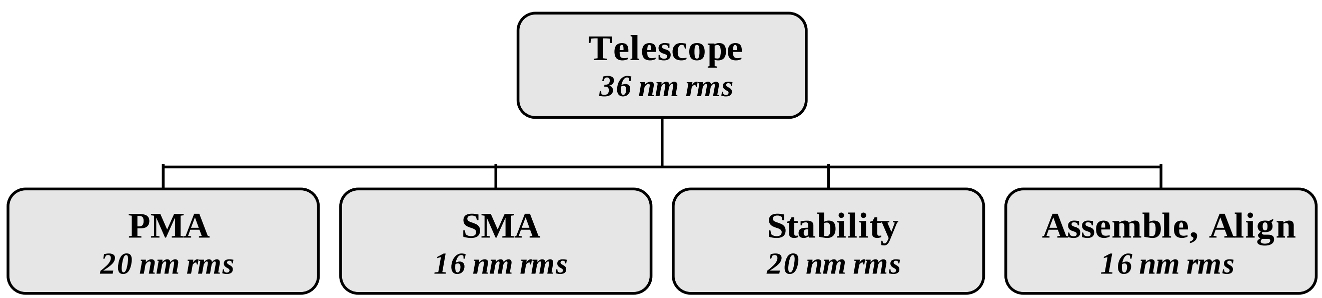
On-axis Segmented 8-m Telescope with External Occulter			
Performance Parameter	Specification	Source	Comments
Maximum total system rms WFE	38 nm	Diffraction limit (80% Strehl ratio at 500 nm)	
Encircled Energy Fraction (EEF)	80% within 16 mas at 500 nm	HST spec, modified to larger aperture & bluer wavelength	Vary < 5% across 4 arcmin FOV
EEF stability	<2%	JWST	
WFE stability over 20 minutes	~ 35 nm	$\lambda/14$ at 500 nm	
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
Maximum segment phasing stability	TBD	Soummer, McIntosh	2013
Pointing stability (jitter)	~2 mas	Guyon, scaled from HST	~ 0.5 mas floor determined by stellar angular diameter.

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:



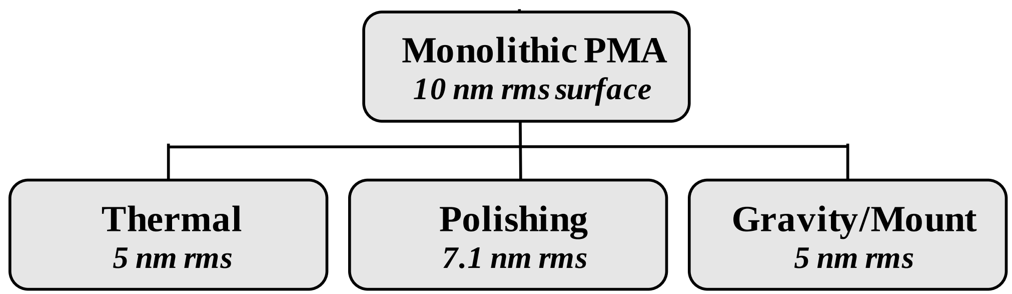
The flowing the Telescope Level Requirements to its major Sub-Systems



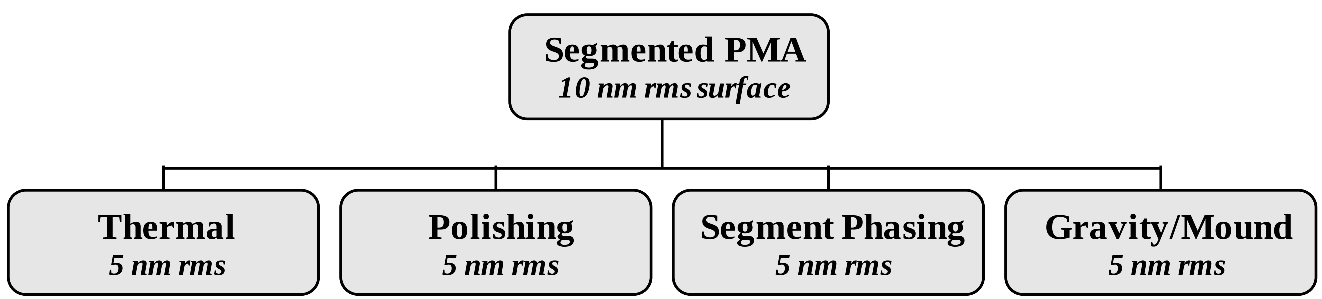
Primary Mirror Total Surface Figure Requirement

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

Monolithic PM Specification depends on its Thermal behavior and Mounting Uncertainty, leaving < ~ 8 nm rms for Total Manufactured WFE.



Segmenting increases complexity and redistributes the error allocations.



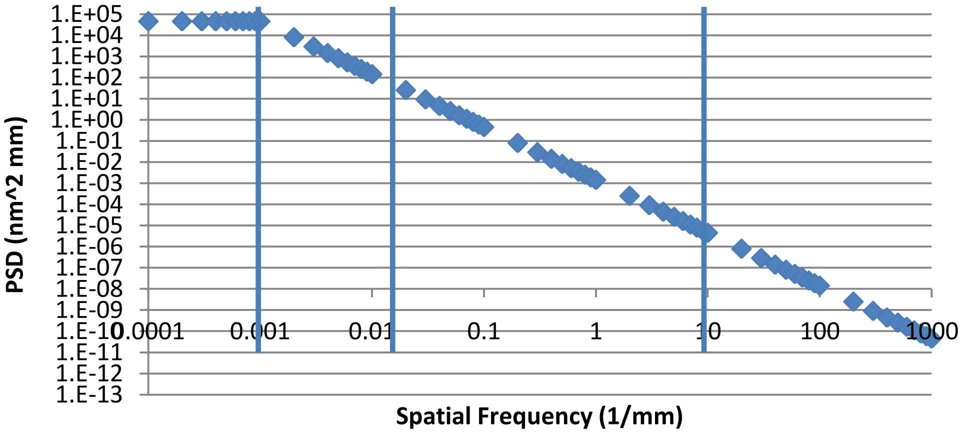
Monolithic PM Manufacturing Specification

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

Low/Mid Spatial Frequency Specification

To best of my knowledge, there is no precise definition for the boundary between Figure/Low and Mid-Spatial Frequency.

Have seen values 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

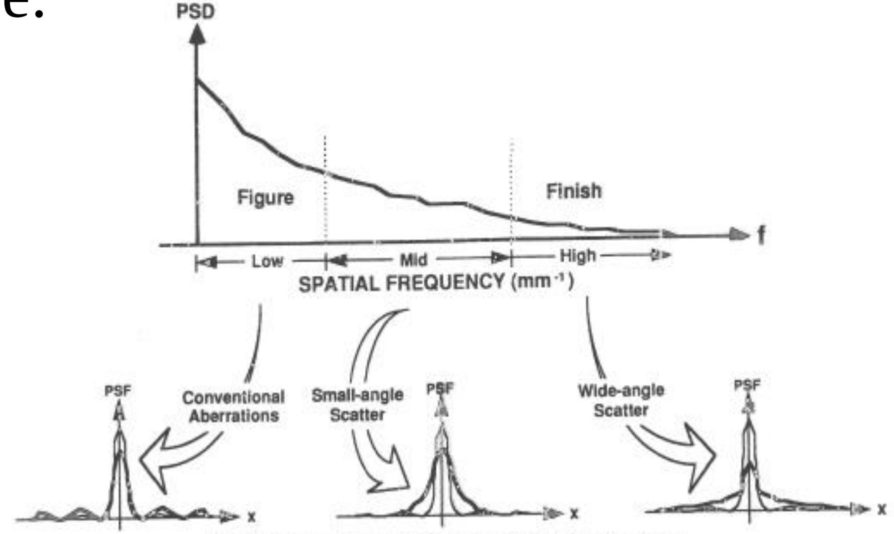


Fig. 11. Effect on image quality differs for each spatial-frequency regime.

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.

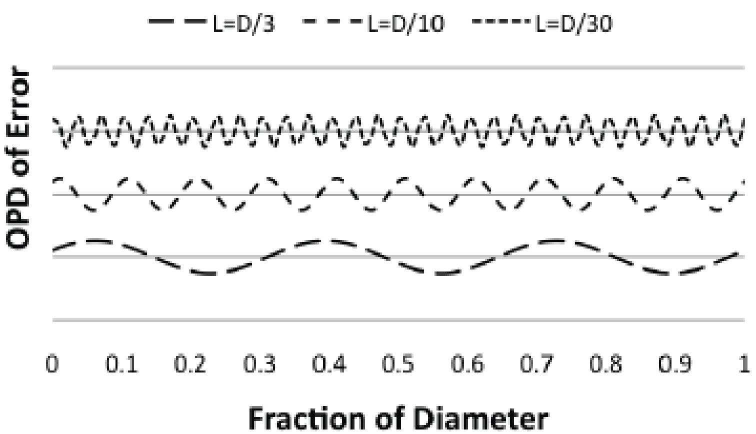
Harvey would define it as the spatial frequency at which energy starts being distributed broadly across the image.

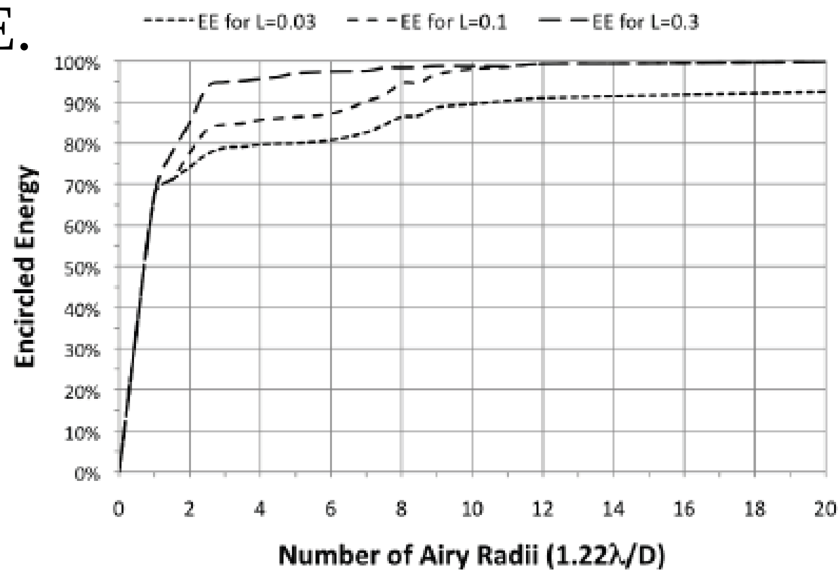
Noll ("Effect ofMid- and High-Spatial Frequencies on Optical Performance", Optical Engineering, Vol. 18, No. 2, pp.137, 1979) seems to define it as the spatial frequency which scatters energy beyond 16 Airy Rings.

Wetherell ("The Calculation of Image Quality", Applied Optics and Optical Engineering, Vol. VIII, Academic Press, 1980) seems to define 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/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

Mid/High Spatial Frequency Specification

Exo-Planet Science requires a Deformable Mirror to correct wavefront errors and create a ‘Dark Hole’ for the coronagraph.

A 64 x 64 DM can theoretically correct spatial frequencies up to 32 cycles per diameter to create the ‘dark hole’ but in practice, the limit is approx 20 cycles per diameter.

3X aliasing can cause spatial frequency errors to put energy into the ‘dark hole’; need smooth WFE up to 60 cycles/diameter.

Higher spatial frequencies scatter energy outside of ‘dark hole’.

We will use 60 cycles as the Mid/High boundary.

Primary Mirror Spatial Frequency Specification

Different manufacturing PSD slopes, results 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

Implementation Issues

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)

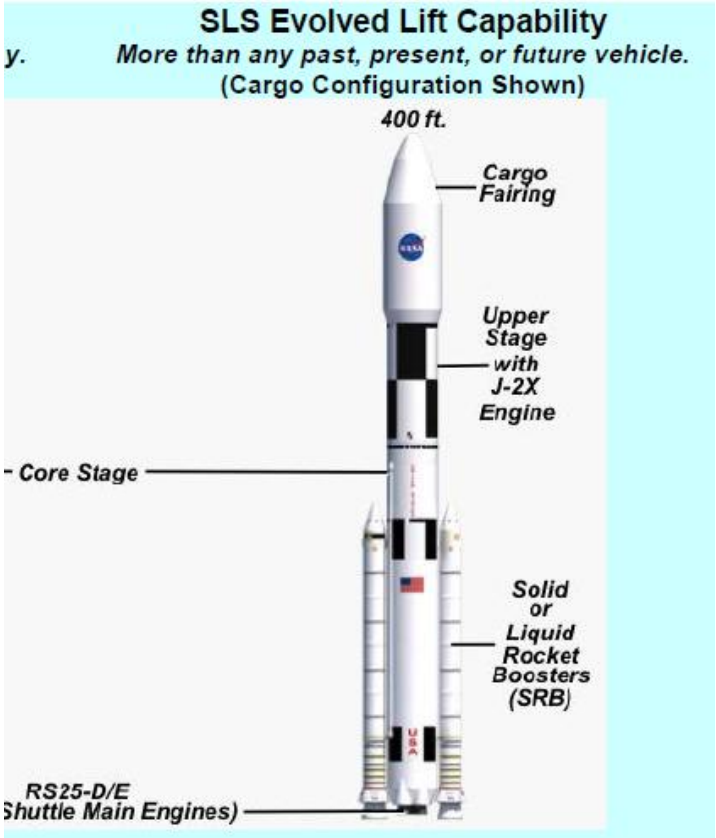
Space Launch System (SLS) Cargo Launch Vehicle specifications

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.

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

Conclusion

The AMTD Science and Systems Engineering Teams are developing Engineering Specifications based on Science Measurement Requirements and Implementation Constraints.

These are ‘living’ documents.

Draft Monolithic Requirements have been developed.

Draft Segmented Requirements will be developed in FY13.