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

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H. Philip Stahl

Space Telescopes & Instrumentation 2014: Optical, Infrared, and Millimeter Wave
Summary
Summary

In AMTD-1 2013 paper we:

• Discussed the flow down to Telescope Aperture Diameter from Science Requirements, including:
  o Habitable Zone Resolution Requirement
  o Signal to Noise Requirement
  o $\eta_{EARTH}$
  o 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

Summary

In AMTD-2 we continue to update and refine our findings.

In this paper we:

• 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

Introduction
Future UVOIR Space Telescope

Astro2010 Decadal Study recommended technology development (page 7-17) for a potential future:
• Exoplanet Mission (New-Worlds Explorer)
• UVOIR Space Telescope (4 meter or larger)

2012 NASA Space Technology Roadmaps & Priorities:
Top Technical Challenge C2 recommended:
• New Astronomical Telescopes that enable discovery of habitable planets, facilitate advances in solar physics, and enable the study of faint structures around bright objects …

2014 Enduring Quests Daring Visions recommended:
• LUVOIR Surveyor with sensitivity to locate the bulk of planets in the solar neighborhood and reveal the details of their atmospheres.
AMTD

Most future space telescope missions require mirror technology.

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

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

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

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

To provide science community with options, we must pursue multiple technology paths: monolithic AND segmented.

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

- Very Smooth Surfaces \(< 10\ \text{nm rms}\)
- Thermal Stability \(\text{Low CTE Material}\)
- Mechanical Stability \(\text{High Stiffness Mirror Substrates}\)
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.
Summary

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

Science Requirements ➔ Engineering Specifications

Exoplanet
- Sample Size
- Spectral Resolution
- Contrast
- Contrast
- Star Size

Telescope Diameter
- Telescope Diameter
- Mid/High Spatial Error
- WFE Stability
- Line of Sight Stability

General Astrophysics
- Diffraction Limit
- Spatial Resolution

Wavefront Error (Low/Mid)
- Telescope Diameter

Launch Vehicle
- Up-Mass Capacity
- Fairing Size

Areal Mass
- 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>
<thead>
<tr>
<th>Science Question</th>
<th>Science Requirements</th>
<th>Measurements Needed</th>
<th>Requirements</th>
</tr>
</thead>
</table>
| 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 |
|                                                               | 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 | ~0.1 nm stable WFE per 2 hr  
|                                                               |                                                                                                           |                                                                                     | ~1.3 to 1.6 mas pointing stability |
| 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 |
| 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 | 500 nm diffraction limit  
|                                                               |                                                                                                           |                                                                                     | 1.3 to 1.6 mas pointing stability |
| 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 |
| How do stars & planets interact with interstellar medium?      | Measure UV Ly-alpha absorption due to Hydrogen “walls” from our heliosphere and atmospheres of nearby stars | High dynamic range, very high spectral resolution (R = 100,000) UV spectroscopy with SNR = 100 for V = 14 mag stars | Sensitivity down to 100 nm wavelength. |
| 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.

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

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?”

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 \( \eta_{\text{Earth}} = 0.1 \) and IWA = 2\( \lambda/D \).

The signature of life is encoded in the spectrum of the Earth.

Optical

Near-Infrared

Thick Atmosphere

Methane

Water

Oxygen

Methane

Telescope Size

Number of Exo-Earths in 100 days of total integration time

If:

\[
\eta_{\text{Earth}} \times f_{\text{Bio}} \sim 1 \quad \text{then} \quad D_{\text{Tel}} \sim 4m
\]

\[
\eta_{\text{Earth}} \times f_{\text{Bio}} < 1 \quad \text{then} \quad D_{\text{Tel}} \sim 8m
\]

\[
\eta_{\text{Earth}} \times f_{\text{Bio}} << 1 \quad \text{then} \quad D_{\text{Tel}} \sim 16m
\]

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 \( \eta_{\text{Earth}} = 0.1 \) and IWA = 2\( \lambda/D \).

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 courtesy Ty Robinson

AT-LAST Wavelength Range for Life Detection, Shawn Domagal-Goldman
Aperture Size Specification
Aperture Size

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 or 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 large values of systematic noise floor.

Fig. 8.— ExoEarth candidate yield for our baseline mission as a function of several mission parameters.
Detect & Characterize versus Aperture Size

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

<table>
<thead>
<tr>
<th>Aperture Diameter</th>
<th>$\text{IWA} = 2 \frac{\lambda}{D}$</th>
<th>$\text{IWA} = 1 \frac{\lambda}{D}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 meter</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>8 meter</td>
<td>15</td>
<td>22</td>
</tr>
<tr>
<td>12 meter</td>
<td>33</td>
<td>44</td>
</tr>
<tr>
<td>16 meter</td>
<td>56</td>
<td>77</td>
</tr>
</tbody>
</table>

Assuming:

- $\text{Eta}_\text{Earth} = 10\%$  (increasing to 20% would double #)
- $\text{Exo-Zodi} = 3$  (increasing to 30 would halve #)

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 Recommendation

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

<table>
<thead>
<tr>
<th>Telescope Diameter</th>
<th>Architecture</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 meter</td>
<td>Monolithic</td>
</tr>
<tr>
<td>8 meter</td>
<td>Segmented</td>
</tr>
<tr>
<td>&gt; 8 meter</td>
<td>Segmented</td>
</tr>
</tbody>
</table>

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
Segmented Mirror Architectures

Two architectures are under consideration
• Hex Segment Architecture (similar to JWST or Keck or TMT)
• Center and Petals (similar to LAMP or ALOT)

Center and Petals can easily produce apertures from 10 to 14 m
  6-m center with 2 to 4 m tall identical petals gives 10 to 14 meters
  8-m center with 1 to 3 m tall identical petals gives 10 to 14 meters
Segmentation Point Spread Function

Hex Segmentation is similar to JWST, Keck, TMT or ELT.

PSF is structured and depends on segment size.

PSF Dimensions is $\lambda/D$
Segmentation Point Spread Function

Petal Segmentation is similar to LAMP or ALOT.

PSF is symmetric and depends on sizes of center and petals.

PSF Dimensions is $\lambda/D$
Areal Density

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

<table>
<thead>
<tr>
<th>Launch Vehicle</th>
<th>SEL2 Payload Mass [kg]</th>
<th>Primary Mirror Assembly [kg]</th>
<th>Aperture [m]</th>
<th>Areal Density [kg/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>JWST</td>
<td>6600</td>
<td>1600</td>
<td>6.5</td>
<td>64</td>
</tr>
<tr>
<td>Delta IVH</td>
<td>10,000</td>
<td>2500</td>
<td>8</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Falcon 9H</td>
<td>15,000</td>
<td>5000</td>
<td>8</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td>SLS Block 1</td>
<td>30,000</td>
<td>15,000</td>
<td>8</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>16</td>
<td>75</td>
</tr>
<tr>
<td>SLS Block 2</td>
<td>60,000</td>
<td>30,000</td>
<td>8</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>16</td>
<td>150</td>
</tr>
</tbody>
</table>
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):

\[
\text{PSF FWHM (mas)} = \left( \frac{0.2063}{S} \right) \times \left( \frac{\lambda (\text{nm})}{D (\text{meters})} \right)
\]

\[
S \sim \exp\left( -\left( \frac{2\pi \times \text{WFE}}{\lambda} \right)^2 \right)
\]

\[
\text{WFE} = \left( \frac{\lambda}{2\pi} \right) \times \sqrt{ -\ln S }
\]

Diffraction limited performance requires S ~ 0.80.

At λ = 500 nm, this requires total system WFE of ~38 nm.
Primary Mirror requirements are derived by flowing System Level diffraction limited and pointing stability requirements to major observatory elements:

Instruments 15 nm rms
Telescope 36 nm rms
Pointing Control 10 nm rms

Then flowing Telescope Requirements to major Sub-Systems

Telescope 36 nm rms

PMA 20 nm rms
SMA 16 nm rms
Stability 20 nm rms
Assemble, Align 16 nm rms
Primary Mirror Total Surface Figure Requirement

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.
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 Exoplanet 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
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

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.

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

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:** $\Delta WFE < 10 \text{ pico-meters per 10 minutes}$
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.

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
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’.

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.

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.
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>
<thead>
<tr>
<th>Telescope diameter (D) &amp; $\lambda$</th>
<th>Number of Segments (N)</th>
<th>Contrast</th>
<th>Target</th>
<th>Cophasing requirement</th>
<th>Stability timescale</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 m, 0.55 μm</td>
<td>10</td>
<td>1e-10</td>
<td>$m_\gamma=8$</td>
<td>2.8 pm</td>
<td>22 mn</td>
</tr>
<tr>
<td>8 m, 0.55 μm</td>
<td>10</td>
<td>1e-10</td>
<td>$m_\gamma=8$</td>
<td>2.8 pm</td>
<td>5.4 mn</td>
</tr>
<tr>
<td>8 m, 0.55 μm</td>
<td>100</td>
<td>1e-10</td>
<td>$m_\gamma=8$</td>
<td>8.7 pm</td>
<td>5.4 mn</td>
</tr>
</tbody>
</table>
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.

The consensus requirement is < 10 pm per 10 minutes.
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 sources 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 40 nm rms 'WFE response.

It takes 14 days to ‘passively’ achieve < 10 pm per 10 min
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 ($a_{\text{rms}}$) divided by square of the structure’s first mode frequency ($f_0$)

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

To achieve $< 10$ pm rms requires

<table>
<thead>
<tr>
<th>First Mode Frequency</th>
<th>RMS Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 HZ</td>
<td>$&lt; 10^{-9}$ g</td>
</tr>
<tr>
<td>100 HZ</td>
<td>$&lt; 10^{-7}$ g</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Diameter (m)</th>
<th>Depth (m)</th>
<th>$f_0$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.2</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>2.0</td>
<td>100</td>
</tr>
<tr>
<td>20</td>
<td>0.4</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>4.0</td>
<td>100</td>
</tr>
</tbody>
</table>

Note: Adding Stiffness requires MASS.

Another way is to increase isolation.

A final way is active control.

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
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.
### On-axis Monolithic 8-m Telescope with Coronagraph

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Specification</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum total system rms WFE</td>
<td>38 nm</td>
<td>Diffraction limit (80% Strehl at 500 nm)</td>
</tr>
<tr>
<td>Encircled Energy Fraction (EEF)</td>
<td>80% within 16 mas at 500 nm</td>
<td>HST spec, modified to larger aperture and slightly bluer wavelength</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vary &lt; 5% across 4 arcmin FOV</td>
</tr>
<tr>
<td>EEF stability</td>
<td>&lt;2%</td>
<td>JWST</td>
</tr>
<tr>
<td>Telescope WFE stability</td>
<td>&lt; 10 pm per 600 sec</td>
<td></td>
</tr>
<tr>
<td>PM rms surface error</td>
<td>5 - 10 nm</td>
<td></td>
</tr>
<tr>
<td>Pointing stability (jitter)</td>
<td>~2 mas</td>
<td>scaled from HST Guyon: ~ 0.5 mas determined by stellar angular diameter.</td>
</tr>
<tr>
<td>Mid-frequency WFE</td>
<td>&lt; 4 nm</td>
<td></td>
</tr>
</tbody>
</table>
## On-axis Segmented 8-m Telescope with Coronagraph

<table>
<thead>
<tr>
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</tr>
</thead>
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<tr>
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<td>80% within 16 mas at 500 nm</td>
<td>HST spec, modified to larger aperture &amp; bluer wavelength Vary &lt; 5% across 4 arcmin FOV</td>
</tr>
<tr>
<td>EEF stability</td>
<td>&lt;2%</td>
<td>JWST</td>
</tr>
<tr>
<td>WFE stability</td>
<td>&lt; 10 pm per 600 sec</td>
<td></td>
</tr>
<tr>
<td>Segment gap stability</td>
<td>TBD</td>
<td>Soummer, McIntosh 2013</td>
</tr>
<tr>
<td>Number and Size of Segments</td>
<td>TBD (1 – 2m, 36 max)</td>
<td>Soummer 2013</td>
</tr>
<tr>
<td>Segment edge roll-off stability</td>
<td>TBD</td>
<td>Sivaramakrishnan 2013</td>
</tr>
<tr>
<td>Segment co-phasing stability</td>
<td>4 to 6 pm per 600 secs</td>
<td>Depends on number of segments</td>
</tr>
</tbody>
</table>
| 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

<table>
<thead>
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<tbody>
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</tr>
<tr>
<td></td>
<td></td>
<td>Vary &lt; 5% across 4 arcmin FOV</td>
</tr>
<tr>
<td>EEF stability</td>
<td>&lt;2%</td>
<td>JWST</td>
</tr>
<tr>
<td>WFE stability</td>
<td>~ 35 nm</td>
<td>Depends on number of segments</td>
</tr>
<tr>
<td>Segment gap stability</td>
<td>TBD</td>
<td>Soummer, McIntosh 2013</td>
</tr>
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<td>Number and Size of Segments</td>
<td>TBD (1 – 2m, 36 max)</td>
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<td>Segment edge roll-off stability</td>
<td>TBD</td>
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<td>TBD</td>
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</tr>
<tr>
<td>Pointing stability (jitter)</td>
<td>~2 mas</td>
<td>scaled from HST</td>
</tr>
</tbody>
</table>
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.