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

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ABSTRACT

The Advance Mirror Technology Development (AMTD) project is in Phase 2 of a multiyear effort, initiated in FY12, to mature by at least a half TRL step six critical technologies required to enable 4 meter or larger UVOIR space telescope primary mirror assemblies for both general astrophysics and ultra-high contrast observations of exoplanets. AMTD uses a science-driven systems engineering approach. We mature technologies required to enable the highest priority science AND provide a high-performance low-cost low-risk system. To give the science community options, we are pursuing multiple technology paths. A key task is deriving engineering specifications for advanced normal-incidence monolithic and segmented mirror systems needed to enable both general astrophysics and ultra-high contrast observations of exoplanets missions as a function of potential launch vehicles and their mass and volume constraints. A key finding of this effort is that the science requires an 8 meter or larger aperture telescope.

Keywords: Space Telescope Mirrors, Mirror Technology Development, Systems Engineering

1. INTRODUCTION

Advanced Mirror Technology Development (AMTD) is a funded NASA Strategic Astrophysics Technology (SAT) project. Begun in 2011, we are in Phase 2. Our objective is to mature to TRL-6 critical technologies needed to produce 4-m or larger flight-qualified ultraviolet, optical and infrared (UVOIR) mirrors by 2018 so that the 2020 Decadal Review can consider a viable UVOIR mission. UVOIR measurements provide robust, often unique, diagnostics for investigating astronomical environments and objects; are responsible for much of our current astrophysics knowledge; and will produce as-yet unimagined paradigm-shifting discoveries. A new, larger UVOIR telescope is needed to help answer fundamental scientific questions, such as: Does life exist on nearby Earth-like exoplanets? How do galaxies assemble their stellar populations? How do galaxies and the intergalactic medium interact? And, how did planets and smaller bodies in our own solar system form and evolve?

AMTD uses a science-driven systems engineering approach. We mature technologies required to enable the highest priority science AND provide a high-performance low-cost low-risk system. One key task is to derive engineering specifications for monolithic and segmented mirror systems needed to enable both general astrophysics and ultra-high contrast exoplanet observations. Perviously[1], we flowed the science requirements of habitable zone resolution, signal to noise and exo-zodi resolution into telescope aperture diameter; flowed the requirement of diffraction limited wavelength performance into a wavefront error (WFE) budget (< 16 nm rms) and a primary mirror surface error power spectral density (PSD) specification (~ 5 nm rms in low-order and ~ 5 nm rms in mid-spatial); and, proposed a wavefront error stability specification (< 10 picometers per 10 minutes). Additionally, we considered the effect of mirror segmentation and reviewed launch vehicle and environmental constraints. Since that paper, the science community has further refined the science requirements. And, a new tool has been developed by to predict the number of ‘candidate Earths’ which can be detected via a space telescope of different sized apertures as a function of assumed observational constraints (such as exo-zodi, spectral signal-to-noise, or inclination angle) and engineering specifications (such as inner working angle and signal noise).[2] Additionally, the proposed wavefront stability specification has been adopted by the community.

In this paper we update and refine our previous finding based on this new model and discuss the impact of launch vehicle constrains on implementing the desired aperture diameter. And, we discuss the consequences of the stability specification to thermal stability and mechanical stiffness as a function of aperture size. Finally, we are not producing a ‘point-design’, but rather a set of ‘enveloping’ engineering specifications which will enable the on-orbit telescope performance required to accomplish the desired science.

2. SCIENCE REQUIREMENTS

AMTD uses a science-driven systems engineering approach. The engineering specifications for the primary mirror are directly traceable to science requirements. And, while any future UVOIR space telescope must perform both Astrophysics and Exoplanet science, it is the exoplanet science requirements[3,4] which are the most stressing.

Table 1: Exoplanet Science Requirements

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=7-10) imaging with IWA ~ 40 mas for ~100 target stars
	Detect habitability and bio-signatures in spectra of Earth-like HZ planets	High contrast (ΔMag>25 mag) SNR=10 R=70-100 spectroscopy with IWA ~ 40 mas. Exposure times <500 ksec

The value η_{EARTH} is commonly used to express the fraction of stars that host a "candidate exoEarth", i.e. a planet that is roughly Earth-size and in the habitable zone of its host star. Habitability is commonly associated with liquid water, thus the value to be determined is η_{WATER}. Similarly, bio-signatures is commonly associated with oxygen, thus the value to determine is η_{OXYGEN}. One way to detect water is with R = 7 to 10 spectroscopy at 900 nm. Molecular oxygen can be detected with R = 70 to 100 spectroscopy at 760 nm. Figure 1 illustrates the sensitivity of identifying the spectral signatures of water and oxygen as a function of spectral resolution (R).[5]

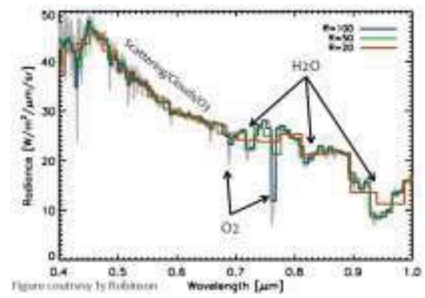

Figure 1: Detection vs Spectral Resolution

As will be discussed in the next section, telescope aperture diameter is driven by the number of planets which need to be imaged and the time necessary to obtain R = 70 spectra (for oxygen) of those planets at SNR = 10. It is also driven by the value of η_{OXYGEN} or η_{WATER} and the confidence level to which we want to know that value. Figure 2 shows the number of candidate earths which need to be characterized to constrain the value of η_{WATER} at a given confidence level (assuming the null result that all characterizations show no evidence for water).[2] The vertical dashed lines mark 1, 2, and 3 sigma. The different colored curves are for different upper limits on η_{WATER}. So, ~20 total candidates all with no water detections constrains $\eta_{WATER} < 0.05$ with 68% confidence, or $\eta_{WATER} < 0.1$ with 90% confidence. To constrain $\eta_{WATER} < 0.1$ with 99% confidence requires ~55 candidates. Using the equation:

$$\text{Number needed to characterize} = \log(1\text{-Confidence}) / \log(1 - \eta_{WATER})$$

One can calculate the total number of Earth candidates which needs to be characterized as a function of probability of occurrence and the confidence with which that probability needs to be measured (Table 2).

Table 2: Number of planets which need to be Characterized as function of occurrence probability and required confidence

	η_{WATER}		
Confidence	0.10	0.15	0.20
99.7% (3 sigma)	55	36	26
95% (2 sigma)	28	18	13
90%	22	14	10
67% (1 sigma)	11	7	5

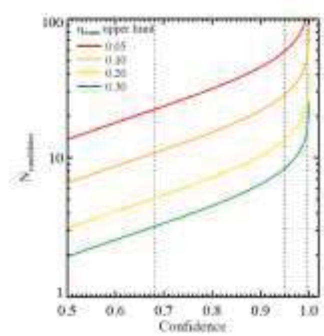

Figure 2: Number needed for Confidence

Please note, this paper is not asserting any specific number of candidate Earths which must be measured by a potential future UVOIR mission.

3. SCIENCE REQUIREMENTS AND APERTURE DIAMETER

Stark et. al.[2] have developed a new tool for estimating the number of candidate Earths which might be discovered and characterized via a V-band R = 5 spectra, assuming a single visit per accessible star, by a telescope with specific properties. Stark et. al. used this model to study the sensitivity of planet discovery and characterization as a function of system specifications. The largest drivers for how many candidate Earths might be discovered and characterized are the diameter of the telescope (D), the inner working angle (IWA), and the Exo-Zodi (n) (Figure 3). However, the sensitivity of required contrast level is very close to Exo-Zodi and the planet albedo may be more important than either.

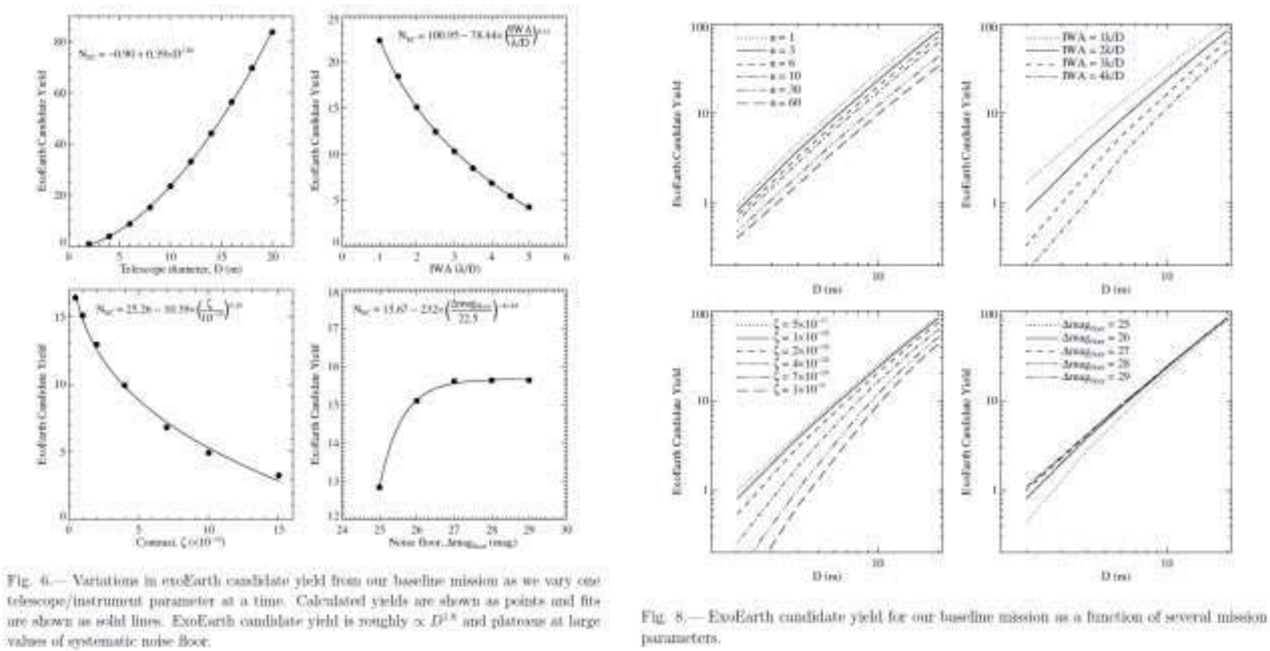

Figure 3: Stark Model paper figures estimating how many candidate Earths might be discovered as a function of Mission Constraints

This work has been expended in Table 3 to give the number of Candidate Earths that can be Detected and Characterized to R = 70 with SNR = 10 in ~1.5 years of mission observation time (i.e. without overhead) as a function of Aperture.

Table 3: Number of Candidate Earths which can be Characterized in 1.5 years

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

This result is calculated by scaling the Stark paper appendix R=5 exposure time to R=70 using equation (from Turnbull et al., 2012)[6]:

t_spec ~ t_image * (image bandpass / spectral resolution element) ~ t_image * (0.11 microns / (0.55 microns / R))

For example, per Stark an 8 meter aperture 2 λ/D telescope can detect and characterize (to R = 5) 15 candidate Earths in one year of observing time (without overhead). And, that it takes 0.8 days to obtain the R = 5 spectra. By the scaling equation, it takes the 8-m telescope 1.6 days to acquire an R = 10 spectra and 11 days to acquire an R = 70 spectra. If all 15 candidate Earths are characterized to R = 70, it adds 189 days (approximately 0.5 year) of observing time.

Please note that Table 3 assumes[2]:

η_{EARTH} = 10% increasing to 20% would double the number of candidate Earths

Exozodi level = 3 zodis increasing to 30 would halve the number of candidate Earths

IWA is at 550 nm	increasing the wavelength to ~900 nm decrease # candidates by ~5 for 8-m aperture (using Stark: $N_{EC} = 100.95 – 78.44*[IWA/(\lambda/D)]^{0.13}$; is only valid for 8-m aperture)
One Visit per Star	a second visit might double the number of candidate Earths

Please note, the numbers in Table 3 are only a range of what might be possible. It may or may not be possible to achieve an IWA of 1 λ/D. Or, new techniques such as PSF subtraction might increase the number of Earth Candidates for each Diameter. Finally, (per Stark) because each new star is harder to examine (i.e. we look at the easiest stars first), adding another 1 year to the observing time would only increase the number of candidate Earths by approximately 40%. Alternatively, adding time for a second or third visit to closer stars may double the number of candidate Earths.

The bottom line is that a potential future UVOIR mission to do exoplanet science needs to be 8 meters or larger.

4. APERTURE CONSIDERATIONS

Given that the desired science requires an aperture diameter of 8 meters or larger, the question is how to achieve that aperture. If NASA continues with its plan to develop a Space Launch System (SLS) Block-2 with a 10 meter faring, then it will be possible to launch an 8 meter class monolithic telescope. But, to launch anything larger will require a segmented aperture or sparse aperture architecture. Also, if the 10 meter rocket is not developed and we have to rely on current or planned rockets with 5 meter capacities, then we will be forced to a segmented architecture regardless. There are multiple approaches for accomplishing a segmented aperture, including hexagonal segments such as JWST or petal segments surrounding a center core similar to the LAMP system. Each system has advantages and disadvantages (such as symmetry and structure of the optical point spread function (PSF)), packaging in the rocket and cost of production (associated with variations or similarity of prescriptions). As shown in Figure 4, the center core with petal architecture has a more symmetric with less structure PSF. Also, the larger the center mirror, the better the central core of the PSF.

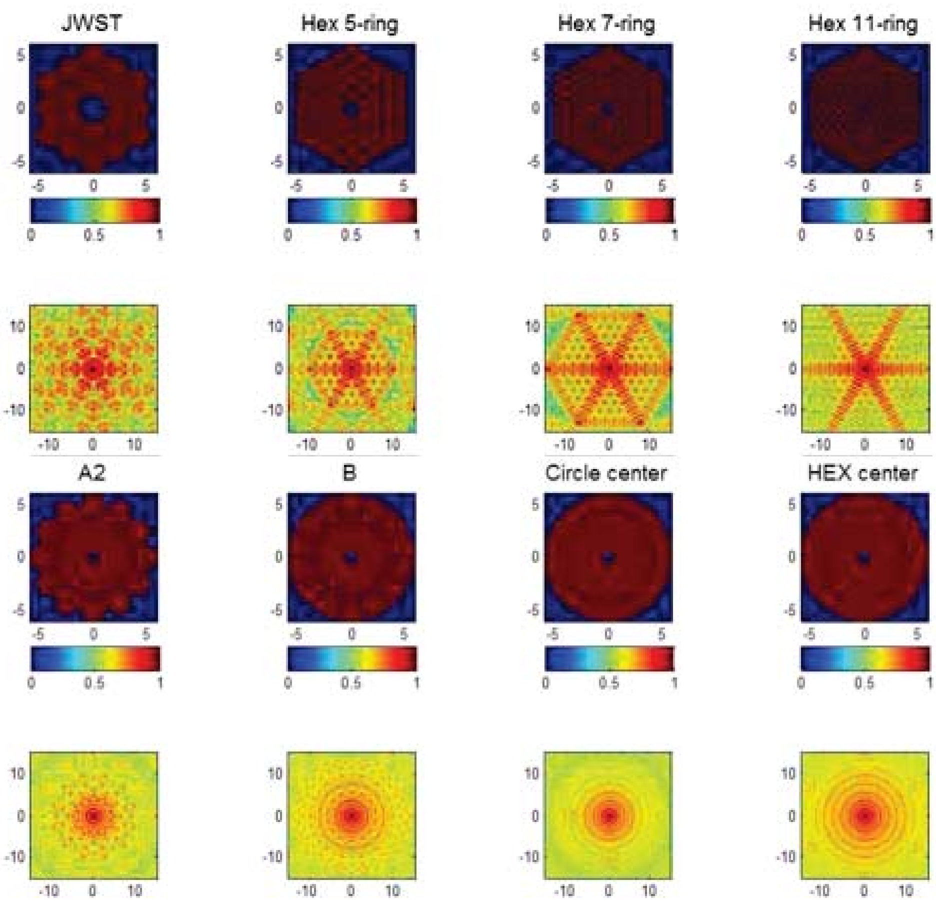

Figure 4: Calculated Point Spread Functions (PSF) for different aperture segmentations

While there are multiple approaches for producing a large aperture telescope, there is one constraining requirement for all potential architectures – MASS. All potential launch vehicles have a maximum up-mass which they can deliver into an SE-L2 orbit. Table 4 summarizes for various potential launch vehicles the maximum mission mass, an allocation for the primary mirror assembly and the primary mirror areal density requirement for various diameter mirrors. Given that JWST defines the state of the art at 65 kg/m2, one might consider any lower areal density to pose an increased risk. Furthermore, there must be an areal density below which current engineering practice cannot enable. Obviously, a heavy lift capacity rocket such as the SLS offers significant advantage to mitigate mass risk. The last line of Table 4 provides the projected areal mass of a Thirty Meter Telescope (TMT) mirror segment (Figure 5)[7]. And, while this mass is only an estimate for just the primary mirror segment assembly, it is also an assembly constructed out of aluminum. It is reasonable to assume that the mass could be easily reduced to 100 kg/m2. And, it is reasonable to assume that the mass would need to be doubled to 200 kg/m2 to account for a support structure. Regardless, the message is that if one has a heavily lift SLS Block 2 launch vehicle, the current state of the art for ground based telescope may be sufficient. This is particularly interesting when one considers the cost difference between make mirrors for ground versus space.

Table 4: Summary of Primary Mirror Areal Density as a function of Aperture Diameter and Launch Vehicle Capacity

Launch Vehicle	SEL2 Payload Mass [kg]	Primary Mirror Assembly [kg]	Aperture [m]	Areal Density [kg/m2]
Ariane V (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
Ground (TMT)		100,000 (mirror segments)	30	150

Another constraint which all potential missions must meet, independent of architecture, is cost. In current year dollars, the cost of the primary mirror assembly for both Hubble and JWST was between \$100M and \$150M. Therefore, it is reasonable to assume that \$150M is a maximum acceptable cost for the primary mirror assembly of a future UVOIR space telescope. This assumption places an areal cost constraint on the primary mirror assembly as summarized in Table 5. Again, at the bottom of the table is the projected areal cost for the entire TMT 30 meter telescope. Clearly, if one could make a space telescope mirror using ground based telescope technology, the budget constraint is achievable.

Figure 5: Prototype TMT 1.44 meter diameter primary mirror assembly segment with a projected total mass of 220 kg and < $400K cost.

Table 5: Areal Cost as a function of Aperture Diameter for $150M Primary Mirror

Mission	Aperture [m]	Areal Cost ($M/m2)
JWST	6.5	$6M
ATLAST	8	$3M
	12	$1.5M
	14	$1M
	16	$0.75M
TMT	30	< $0.3M

5. WAVEFRONT STABILITY IMPLICATIONS

To achieve the required 10^-11 contrast stability necessary to perform exoplanet science requires a telescope whose total wavefront error is stable to less than 10 picometers per 10 minutes per spatial frequency.[1] There are two disturbance sources which can introduce wavefront error: mechanical and thermal.

The problem is that while thermal wavefront error drift tends to be slower than 10 minutes, mechanical vibration tends to be faster than 10 minutes. Therefore, it is necessary to reduce the total WFE amplitude from mechanical vibration to less than 10 picometers. Per Lake[8], 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 either a very stiff system or very low acceleration loads (Figure 6, Table 6).

Table 6: Accelerations required for First Mode Frequency to achieve < 10 pm rms WFE

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

Obviously, the stiffer one can make the telescope system (i.e. the higher its first mode frequency) the less vibration isolation is required to minimize acceleration loads. Typically, one gains stiffness by making the support system deeper (which adds mass) (Figure 7, Table 7). Lake's rule of thumb is to have the support system mass equal to the mirror segment's mass. But, there is a limit to how thick (or how stiff) of a system one can manufacture for space. Therefore, to achieve the required < 10 pm rms stability will require active vibration isolation.

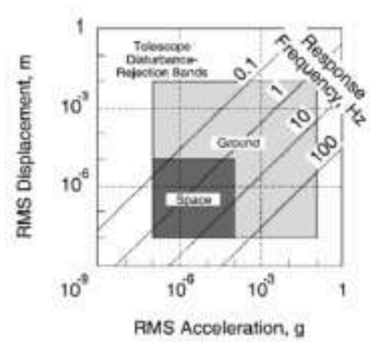

Figure 6: Displacement vs Acceleration

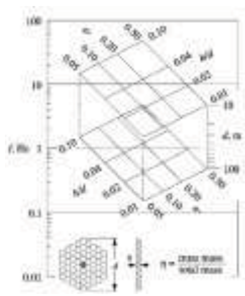

Figure 7: Truss Depth versus Mirror Diameter for given First Mode Frequency

Table 7: Support Depth vs First Mode Frequency (assuming truss mass = mirror substrate mass)

Diameter	Depth	f0
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

While not designed to meet the requirements of a UVOIR exoplanet science mission, JWST can serve as an example of what is possible. The predicted response of JWST is less than 13 nm rms for temporal frequencies up to 70 Hz (Figure 8) [9]. The JWST structure has an ~ 40 nm rms 'wing flap' mode at ~ 20 Hz and the individual PMSAs (Primary Mirror Segment Assemblies) have a ~ 20 nm rms 'rocking' mode at ~ 40 Hz.

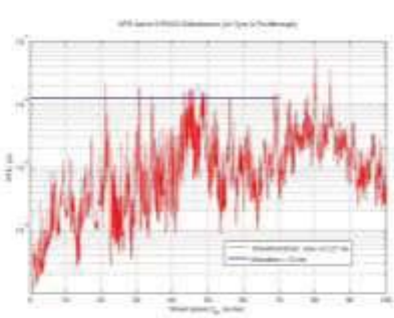

Figure 8: JWST Reaction Wheel-induced Wavefront Error Estimated Performance

Jitter response is evaluated for each of the six reaction wheels as a function of wheel speed. The curve shown in Figure 6 is the maximum (envelope) of the six responses at any given speed. The responses include a model uncertainty factor (MUF) of 1.9 below 20 Hz and 3.7 above 40 Hz, with a linear ramp from 20-40 Hz. The horizontal line from 0-70 rev/sec is the 13 nm allocation plotted over the operational wheel speed range, extended by 10% to allow for frequency uncertainty in the structural model. Note that for JWST the 13 nm is not a hard requirement, but rather a goal, as jitter is just one error term among many that affect JWST's Strehl and Encircled Energy Stability requirements. As these requirements are met with margin the exceedances shown above are not a concern. For purposes of deriving the isolation system requirement for a UVOIR space telescope, the sharp peaks at 21 Hz, 30.5 Hz and 34 Hz are ignored. These are driven by discrete structural modes that do not involve tip/tilt of the primary mirror (PM) segments. It is assumed that any similar modes will be handled through use of tuned mass dampers, reaction wheel speed-control algorithms, or other means. The cluster of peaks between 40-50 Hz corresponds to a band of modes associated with PM tip/tilt. These modes are less amenable to attenuation than the discrete modes below 40 Hz and hence an improvement in JWST's broadband isolation system would be required to achieve performance levels.

Using JWST as a starting point, to meet the exoplanet WFE stability requirement, we need to reduce these amplitudes by 1000X. JWST engineers estimate that they can meet this goal by the combination of three design elements. The first is to make an adjustment for structural damping. JWST assumes 0.02% of critical damping for the cold (~40K) telescope. Conservatively, a minimum of 0.2% damping could be assumed for a room-temperature (RT) structure. Hence, one could conclude that jitter for a warm JWST-like structure would be ~2 nm RMS. Second, is to make the telescope structure stiffer. Because JWST is an infrared wavelength telescope and thus diffraction limited at 2 micrometers, mass was deliberately removed from the structure to reduce total mass. Adding these structural elements back will increase system stiffness. Finally, it is necessary to use active vibration isolation. JWST uses a two-stage passive isolation system, with stage 1 being the 1-Hz Isolator Assembly at the spacecraft-payload interface and stage 2 being the 8-Hz Reaction Wheel Isolator Assemblies (one hexapod per wheel) at the wheel-spacecraft interfaces. At 40 Hz the JWST attenuation is estimated to be -92 dB. Thus, to reduce a 'warm' JWST vibration of ~ 2 nm rms further requires additional isolation (Table 8).

Table 8: Vibration Isolation System Requirements

PM Jitter Requirement	Additional Isolation beyond JWST	Total System Isolation Requirement (> 40HZ)
100 picometers (baseline)	-26 dB (0.005)	-118 dB
10 picometers (stretch)	-46 dB (0.0005)	-138 dB

The other significant source of wavefront error instability is thermal drift. When the telescope slews or rolls relative to the sun, its thermal environment changes. This change can introduce thermal gradients in the telescope structure and optical components. These gradients result in a wavefront error which changes as a function of time while the telescope comes to a new thermal equilibrium. The amplitude of this drift depends on the CTE (coefficient of thermal expansion) of the structure and mirror materials. The rate of this drift will vary depending upon system properties such as thermal conductivity, thermal capacity, and whether the system has passive or active thermal control. At the system level, the thermal control system depends on the CTE of the material. A high CTE material such as Silicon Carbide will require a more precise thermal control system than a low CTE material such as ULE© glass or Zerodur© (Table 9).

Table 9: Thermal Stability required to maintain < 10 pm per 10 minutes

Material	CTE	Thermal Stability
ULE© or Zerodur©	< 10 ppb	< 0.001K per 10 minutes.
SiC	< 10 ppm	< 0.000001K per 10 minutes.

Again, while not designed to meet the requirements of a UVOIR exoplanet science mission, JWST can serve as an example of what is possible. JWST is predicted to have a 31 nm rms WFE response to a worst-case thermal slew of 0.22K and take 14 days to 'passively' achieve < 10 pm per 10 min WFE stability (Figure 9) [10].

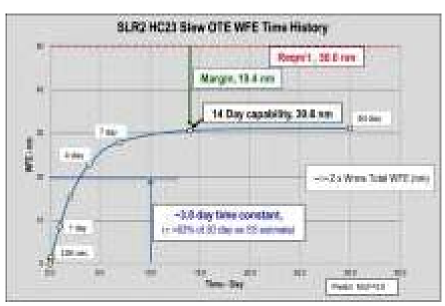

Figure 9: JWST predicted WFE response to a worst case thermal slew.

6. CONCLUSIONS

The Advance Mirror Technology Development (AMTD) project is in Phase 2 of a multiyear effort, initiated in FY12, to mature by at least a half TRL step six critical technologies required to enable 4 meter or larger UVOIR space telescope primary mirror assemblies for both general astrophysics and ultra-high contrast observations of exoplanets. AMTD uses a science-driven systems engineering approach. We mature technologies required to enable the highest priority science AND provide a high-performance low-cost low-risk system.

A key AMTD task is to derive from science requirements engineering specifications for monolithic and segmented mirror systems needed to enable both general astrophysics and ultra-high contrast observations of exoplanets missions as a function of potential launch vehicles and their mass and volume constraints.

Previously, we flowed the science requirements of habitable zone resolution, signal to noise and exo-zodi resolution into telescope aperture diameter; flowed the science requirement of diffraction limited wavelength performance into a wavefront error (WFE) budget (< 16 nm rms) and a primary mirror surface error power spectral density (PSD) specification (~ 5 nm rms in low-order and ~ 5 nm rms in mid-spatial frequency error); and, proposed a wavefront error stability specification (< 10 picometers per 10 minutes). Additionally, we considered the effect of mirror segmentation and reviewed launch vehicle and environmental constraints.

This paper updates the aperture size requirement based on a new tool developed to predict the number of 'candidate Earths' which can be detected via a space telescope of different sized apertures as a function of assumed observational constraints (such as exo-zodi, spectral signal-to-noise, or inclination angle) and engineering specifications (such as inner working angle and signal noise). The key finding is that an aperture diameter of 8 meters or larger is required.

Next, this paper considers the implications a large telescope aperture based on launch vehicle mass constraint and budget constraint. Finally, we consider the implications of the 10 pm rms per 10 min per spatial frequency wavefront error stability requirement on the telescope's mechanical and thermal design.

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