Beyond JWST: Performance requirements for a future large UVOIR space telescope

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ABSTRACT

This paper considers requirements for a future large space telescope to follow the James Webb Space Telescope, starting in the next decade. Its ambitious science program includes direct imaging and spectroscopy of Earth-like planets orbiting other stars, resolving individual stars in nearby galaxies, and probing the most distant regions of the observable universe to a visible-light resolution of 100 parsec, while providing high spectral resolution for wavelengths from 100 to 2,500 nm. The top-level optical requirements flowdown is briefly described, with reference to existing and future capabilities. The intent is to identify technology development needed in the last half of this decade, to support the priorities of the 2020 Decadal Survey.

Keywords: Space telescopes, segmented apertures, starlight suppression.

1. INTRODUCTION

The many recent discoveries of planets orbiting other stars, first by ground-based methods such as radial velocity measurement, and more recently by the Kepler Space Telescope using transit photometry, indicate that many if not most stars do have planets, and that some have planets in the so-called Habitable Zone (HZ): in the range of orbits where liquid surface water can exist. Some of these HZ planets can be expected to be rocky, with atmospheric conditions that might make life possible – and a further small fraction of these might indeed harbor life. This realization is spurring great interest in building a telescope capable of directly imaging and spectrally characterizing exo-planets around nearby stars, to discover which are possible exo-Earths, and to probe for extra-terrestrial life.

A telescope capable of discovering and characterizing exo-Earths will also be enormously capable for general astronomy and astrophysics. To achieve the high resolution needed to image dim planets orbiting distant stars, the telescope will necessarily have a large aperture – large enough to resolve stellar populations in nearby galaxies, and large enough for efficient high-resolution spectroscopy. The optical quality required to separate the light from the dim planet from its parent star can only be achieved with a space telescope with extremely stable optics – making it capable of diffraction-limited imaging into the UV.

This paper examines the basic requirements for such a space telescope, flowing down key science requirements to establish specifications for the optical telescope and instrumentation. It provides a snapshot of work in progress, as some of the driving requirements depend on an evolving understanding of nature of exo-planets, especially the rate of occurrence of exo-Earths η_{Earth}, and the average density n of the exo-zodiacal dust clouds surrounding target star systems.

2. SCIENCE REQUIREMENTS

NASA's recently published 30-year roadmap[1] identifies 3 key science questions for Astrophysics, of which 2 can be addressed with a large-aperture space telescope. The first question, "Are we alone?," asks if there are there planets with the conditions for life elsewhere in our galaxy – and if so, how many. Can we find life – other Living Earths? The second question, "How did we get here?," looks towards a comprehensive theory of star and galaxy formation, probing galaxies and the Inter Galactic Medium (IGM), near and far.

The search for habitable planets will be done using new observational capabilities, for direct observation and characterization of many Earth-like planets orbiting solar type stars. This will require:

- Deep suppression of the light from the central star, using a coronagraph, or an external occulter, to expose any nearby dim planets. In particular, a contrast ratio of 10^{-10} between the peak intensity of the star image and the dark search region is required, with contrast stability of about 10^{-11}.
- High angular resolution, to be able to look close to the suppressed star, to the near edge of its HZ, where exo-Earth candidates will be. This will require an inner working angle (IWA) of about 40 milliarcsec for more distant stars.
- The sensitivity and resolution to find enough exoEarth candidates to provide a statistically meaningful result, by probing a large volume of space, out to about 30 parsec. This will require a large aperture as discussed below.
- The spectral resolution to find the signature of water, to identify potentially habitable planets. This can be done with spectroscopic resolution R of ~70 in the visible, after starlight suppression.
- The spectral resolution and sensitivity to resolve O_2 and O_3, and ultimately methane, to probe for the actual presence of life. This can be done with R < 500 in the visible and near-IR (VNIR) bands, after starlight suppression.

Ongoing studies of exo-Earth yield, by Stark[2], Brown[3,4] and others, based on the Hipparcos star catalog, are providing estimates of the numbers of Earth-like planets around long-lived stars for which spectra can be obtained, as functions of aperture size, mission time, observational efficiency, contrast and IWA, and of natural parameters such as η_{Earth} and n. Current estimates are summarized in Fig. 1, showing that an 8 m aperture telescope can find ~16 exo-Earth candidates, while a 16 m aperture yields ~60 candidates, assuming η_{Earth} = 0.1 and 1 year of integration time.

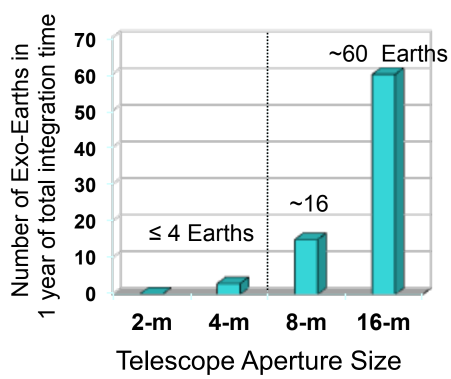

Figure 1. Exo-Earth yield vs. aperture diameter, from C. Stark et al[2]. Assumes η_{Earth} = 0.1.

A more general result for exo-Earth yield, vs. aperture diameter D and integration time t, while assuming η_{Earth} = 0.1 and n = 3 times solar dust levels, and a single visit, is:

$$N_{Earth} \sim 25(D/10\text{ m})^{1.8}\,(t/1\text{ year})^{0.4}$$

Developing statistically significant results for the rate of habitability and the rate of occurrence of life will require characterization of at least 2 dozen exo-Earth candidates. By this model and assumptions, a "10-meter class" telescope aperture will be required, with a minimum size of 8 to 10 m. This result is preliminary, and may change as the Kepler data continues to be analyzed, and as the operations concept built into the model improves.

A 10-meter class space telescope capable of characterizing dozens of exo-Earths will have the aperture and optical quality necessary for high-resolution UV-optical imaging and spectroscopy. It will be capable of resolving regions down to 100 parsecs in size anywhere in the visible universe (a trick enabled by the expansion of the universe), a key size scale in star forming regions in galaxies at almost any redshift. In nearby galaxies it will resolve regions down to 1 parsec, a capability that is critical for accurately determining star formation histories and gas flows within and surrounding those galaxies. An illustration of the resolution afforded by a large telescope vs. the Hubble telescope is provided in Fig. 2. A more detailed exposition of the scientific capabilities of a 10-m class space telescope, and the requirements flowing from that science, is provided in Postman[5].

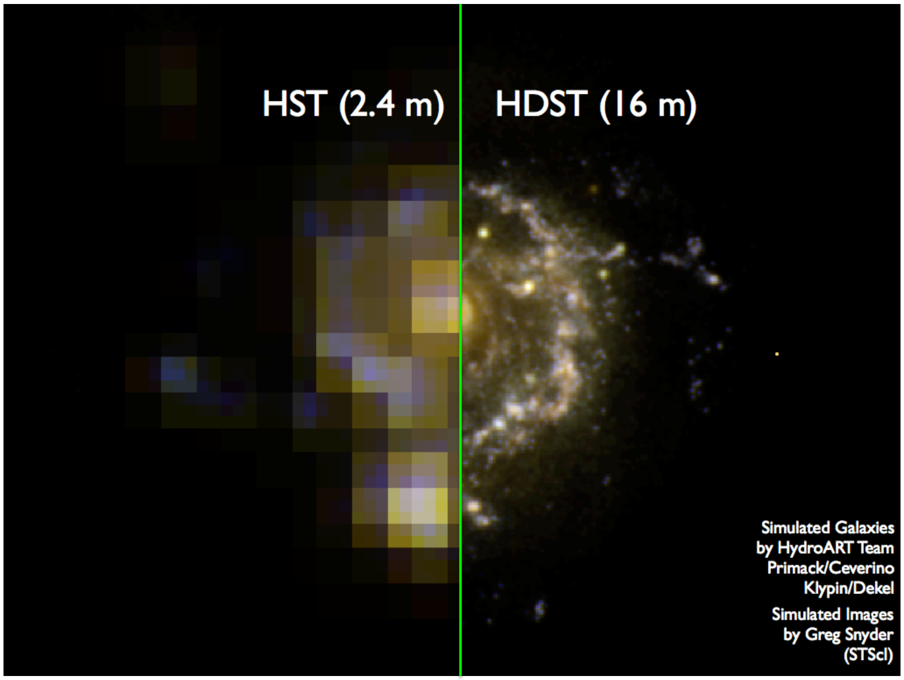

Figure 2. Comparison of the resolution of the Hubble Space Telescope (left) to that of a 16 m telescope, illustrating the resolving power of the larger aperture.

Other key requirements for general astrophysics, drawing the discussion in Postman[5], include:

- Broad spectral sensitivity: UV sensitivity from 110 to 300 nm wavelength, with a stretch goal of 90 nm to capture the Lyman α lines, and VNIR sensitivity from 300 to 2,500 nm.
- A wide field of view for VNIR imaging and photometry, from 4 to 8 arcmin, Nyquist sampled.
- Pointing stability to 1.3 to 1.6 mas.
- Diffraction-limited image quality at a wavelength ≤ 500 nm.

Table 1 summarizes the key science-driven requirements.

Table 1. Summary of driving science requirements. Stretch goals are in grayed out text.

Telescope Parameter	Consensus Value
Primary mirror diameter	≥ 8 meters
UV Sensitivity	(900 Å) 1100 Å – 3000 Å
Vis / NIR Sensitivity	0.3 μm – 2.5 μm (8 μm)
Pointing stability	~1.3 – 1.6 mas
WFE:	
General Astrophysics	Diffraction limited at 0.5 μm (~35 nm WFE)
Exoplanet Observations	~0.01 nm WF stability over ~600 sec (w/ actively controlled coronagraph)
Instrument Parameters	**Consensus Value**
Starlight suppression	10^{-10} down to IWA ~40 mas
UV Spectroscopy	R = 20,000 – 150,000
Exoplanet Spectroscopy	R = 70 - 500
Vis / NIR Imaging	FOV: 4 – 8 arcmin, Nyquist
UV Imaging	FOV: ~1-2 arcmin

3. ARCHITECTURAL CONSIDERATIONS

3.1 Aperture and launch vehicle

What sort of telescope can accomplish the scientific goals just described? Perhaps the first consideration is, should the aperture be monolithic – a single large mirror – or can it be segmented into multiple smaller mirrors, which are launched in a compact form and then deployed and phased together after launch? The answer to this question is important, because the launch vehicles that will be available in the coming decades have limited shroud sizes, imposing a limit on the aperture size of a monolith.

A rough estimate of candidate launch vehicles, and their shroud sizes, is provided in Table 2. As shown, only the SLS Block 2 vehicle with a 10 m diameter shroud would be large enough to launch a "10-meter class" monolith – and then the aperture would be limited to the low end of that range, to about 8 m. The 10 m SLS-2 shroud is not yet on a clear development path, however.

Table 2. Approximate launch vehicle availability.

		Shroud Size	***Mass to L2***	***Estimated Availability*** (2010, 2015, 2020, 2025, 2030, 2035)
EELV-Class	Atlas V 551	4.6x11 m	6,100 kg	
	Delta IV Heavy	4.6x11 m	9,800 kg	
	Falcon 9 Heavy	4.6x11 m	14,000 kg	
SLS	SLS Block 1	5x14 m	25,000 kg	
	SLS Block 2 8.4m	8.4x29 m	50,000 kg	One of these to be chosen
	SLS Block 2 10m	10x31 m	50,000 kg	

Segmented apertures avoid this problem. They can be launched in a folded configuration, like the James Webb Space Telescope (JWST), and then unfolded after launch to achieve an aperture larger than the shroud internal diameter, perhaps as much as 2.5 times larger. As discussed in Feinberg et al[6], and summarized briefly below, existing and projected EELV-class launch vehicles with 5-meter class shrouds can launch JWST-derived deployed apertures of 9-12 m size. Segmented apertures can also be assembled on orbit to nearly arbitrary size, though the infrastructure for on-orbit assembly would be quite costly. In the current situation, the science-driven requirement for 10-meter class aperture, plus launchability using existing as well as projected launch vehicles, favors the segmented aperture approach.

3.2 Starlight suppression

The primary concern for segmented apertures in the past has been their suitability for use with a coronagraph. The classic Lyot coronagraph for exo-planet imaging is an optical instrument that focuses the light from the large telescope onto an occulting mask – a carefully shaped spot or a line that obscures the light at the center of the field. Then the beam is re-expanded and passed through a Lyot stop, a shaped mask placed at a pupil image, which suppresses the immediate scatter from the occulting mask. The light is then refocused at a detector. The effect is to suppress the light at the center of the field – the central star – while passing the light from nearby objects such as planets, reducing the contrast at the detector between the residual starlight and the planet by many orders of magnitude.

Coronagraphs require careful shaping of the wavefront to avoid speckles from aberrations showing up in the detection region – the "dark hole." Speckles can be beaten down using a deformable mirror, driven in closed loop using a "speckle nulling" wavefront control algorithm. Complications arise in this scheme when there are aberrations on multiple optical surfaces, or variations in reflectivity across the pupil, effects which affect not only the phase but also the amplitude of the light. Adding a second deformable mirror at a different location in the beam train enables control of both the phase and amplitude, over a limited spectral band, to provide the needed contrast.

The challenge for an obscured and/or segmented aperture is that diffraction from gaps and edges scatters light across all spatial frequencies at the image plane, potentially filling the "dark hole" of a Lyot-style coronagraph and limiting its contrast performance. Recent progress in coronagraph design, extending the multiple deformable mirror approach to fill the gaps and obscurations of the aperture, has shown that this problem can be solved, at least at a theoretical level. A conceptual sketch of this approach for a JWST aperture is shown in Fig. 3. Other challenges for any image-plane coronagraph include very high sensitivity to changes in the system wavefront – requiring stability at the 10 picometer level to limit changes in contrast to the 10^{-11} level.

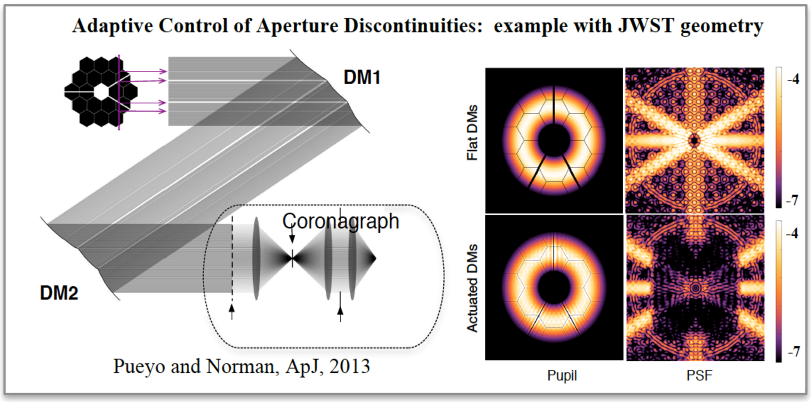

Figure 3. Sketch of a segmented aperture coronagraph, showing the use of multiple deformable mirrors to fill in gaps and obscurations to improve contrast performance[8]. The top 2 images on the right show the pupil and image plane illumination without DM correction; the bottom 2 images show illumination with DM shaping, with a much larger dark hole.

A different, interferometric approach to coronagraphic starlight suppression, using interference of the pupil with itself to null the light of the central star while passing light from nearby planets, offers potential advantages: nulling at the pupil reduces edge and obscuration diffraction effects. Examples are discussed in Lyon et al[9] and Shao et al[10].

Starlight suppression using an external occulter is also possible[11]. In this approach a separate "starshade" spacecraft, with a large deployed flat disc shaped to suppress the light from the central star, and precisely positioned between the telescope and the target star, can produce the required contrast for a segmented or monolithic aperture – see Fig. 4. In fact, using a starshade for starlight suppression would significantly ease the performance required of the telescope, relaxing scattered light, image quality and wavefront error stability requirements in some cases by as much as 1000x. Starshades have higher throughput, and are better adapted to broad-band observations, than coronagraphs: both important advantages.

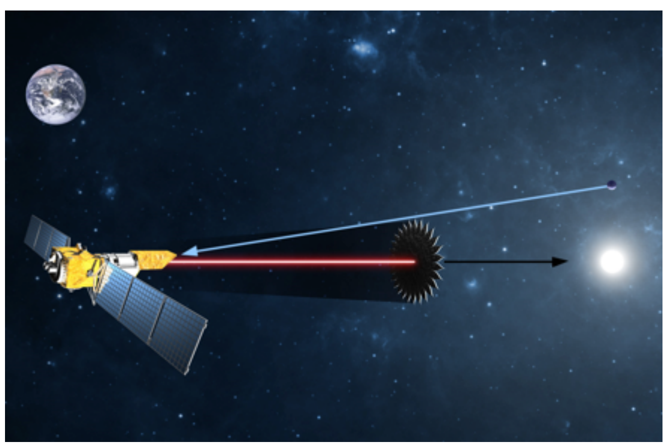

Figure 4. Sketch illustrating operation of a starshade and telescope, not to scale[11].

There are problems with starshades, however:

- The starshade spacecraft is large: 80 m or larger for an occulter optimized for a 10-m class telescope. Its launch, deployment and control represent significant challenges.

- The starshade spacecraft must be placed very far from the telescope, about 100,000 km if optimized for a 10-m class telescope.
- Retargeting times will be days to weeks, leading to poor observing efficiency. The large distances involved make changing targets a time consuming process.
- Other challenges include precision of edge shape, stationkeeping in a dynamic orbital environment, and the likelihood that each starshade will require a separate launch.

The current expectation is that coronagraphic methods will offer the most economical and efficient starlight suppression approach, provided of course that the theoretical performance predictions can in fact be achieved in real hardware. The strengths of the starshade approach are significant, however, and both methods should remain in consideration.

3.3 Instrumentation

The optical instruments for a coronagraph-equipped telescope are shown in schematic form in Fig. 5. As indicated, there are 2 sets of instruments. The UV imager and spectrograph, and the coronagraphic exoplanet imager and spectrograph, will be located at the Cassegrain focus, after the primary and secondary mirror only, to minimize the bounces the light takes. This is important for the shortest UV wavelengths, where transmission losses due to coatings are very high; and helps reduce the aberrations for the coronagraphic instrument. The second set of instruments is located at a Three-Mirror Anastigmat focus, following a tertiary mirror, to provide a much wider field of view for general astrophysics in the visible and near-IR bands. Key instrument specifications are noted on the figure.

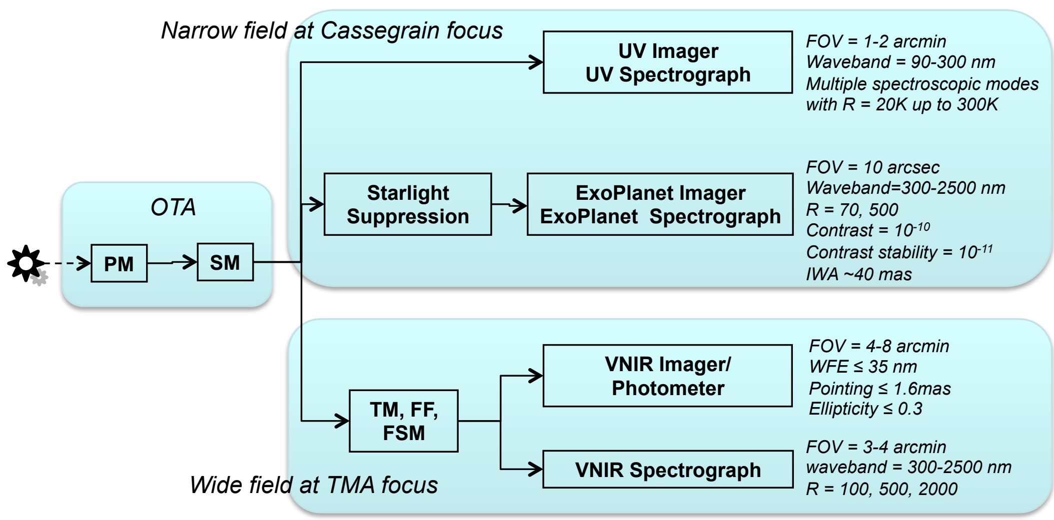

Figure 5. Instrument complement to meet science objectives.

4. TELESCOPE REQUIREMENTS

Can such a telescope be built? What new technologies will be required? How much will it cost, and how long will it take? To begin to address these questions it is helpful to flow down the top-level science requirements to key telescope subsystems. Some of this can be done in general, without requiring a particular design. In this section we do this at a very top level, for image quality for imaging, and for contrast performance with a coronagraph for starlight suppression.

- For image quality performance, the flowdown is to telescope wavefront error and line-of-sight stability, and then to mirror quality – and then we can address the readiness of particular mirror technologies.
- For contrast performance, the critical flowdown is to the coronagraph wavefront sensing and control loop, and then to telescope wavefront stability – providing a second critical specification for the mirrors and support structures.

This can be done for a monolithic or segmented aperture, with active or passive mirrors, to generate first-cut subsystem performance specifications for the Optical Telescope Element (OTE) – the primary and secondary mirrors and associated structures and subsystems. Then more detailed, design-specific work can be done to address the lower-level specs.

The image quality requirement for UV and VNIR imaging is that the telescope be diffraction limited at 500 nm wavelength (Table 1). This is interpreted as a requirement that the Strehl ratio in the imaging cameras should be 80% or better, critically sampled at 500 nm. Strehl ratio is driven by wavefront error, line-of-sight jitter and smear, and detector effects, as indicated in Fig. 6. The LOS contribution to Strehl is limited by the requirement that pointing stability is < 1.6 mas – this corresponds to a 5% reduction in Strehl. This is then reallocated to jitter and smear as shown. With a similar 5% allocation to the focal plane array detector, the Strehl from wavefront error is determined to be 0.89, corresponding to a total wavefront error of 27 nm RMS.

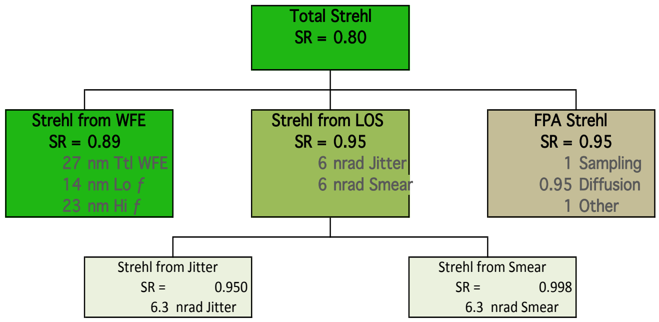

Figure 6. Flowdown from image quality to system wavefront error, line of sight pointing stability, and detector MTF.

This 27 nm total wavefront error is further flowed down as shown in Fig 7, to static and drift terms, in the OTE and instruments. The static errors represent post-wavefront control residuals – the errors that remain after the mirrors are carefully aligned and phased during periodic calibration sessions. The drift terms represent the largest permitted change in wavefront error between wavefront control intervals – the trigger values for recalibration. The numbers in the boxes correspond to the corrected wavefront error contribution from each subsystem – further flowdown is needed to set design-specific component level error specs.

Perhaps the most significant result is the primary mirror figure error specification of 19 nm wavefront error RMS. This level of performance sets an achievable target for mirror segment technologies. While further development work is required, both ultra-low expansion glass and SiC mirror technologies offer lightweight solutions capable of meeting this performance level[13,14] (Fig. 8).

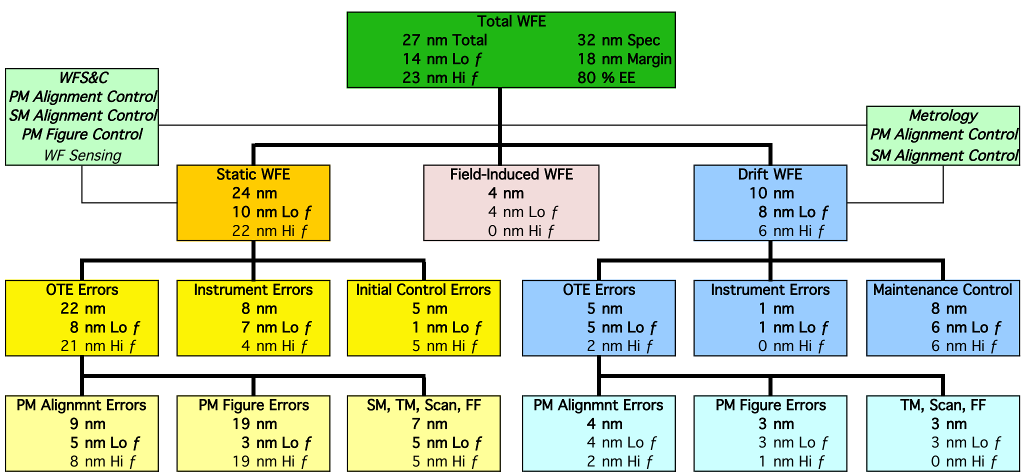

Figure 7. Flowdown from system wavefront error to OTE and instrument wavefront errors.

The flowdown from system contrast (Fig. 9) takes into account the wavefront sensing and control capabilities of the coronagraphic instrument. This is assumed to be capable of taking the telescope wavefront error as input, and using speckle-nulling wavefront control, using its deformable mirrors to reduce contrast to the target 10^{-10} level. The speckle-nulling loop is further assumed to operate at regular intervals, measuring the wavefront and updating the control, to keep contrast stable at the 10^{-11} level. The relevant interval is set by the number of photons that can be collected in the spatial frequency band of interest, namely dim speckles in the dark hole region, and there are few such photons. Consequently the time interval for control updates is long, about 10 minutes. Within this time interval, the telescope and coronagraph wavefront error drift must not exceed 10 picometers RMS. Thus the requirement for stability of the OTE is <10 picometers wavefront error per 10 minutes.

This stability requirement is very challenging, and must be a main focus of development efforts going forward. Can it best be met with low CTE materials and slow thermal control response – or is a high thermal conductivity and more aggressive thermal control the better solution? The answer to this requires more design specifics.

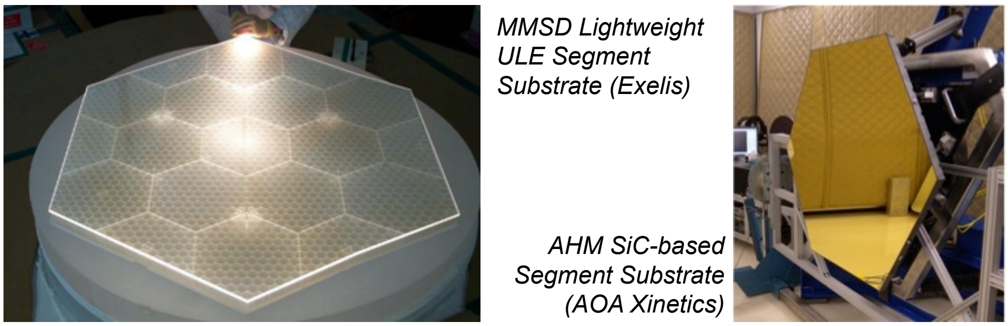

Figure 8. Example segmented mirror technologies.

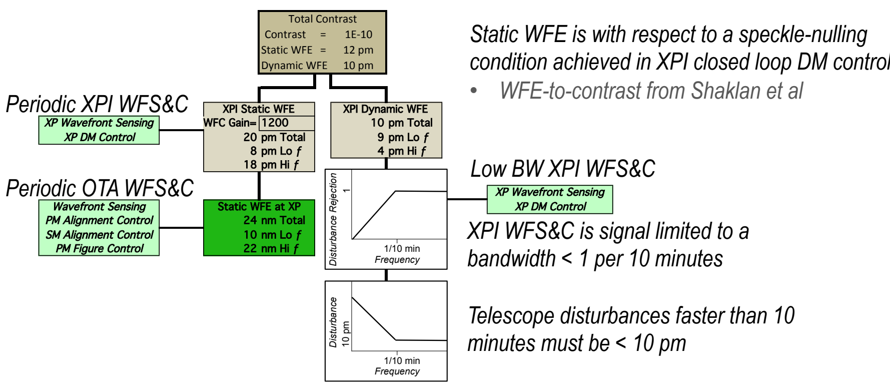

Figure 9. Coronagraph contrast error flow.

5. ATLAST STUDY

To provide the design specifics needed to make a more detailed assessment of feasibility and technology readiness, a NASA center-funded Advanced Technology Large Aperture Space Telescope (ATLAST) study is underway, with participation from Goddard, JPL, Marshall and the Space Telescope Science Institute. The scope of the study includes developing a sound science program for roadmap[1] objectives, as well as exploring technical and programmatic feasibility of candidate space telescopes and the identification of technology shortfalls. Most importantly from a requirements point of view, this activity includes an Engineering Reference Design (ERD) point design mission study, to provide design specifics for detailed engineering analysis. The ERD is sketched in Fig. 4 and described in more detail in Feinberg et al[6].

The ERD is not intended to be "the" design for NASA's eventual large UVOIR space telescope. Rather it is used to provide context for exploration of detailed technical issues, focusing on a segmented architecture with a coronagraph. It is representative of a range of such solutions, and will scale up to 16 m aperture – larger if on-orbit assembly is enabled. The final size and other key system parameters will change if science requirements change, as more observational data is processed, from Kepler and other sources. That said, the ERD is intended to be a feasible design as is.

The ERD design builds on JWST experience, leveraging many lessons learned, while avoiding some key cost drivers. It utilizes JWST deployment techniques, wavefront sensing and control technology, and a flat sunshade. It avoids cryogenic systems, a major JWST cost driver. The primary mirror optics will be relatively conventional, low-expansion glass or SiC, which can be manufactured in far less time than the cryogenic Be mirrors JWST uses. It uses a simpler, 3-layer sunshade, with a more robust flat deployment approach.

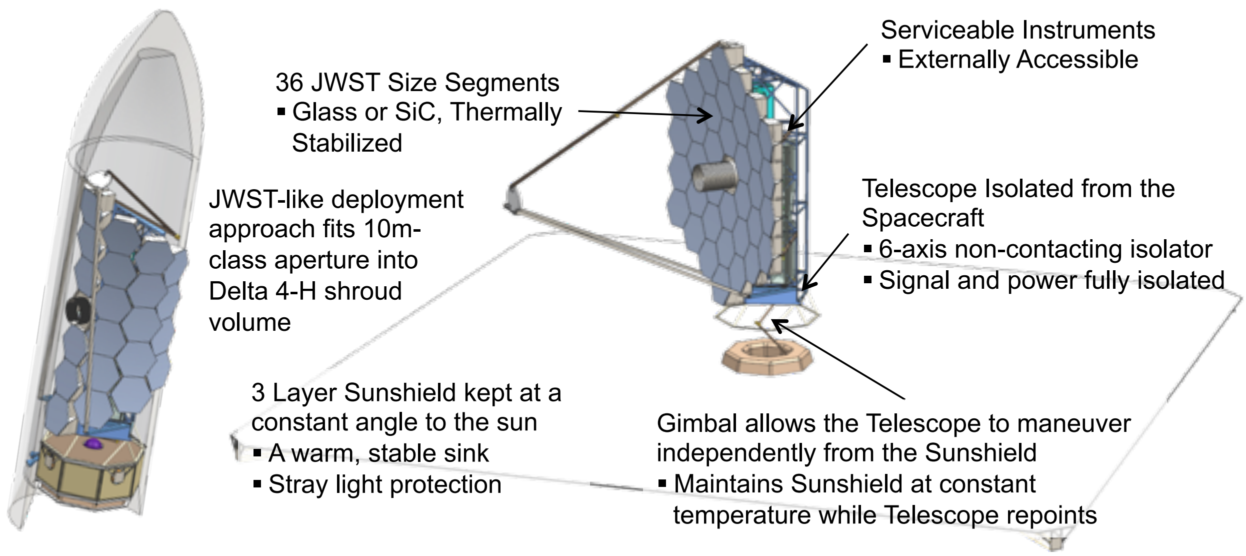

Figure 10. ATLAST 9.2 m aperture Engineering Reference Design concept.

Issues that the ERD will be used to explore include thermal and dynamical stability of the wavefront and line-of-sight, thermal control of optics and structures, isolation and vibration suppression requirements, wavefront control and metrology, and especially starlight suppression performance. These issues require detailed analysis, but will provide insight that can be extended to a range of telescope designs.

6. CONCLUSION

A space telescope capable of meeting the ambitious science goals discussed here could be built in the decade after 2020 if certain key technology issues are addressed in this decade. The highest priority development items are clear:

- Development of internal coronagraph designs capable of 10^{-10} contrast at an inner working angle of 2-3 λ/D, with an obscured, segmented aperture, suitable for operation with a 10m-class telescope; and development of large starshade designs suitable for operation with a 10-meter-class telescope.
- Investment in segmented mirror systems, to prove mirror system performance, dynamical stability, thermal stability, and cost for 10 meter-class apertures, to the levels required for coronagraphy; with testing to validate the models.
- Advancement in UV-Visible-NIR detector and mirror coating technologies, to realize the high spatial resolution and high sensitivity enabled by a large telescope and to maximize the scientific return of its instruments.

7. ACKNOWLEDGEMENTS

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