

LUVOIR Tech Notes

Matthew R. Bolcar

Below we present nine “tech notes” prepared by the Large UV/Optical/Infrared (LUVOIR) Science and Technology Definition Team (STDT), Study Office, and Technology Working Group. These tech notes are intended to highlight technical challenges that represent boundaries in the trade space for developing the LUVOIR architecture that may impact the science objectives being developed by the STDT. These tech notes are intended to be high-level discussions of the technical challenges and will serve as starting points for more in-depth analysis as the LUVOIR study progresses.

The nine tech notes are as follows:

Starlight Suppression with Coronagraphs – Stuart Shaklan

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The Long Wavelength Limit of LUVOIR – Michael Werner

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Starlight Suppression with Coronagraphs

Stuart Shaklan

Stellar coronagraphs are instruments designed to suppress the veiling glare of starlight so that faint planets can be seen adjacent to their parent stars. The glare is caused by both diffraction (sidelobes) from the aperture boundaries including the outer limit of the pupil, the secondary obscuration, secondary support structures, and mirror segment gaps, and scatter from the imperfect optical surfaces in the telescope and instrument. Generally speaking, coronagraphs are easier to implement on filled, off-axis apertures than on segmented, on-axis apertures.

The diffraction problem can be addressed in three ways. First, the pupil can be apodized, either by placing a mask at a pupil image, or by using optics to concentrate the beam in an advantageous way. Apodization, like a low-pass electronic filter, reduces sidelobes. Figure 1 shows a gray scale apodization function for a segmented aperture telescope, while Figure 2 shows an optical remapping solution. The second approach is to use specially shaped masks in the image plane followed by another mask at the reimaged pupil, called the Lyot plane (Figure 3). The first mask causes on-axis light in the image plane to diffract outside the Lyot stop. Off-axis light from a nearby star passes around the mask and then through the Lyot stop. Third, the pupil light can be split into two beams and then recombined using a phase shift and beam shear to cancel the on-axis starlight (Figure 4). Coronagraph designers are gravitating toward hybrid approaches combining pupil apodization and image plane masking to deal with segmented apertures.

With diffracted light eliminated from the system, scattered light originating with aberrations, coating defects, and contamination remains and must be removed. This is achieved by flattening the wavefront using a deformable mirror (DM), with typically > 1000 actuators within the pupil (Figure 5). To control the wavefront, it must first be sensed. This is done by adjusting the DM surface several times while recording the change in image plane illumination. An algorithm then determines the required wavefront correction and commands the DM to form a new surface shape. This is repeated until a “dark hole” is formed with a level of glare low enough to expose a planet. Figure 6 shows a dark hole achieved in the laboratory in a 10% bandpass.

The desired level of suppression is 10^{-10} ; that is, the residual scatter in the image plane after diffraction and wavefront control is 10 billion times below the level of the incident starlight. Amazingly, this can be achieved using standard quality optics and is limited mainly by the ability to accurately set the DM and to hold the system stable. The stability issue is perhaps the most challenging, with sub-nanometer requirements imposed on the wavefront. This is particularly challenging when it comes to low-order aberrations such as pointing, focus, coma, and astigmatism. To measure and control these terms, low-order wavefront sensors with fast response times using the rejected starlight are being developed.

The effectiveness of coronagraphs is a function of the inner working angle (IWA), bandwidth, throughput, and level of glare suppression. Typically, more aggressive coronagraphs (those with small IWA that suppress glare very close to the star) have lower throughput and greater sensitivity to the finite stellar diameter, resulting in light leaking into the image plane. The challenge of suppression increases with optical bandwidth; the broader the band (more signal photons), the more background appears. Perhaps most importantly, the IWA scales proportionally with wavelength. The same coronagraph that works at 50 milli-arcsec (mas) at a wavelength of 500 nm will be limited to about 100 mas at 1 μm . This is an important factor when characterizing exoplanet spectra in the near IR.

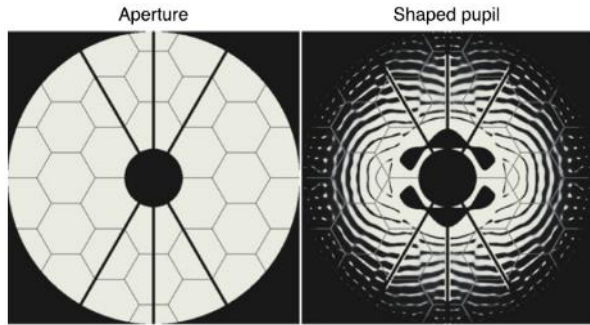


Figure 1: Pupil apodization on a segmented aperture. N'diaye *et al.*, *ApJ* 818:163 (2016).

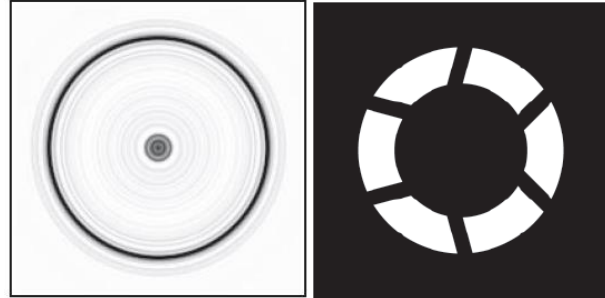


Figure 3: Hybrid Lyot image plane mask (left) and Lyot mask (right) for the WFIRST coronagraph. Trauger *et al.*, *Proc. SPIE* 8864, 886412 (2013).

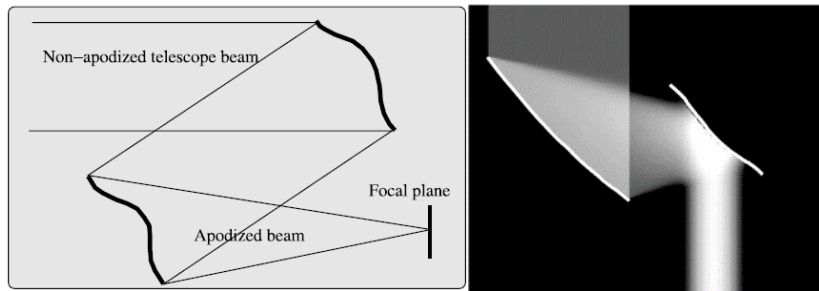


Figure 2: Pupil remapping. Guyon *et al.*, *ApJ* 622:744 (2005).



Figure 5: 64 x 64 element DM with a fused silica facesheet. Trauger *et al.*, *Proc. SPIE* 8151, 81510G (2011).

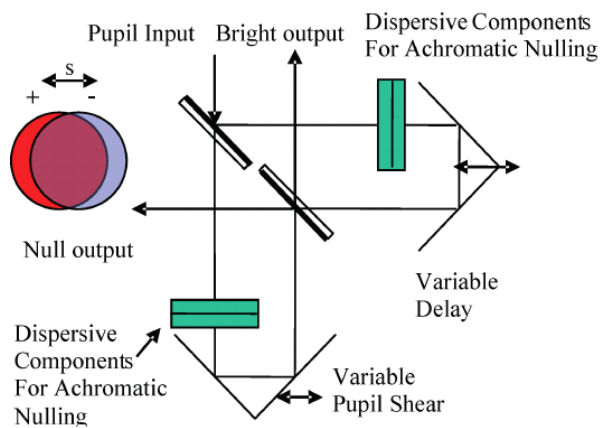


Figure 4: Nulling coronagraph. Shao *et al.*, *Proc SPIE* 6265, 626517 (2006).

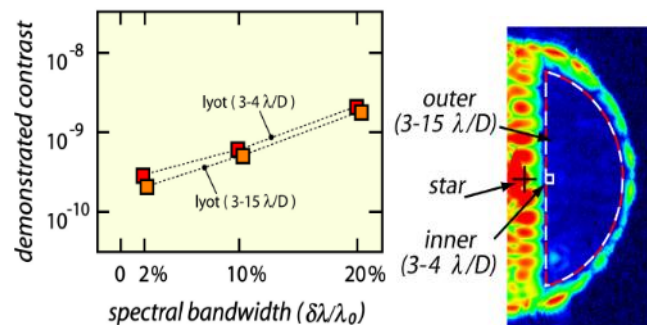


Figure 6: Dark hole in broadband light, demonstrated at the JPL High Contrast Imaging Testbed. Trauger *et al.*, *Proc. SPIE* 8151, 81510G

High-Contrast Imaging with Starshades

Aki Roberge

Starshades are a relatively newer idea for providing the extreme high-contrast needed for exoplanet direct observations. They have strengths and weaknesses that are complimentary to those of coronagraphs. A starshade is an independent spacecraft flying in formation with the telescope (Figure). The goal is to keep the telescope in the shadow cast by the starshade, and keep both spacecraft aligned with the target star. The larger the telescope, the larger the starshade needs to be. The edges of a starshade have a very particular shape to control diffraction and deepen the shadow at the location of the telescope. An example of a small starshade mission concept can be seen in this video: <https://exoplanets.nasa.gov/resources/1015/>. A lecture on the Theory and Development of Starshades given at the 2014 Sagan Summer Workshop is available here: https://www.youtube.com/watch?feature=player_detailpage&v=h5w6z0jow1Q#t=0.

A starshade blocks the unwanted bright light from an exoplanet host star before it enters the telescope, while allowing light from nearby planets to pass nearly unattenuated. Therefore, internally scattered light reaching the detector is minimized. Telescope segments and obstructions do not need to be masked out and the wavefront does not need to be corrected with deformable mirrors. The contrast and inner working angle (IWA) no longer depend on the telescope diameter but rather the starshade size and separation from the telescope. For planets in habitable zones of nearby sun-like stars, the separations are tens to hundreds of thousands of km depending on the size of the starshade, which is several tens of meters in diameter.

Starshades have no intrinsic outer working angle. They can be designed to operate over large bandpasses (several times larger than coronagraph bandpasses) and to provide small IWAs at virtually any wavelength. For a fixed IWA and contrast level, the required starshade size increases with wavelength. Since the starshade is not part of the optics train, internal reflections are kept to a minimum and total throughput is high. This makes them excellent for deep spectroscopy, especially in the NIR where coronagraphs struggle to provide small IWAs. On the negative side, the need to slew the starshade over huge arcs to realign it with different target stars means there are long intervals (days to weeks) between the high-contrast observations and the total number of observations is fuel limited. The telescope can do other kinds of astronomical observations in the intervals, but starshades are relatively inefficient for high-contrast surveys. The starshade and telescope must be precisely aligned during observations to maintain high contrast. Keeping the telescope in the darkest part of the starshade shadow generally translates to lateral position precision of about a meter (the separation precision is much less stringent).

Full-scale end-to-end system tests on the ground are not possible, although sub-scale tests are being done in the lab and in the field (Figure). The large sizes of starshades means that they must be folded up for launch and deployed in space. The exact shape of the optical edge must be accurate (on the order of 100 μm tolerance for contrast in the 10^{-10} range) after deployment. Further, the thin edge of the starshade must be engineered to minimize sunlight scattering back into the telescope. More information on starshade technology development may be found at <https://exoplanets.nasa.gov/exep/technology/technology-overview/>.

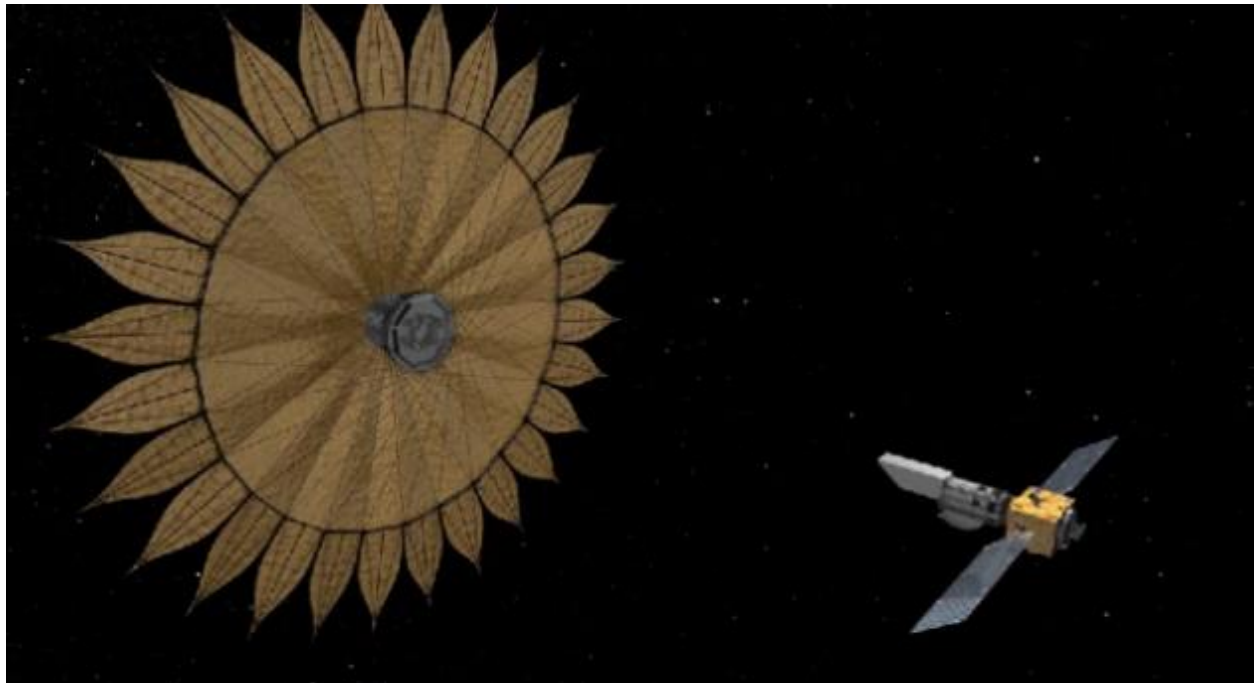


Figure 1: Artist's conception of the Exo-S mission concept, a starshade paired with a small telescope. The image captures a moment just after starshade deployment. Credit: NASA / JPL / Caltech.

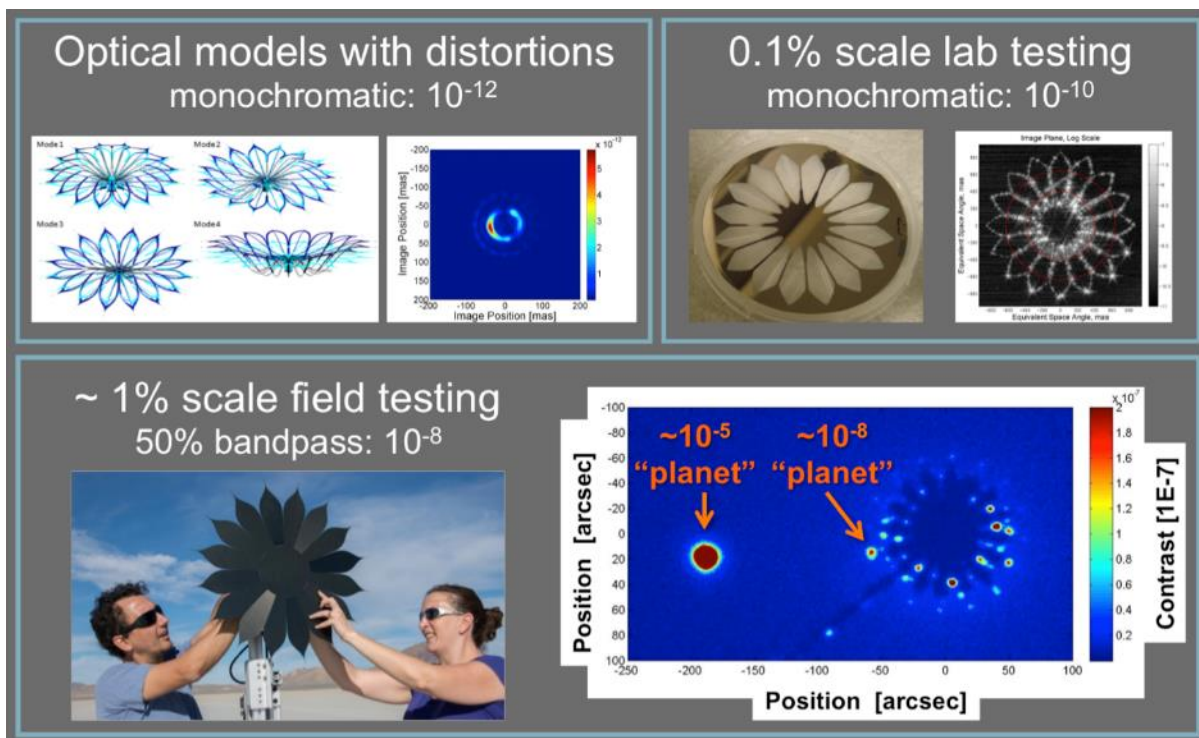


Figure 2: Summary of recent starshade contrast performance testing: modeling done at JPL (upper left panel), sub-scale lab demonstrations in the Princeton University testbed (upper right) panel, and sub-scale field demonstrations executed by Northrop Grumman (lower panel).

Impacts of Optical Coatings on Polarization and Coronagraphy

Matthew R. Bolcar

The LUVUOIR mission's exoplanet science objectives require high-contrast imaging with an internal coronagraph. A coronagraph's wavefront control system uses deformable mirrors to correct amplitude and wavefront aberrations in the optical system, allowing the diffracted starlight to be suppressed so that orbiting exoplanets can be directly observed. Metallic coatings that are typically used on mirror surfaces present a challenge for a coronagraph's wavefront control system. Specifically, the orthogonal polarization states of light (often denoted by "s" and "p") are affected differently by the coating, as a function of wavelength, angle of incidence, and coating properties.

There are two effects of concern. The first effect is polarization aberration, where each polarization state sees a different amplitude (*diattenuation*) and phase change (*retardance*) upon reflecting from a metallic surface (see Figure 1). The second is cross-polarization leakage, where some portion of a polarization state is converted into the orthogonal state upon reflection. The result of these two effects is that when unpolarized light (such as starlight) reflects from a metallic surface, four independent (or incoherent) electric fields are created: *s*-incident light reflected in the *s*-state ("ss"), *s*-incident light reflected in the *p*-state ("sp"), *p*-incident light reflected in the *p*-state ("pp"), and *p*-incident light reflected in the *s*-state ("ps"). Since these fields are incoherent, a coronagraph can only control and correct for one of these fields at a time. Thus, if the wavefront control system is sensing and correcting the amplitude and wavefront aberrations of the *ss* electric field, the other three fields will contribute to leaked starlight that could potentially obscure an exoplanet. It is important to note that the cross-polarization terms (*sp* and *ps*) are orders of magnitude smaller than the primary terms (*ss* and *pp*).

There are several ways to address the polarization issues:

Telescope Design Considerations: Both effects are strongly dependent on the angle-of-incidence (AOI) of the light at the optical surface. Slower (high-F/#) optics will have lower AOIs across the surface of the mirrors, thus minimizing the polarization effects. Flat mirrors that are used to fold the optical path at large angles should also be avoided, or used in pairs such that the effects are cancelled out. Slower optics, however, can lead to longer systems with smaller fields-of-view. The impacts of polarization aberration and cross-polarization leakage must therefore be traded against volume constraints and science objectives.

Coating Properties: The polarization effects are also dependent on the coating properties, specifically the index of refraction; choosing appropriate materials can help minimize the effects. To enable the LUVUOIR mission's ultraviolet (UV) science objectives requires a protected aluminum coating on at least the primary and secondary mirrors. It is expected that there is little that can be done from a coating perspective to further reduce the polarization effects, aside from ensuring that the protective overcoat material does not significantly increase the effects over the base aluminum layer.

Coronagraph Architecture: Perhaps the most effective way to deal with polarization aberrations is to split the light at the coronagraph and only observe one polarization at a time. This can be done serially by a single instrument. A polarized filter would select a single polarization state for

which the aberrations would be sensed and observed, allowing for exoplanet detection and correction in that polarization state. The orthogonal polarization state could then be selected and the observation repeated. This approach is similar to that adopted by the WFIRST coronagraph instrument, but has the drawback of requiring twice the amount of time to capture all of the exoplanet photons. Alternatively, the polarization states can be split with a polarizing beam-splitter, with each being sent to a separate coronagraph instrument. This allows for simultaneous observation of all of the exoplanet photons, at the expense of requiring two coronagraph instruments, each with its own focal plane, filter wheels, deformable mirrors, and associated electronics.

Regardless of the approach taken, there are two key questions that remain to be answered. The first question is how effective polarizing filters or polarizing beam-splitters are at separating the orthogonal states. Achieving 10^{-10} raw contrast may require polarizing optical components that are beyond the state-of-the-art. The second question regards the cross-polarization leakage term. When a single polarization state is selected (say, s), both the ss and ps components are transmitted. If the coronagraph wavefront control system senses and corrects the ss component, then the ps component will contribute a static speckle background that may obscure an exoplanet. Modeling must be performed on a LUVUOIR-relevant architecture to fully understand the magnitude of the cross-polarization terms and if they are significant enough to be of concern. If they are, additional post-processing steps may need to be taken to calibrate these terms out.

It is important to note that coating-induced polarization aberration and cross-polarization leakage will be generated by *any* metallic mirror coating. Figure 2 shows the diattenuation and retardance for both a bare aluminum-coated and bare silver-coated mirror. Both aluminum and silver have similar order-of-magnitude effects. ***It is therefore a false assumption to believe that high-contrast coronagraphy can be prioritized over UV-observations by switching from an aluminum coating to a silver coating.***

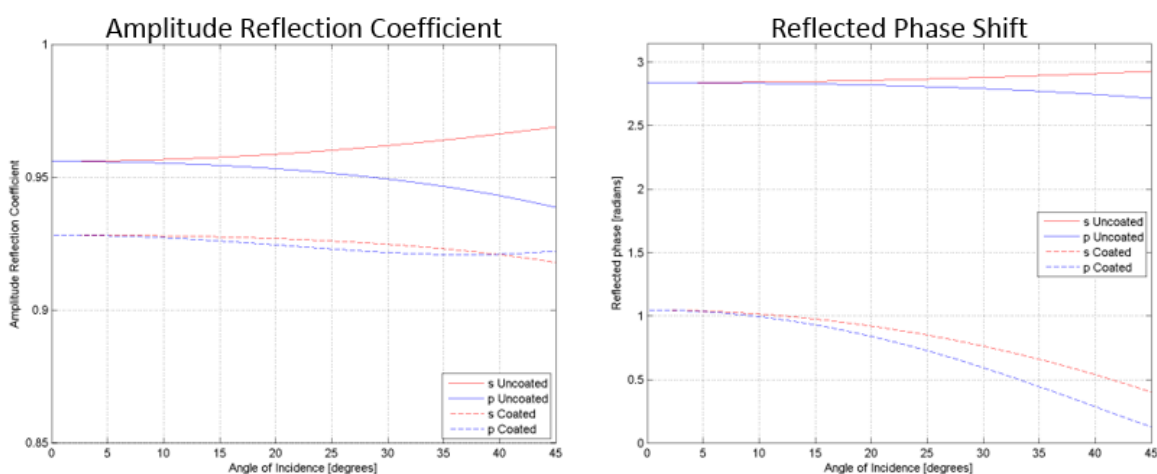


Figure 1 – Left: Amplitude reflection coefficient for each polarization state as a function of angle of incidence for a bare aluminum mirror (*solid lines*) and an aluminum mirror coated with a quarter-wave of MgF_2 (*dashed lines*). **Right:** The reflected phase shift for the same two cases. In each case, the orthogonal polarization states experience a different amplitude and phase change upon reflection. Angles of incidence at the primary and secondary mirrors for an on-axis, 12-m-class telescope would typically be less than 15 degrees.

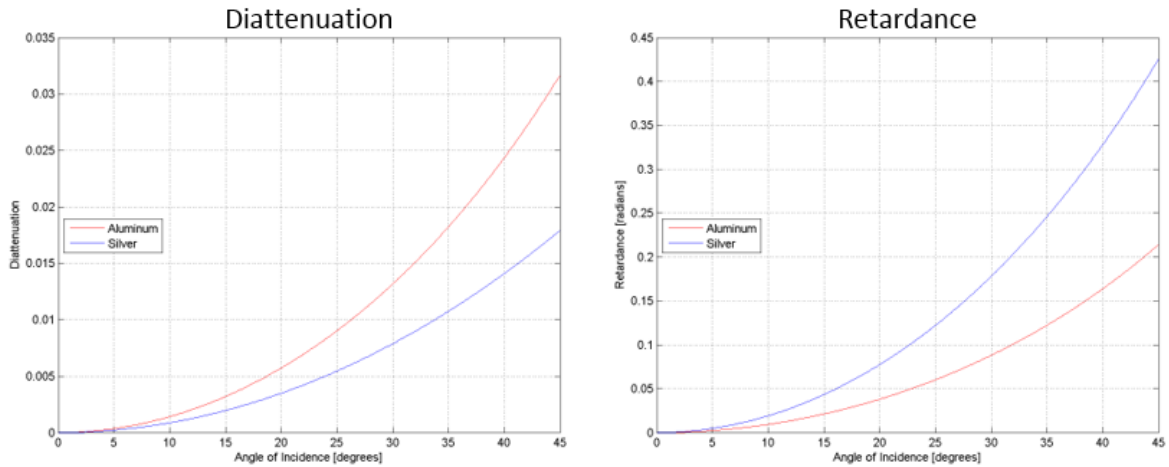


Figure 2 – *Left*: The diattenuation (normalized reflected amplitude difference between polarization states) as a function of angle of incidence for bare aluminum and bare silver coatings. *Right*: The retardance (absolute reflected phase difference between polarization states) as a function of angle of incidence for the same two metals. Angles of incidence at the primary and secondary mirrors for an on-axis, 12-m-class telescope would typically be less than 15 degrees.

Getting to Orbit: Launch Vehicles

Norman Rioux

The LUVVOIR mission has the potential to enable revolutionary scientific breakthroughs with the largest telescope aperture ever deployed in space. While in the distant future, telescopes might be assembled in space, the most economical and immediate path forward is to put a large aperture in space with a single launch. In the mid-2020s, the launch vehicle industry will not be exactly the same as it is now. Here we summarize our understanding of the current and future launch capabilities.

A strong candidate for the orbit of the LUVVOIR observatory will be at Sun-Earth L2, which provides a stable thermal environment and excellent field of regard. Constraints on the size of the telescope aperture and the instrument suite include the mass-to-orbit and the size of the fairing that the launcher can provide. A mission with the ambitious goals of LUVVOIR will surely need a heavy lift launch vehicle. In order to control launch vehicle risk and its associated costs, telescope designs with the flexibility to use a variety of different launch vehicles and fairings are desirable.

Figure 1 depicts representative values of lift capabilities for a variety of launch vehicles to Sun-Earth L2 orbit. Figure 2 depicts the outer diameters of the associated fairings. Not all of this space will be available to the payload; margins of roughly 0.5 to 1 m are needed to allow payload motions during launch. These launch vehicles range in maturity from existing vehicles with proven flight records to vehicles that are undergoing development. Below we highlight a few of the larger vehicles most relevant for LUVVOIR.

Delta IV Heavy is an existing heavy lift launch vehicle with a proven track record. It supports a fairing with a 5-m outer diameter and a 4.6-m inner diameter. United Launch Alliance (ULA) has stated that they will continue to manufacture the Delta IV Heavy for as long as the US Air Force wants it. ULA indicates that they intend to build a heavy lift successor to the Delta IV Heavy that will compete with the Falcon Heavy discussed below.

Falcon Heavy is in development by Space X; it will offer lift capability in excess of the Delta IV Heavy. Its payload fairing is currently in development and indicated as having a 5.2-m outer diameter. The inner diameter of the fairing is not currently specified, but it is reasonable to assume it will be similar to that of other 5-m-class fairings. The Falcon Heavy is expected to be relatively economical (launch cost of order \$100M).

Space Launch System (SLS) is currently in development in a variety of versions. Options are under study for fairings with 5-m, 8.4-m, and 10-m outer diameters. GSFC and the SLS Program Office at MSFC have instituted engineer-to-engineer working group meetings to develop conceptual interfaces between large aperture telescope observatory concepts and the SLS launch vehicle. The unsurpassed mass-to-orbit and fairing volume of SLS provide obvious advantages for a large aperture space telescope.

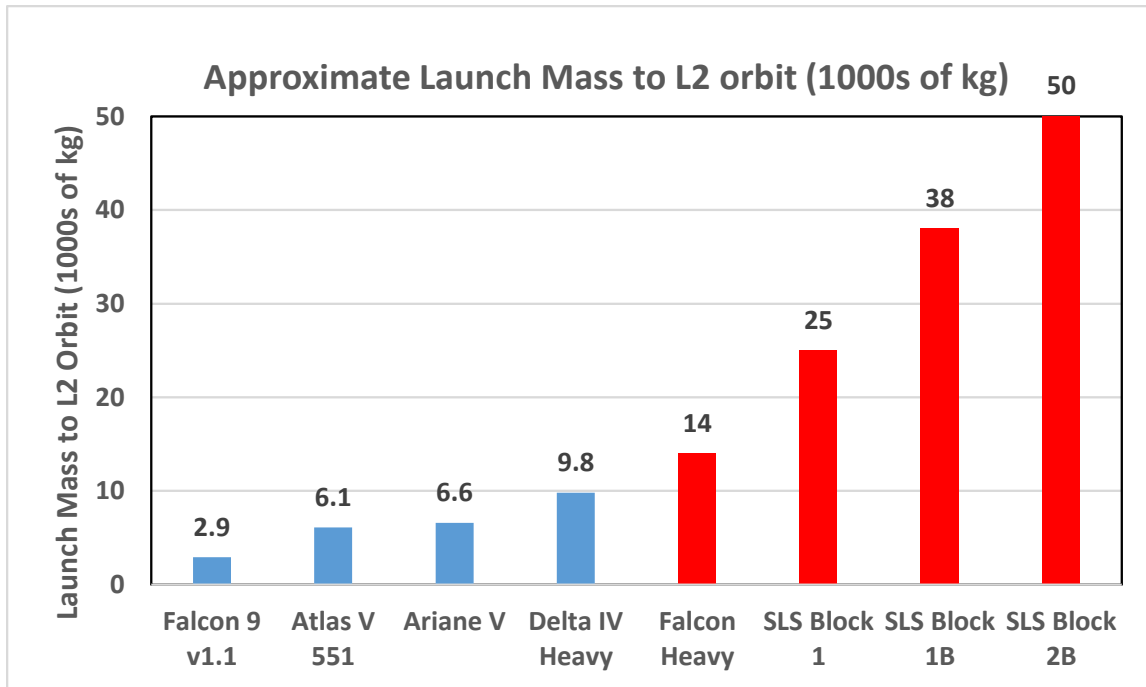


Figure 1 - Launch mass to Sun-Earth L2 orbit for a variety of current and future launch vehicles. Existing vehicles are in blue, ones in development are in red. These are representative values subject to refinement of designs in development and evolution of existing vehicles.

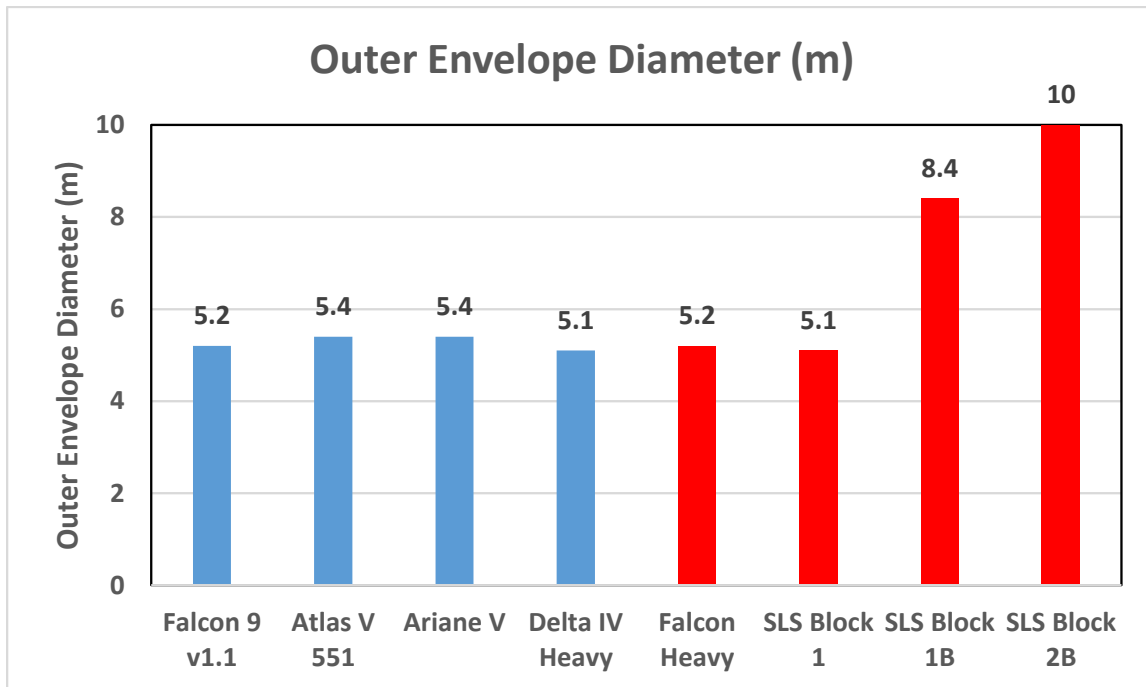


Figure 2 - Launch fairing diameters for a variety of current and future launch vehicles. Existing vehicles are in blue, ones in development are in red. These outer diameters correspond to the exterior physical extent of the fairing. Inner diameters are developed through coupled loads analyses with particular payloads and are roughly 0.5 to 1 m smaller. All these fairing diameters are representative values subject to evolution of existing vehicles and refinement of designs in development.

LUVUOIR Telescope Temperature

Lee Feinberg

Motivation

The LUVUOIR team would like to understand if operating the telescope below “room temperature,” nominally 290 K, will help improve the 1.7 μm hard stop where thermal emission becomes an issue. This whitepaper discusses the issues with operating LUVUOIR at temperatures below 290 K.

Temperature vs. Zodiacal Light

The first question is what temperature a telescope needs to operate at to enable longer wavelength science. To assess this, one must consider the temperature of everything in the optical chain (primary mirror, secondary mirror and struts, instrument optics and components, etc.). For simplicity, one can consider the radiance vs. wavelength of the telescope, including coatings, for varying temperatures. This assessment is shown below and was provided by Paul Lightsey of Ball Aerospace Technology Corporation. The case is a bounding case since it uses minimum Zodiacal emission (“Zodi”) and 1.2 \times Zodi for comparison. When looking in the ecliptic, the zodiacal light is nearly 3 \times brighter. This analysis also uses Aluminum coatings which is the more pessimistic for IR emission, but the preferable coating for observations in the UV. However, gold and silver coatings, instead of aluminum, do not have a large impact to the story for telescope temperature and can be ignored at this level of fidelity.

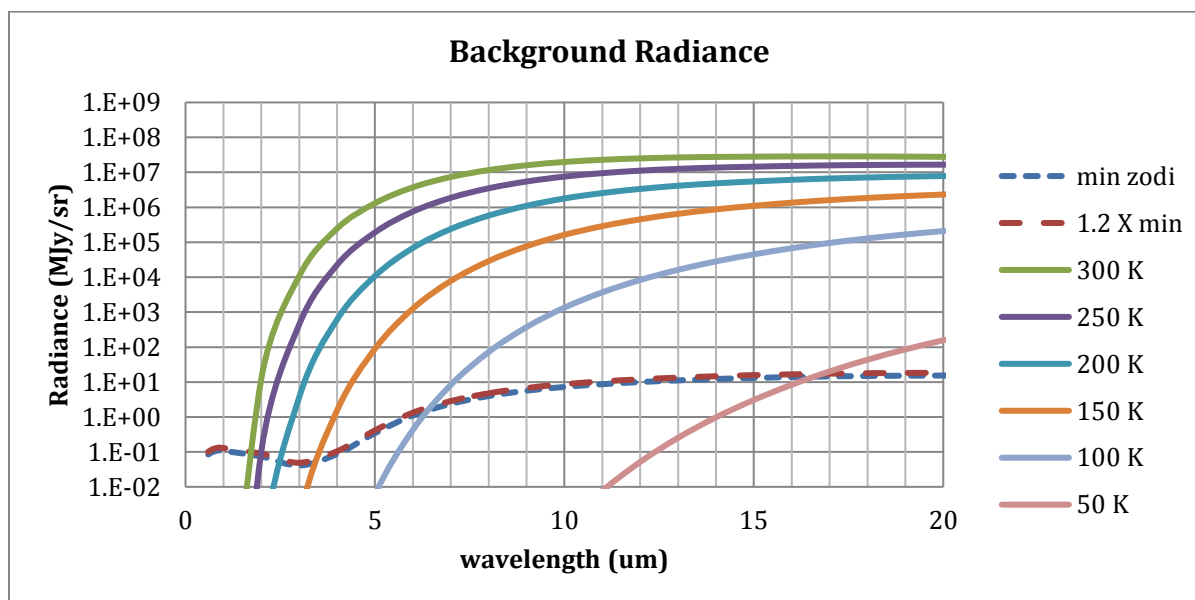


Figure 1: Radiance for different telescope temperatures

While achieving Zodi-limited performance may not be necessary, Fig. 1 shows that to get to 2.5 μm means a telescope needs to be roughly 200 K. Also, a reduction of approximately 50 K from room temperature buys about 0.3 μm near the Zodi limit.

Impacts

There are a number of issues associated with operating a telescope at cold temperatures

and the impacts vary depending on temperature and system architecture. A summary of these options and the level of complexity they add at different temperature regimes is shown in Figure 2 below. The temperatures chosen were natural break points which derive from physics. For example, we know that quartz crystal microbalance (QCM) monitors during JWST testing start to show large depositions at 260 K (a point where molecular deposition starts to happen), 200 K is above the upper bound of where ice forms in vacuum (roughly 140 K to 170 K) but includes other molecular depositions, 140 K is at the lower bound of where ice forms in vacuum and where some materials have become CTE-stable (coefficient of thermal expansion), and 50 K is the JWST heritage where everything is frozen and Beryllium and JWST M55J laminates are stable.

	293K	260K	200K	140K	50K	NOTES:
	Room temperature	Where molecules start to stick	Above ice allows 2.5um Zodi limited	Water is frozen	JWST Heritage	
Areas:						
Stability for ULE, Zerodur	Green	Yellow	Yellow	Yellow	Yellow	ULE at room temp has best published performance
Stability for SiC (Assume Cladded Si)	Yellow	Yellow	Yellow	Yellow	Yellow	Can use integrated actuators at room temp, cryo is tbd
Stability for Beryllium	Green	Yellow	Yellow	Yellow	Green	
Stable Composite CTE Heritage	Green	Yellow	Yellow	Yellow	Green	
Composite Complexity	Green	Yellow	Yellow	Yellow	Yellow	Strength of bonds, tube CTE, etc
Room Temperature Alignment	Green	Yellow	Yellow	Yellow	Yellow	
Cryo/Cold Polishing Complexity	Green	Yellow	Yellow	Yellow	Yellow	
Molecular Sticking for UV	Green	Yellow	Yellow	Yellow	Yellow	
Dynamics/Damping	Green	Yellow	Yellow	Yellow	Yellow	
Coronagraph	Green	Yellow	Yellow	Yellow	Yellow	WFIRST and HCIT heritage is room temp, includes DM's
Material Stress/Strength	Green	Yellow	Yellow	Yellow	Yellow	
Heater Power/Thermal	Yellow	Yellow	Yellow	Green	Yellow	
Cryo/Thermal Testing	Green	Yellow	Yellow	Yellow	Yellow	
Lubricants	Green	Yellow	Yellow	Yellow	Yellow	
System Optical Testing	Green	Yellow	Yellow	Yellow	Yellow	Requires cold system optical testing
Epoxy and bond considerations	Green	Yellow	Yellow	Yellow	Yellow	
Shock	Green	Yellow	Yellow	Yellow	Yellow	
Composite Coef Moisture (CME)	Yellow	Yellow	Yellow	Yellow	Green	
		Highest Risk/Very Ha	Intermediate Risk/Moderately Hard	Lowest Risk/Easy		

Figure 2: Temperature Cases vs. Complexity Considerations

Below is a summary of each of the considerations in the table. The topics are grouped by whether they are a significant factor in the trade space or not.

Significant Factors:

UV Molecular Sticking – A critical factor in considering cold telescope is the fact that UV systems are extremely sensitive to even monolayers of UV absorbing molecules. The physics of this is related to absorption due to thickness of the contamination layer and the actual molecule type. As contaminants build up, the shortest wavelengths will see reductions first in throughput for layers as thin as a few Angstroms. For thicker films, quarter-wave effects will also come into play, but the first order phenomena is absorption.

To deal with molecular absorption, a key driver in UV systems is to carefully select, bake,

and certify all materials to minimize molecular adherence and there is a long heritage of doing this at room temperature where the sticking coefficients in vacuum are low. Despite extensive work, epoxies, plasticizers used in cables, hydrocarbons from lubricants, and many other small residuals will exist and would stick depending on mirror temperatures. Water will also absorb and sticks in the 140-170 K range. For cryogenic optics or components, it is very possible that frequent bakeouts would be needed or even dual modes where baked off products are carefully managed (venting of cold fingers). There is not a heritage of doing this for UV systems because of the complexity.

An obvious question is whether any reduction in temperature can be acceptable. During JWST instrument testing, it was routinely found that at 243 K the QCM sensor would show significant depositions while at 258 K they did not. This suggests that 258 K is an approximate cutoff where molecules deposit (how many are UV absorbing will depend on species). One strategy with cryogenic systems is to freeze water and other species out by going below 140 K (keeping mirrors warmer during cool-down). However, warm electronics and mechanisms make this very difficult and the UV instruments themselves have many technologies that operate at warm temperature (for example, microchannel plates). For NUV, one could use a warm window to an instrument but at shorter wavelengths the availability of wide-band, highly-transmissive windows is limited. In short, while it is not physically impossible to engineer solutions to this issue, it would add a high degree of complexity with many unknowns and with no true heritage.

Mirror Stability – Mirror stability is driven by the architecture of the mirror subsystem, which combines the material stability of the mirror substrate with local thermal controls designed to keep the temperature of the mirrors constant in the operational environment. The current architecture is based on the high material stability of ULE[®] or Zerodur[®], and low thermal and optical control authority, operating at room temperature. Other approaches are possible, with substrates with high thermal controllability, together with very precise thermal sensing and control, allowing use of stronger materials such as Silicon Carbide (SiC) and operation at a wider range of temperatures. Either way requires individual mirror segment subsystem stability of a few picometers RMS which is a very significant technological challenge.

Material options for LUVUOIR include ULE[®], Zerodur[®], and SiC for room temperature operation, and the same materials plus beryllium and silicon for colder temperatures. To date, ULE[®] CTE and modeling at room temperature has been demonstrated to have the best uncontrolled thermal stability performance to meet this challenging requirement. ULE[®] at room temperature has heritage for high stability studies dating back to the TPF-C and Exo-C studies. A study conducted by Mike Eisenhower of SAO performed detailed modeling of ULE[®] at room temperature with CTE values measured from a real representative mirror boule. Eisenhower shows wavefront stability changes as small as 0.5 pm for a 1.2 meter flat-to-flat hexagonal mirror (approximately LUVUOIR size) controlled with a 1 mK backplane heater plate (deemed feasible but challenging) and this is a key result for demonstrating the feasibility of LUVUOIR.

Another consideration for LUVUOIR mirrors is the degree of optical figure actuation that will be needed to meet stringent wavefront performance goals. ULE[®] mirrors can be equipped with mechanical actuators, to permit a certain degree of correctability. It remains to be shown how this will impact the thermal stability of the segment subsystem, however. SiC mirrors have been demonstrated with high levels of correctability by incorporating electrostrictive or piezoelectric actuators into the substrate structure. This gives SiC active mirrors the ability to operate at the

required optical performance level both at 1G and 0G. It provides correctability for wavefront errors that can easily arise (and have often arisen in the past) during fabrication, test, assembly or launch. SiC mirrors have lower passive thermal stability at room temperature, but higher thermal controllability, than ULE[®]. SiC at room temperature is a viable approach for LUVUOIR mirrors provided that very precise thermal controls (to < 0.1 mK) are used. If temperatures below 150 K are desired, SiC stability improves to be better than conventional ULE[®].

While additional details on mirror CTE and stability are controlled by International Trafficking and Arms Regulations (ITAR), the key point is that a ULE[®]-based, room-temperature approach appears to be feasible, while offering the least departure from traditional practice. While ULE[®] and Zerodur[®] can be tailored to cryogenic temperatures, picometer stability performance has not been assessed. At a minimum, going away from room temperature would risk the best possible stability performance that has been demonstrated and that builds on a large database and history including heritage back to the TPF-C design. While it is true other materials like SiC could have advantages for optical control, thermal control, mass efficiency, or dynamics stability, the need for these advantages is yet to be determined. Certainly dynamics can be addressed by making a stiff enough mirror through an increase in thickness for this segment size range (at larger diameters stiffness is a bigger concern).

Other materials like SiC, silicon, and beryllium have high CTE at room temperature but are thermally conductive and may offer stable solutions at colder temperatures and even Zerodur[®] or ULE[®] can be tailored for very low cryogenic CTE (e.g., at 150 K). While these solutions could offer stable solutions at cryogenic temperatures, more work would need to be done with substrate CTE measurements and modeling equivalent to the Eisenhower analysis. Note that while some mirror manufacturers will consider thermal conductivity when assessing stability, the LUVUOIR architecture is not driven by thermal conductivity but rather is driven primarily by CTE performance and thermal inertia.

Dynamics/Temperature Dependent Damping – Thermal damping affects dynamics stability and the change in damping is as much as 10× from room temperature to 50 K. Damping follows curves for each type of material and small changes will have very small impacts. However, in general, warmer is better for dynamic damping. Less damping would impact WFE and line-of-sight dynamics.

Inclusion of electro-ceramic actuators in active SiC mirrors offers the possibility of passive or active damping of the mirror vibrations through simple shunt circuitry.

Coronagraph Temperature – To achieve longer wavelength performance, not only does the telescope need to be cold, but so does the entire coronagraph instrument including the deformable mirrors, Lyot stops, occulting mask, and optical train. All of these coronagraph technologies have a long technological history for picometer stability and high contrast at room temperature. While some actuators can work at colder temperatures, a whole technology development program would be needed including the picometer stability performance of such systems at colder temperatures. This essentially would restart the coronagraph technology effort and would prevent using WFIRST heritage directly.

Cryo Polishing – The wavefront budget for LUVUOIR is surprisingly tight for a 500 nm diffraction-limited wavefront performance. A single primary mirror segment needs to have 10 nm RMS wavefront (5 nm RMS surface) which is roughly 4× tighter than what was done on JWST. This

includes gravity backout and metrology uncertainties and is already considered a very challenging requirement at room temperature (especially gravity effects and the need to match radius of curvature). Due to CTE effects, mirrors distort as they go cold by many nanometers so cold optics will need to be tested at temperature and go through a cryo-polishing iteration, adding metrology uncertainty, and requiring significantly more time. A single cryogenic test for a JWST mirror would take anywhere from 3-6 months when you consider all of the logistics and pre- and post-integration and testing needed. Testing many segments could add one or more years to the critical path of the telescope.

Material Strength / Mismatch – Any material mismatch (mirror to mounts, mounts to flexures, etc.) will have temperature induced stresses. This can impact strength margins and every material mismatch will need to be analyzed and likely tested at temperature (pull tests). Also, other material properties like stiffness can vary with temperature and material testing may be needed. These issues required complex flexures to be included on JWST that required a significant amount of time and testing in the design phase and additional time in the production phase. Just the additional time to design the very complex flexures for JWST likely added more than a year to the design phase of the mirror segments.

Cryo Alignments – it is highly desirable to be able to align the system at room temperature and know that it will be aligned at operating temperature. Otherwise accurate models will be needed to predict alignment changes, compensated, and verified at temperature. A way to deal with this is to use cryo actuators to compensate for misalignments as done on JWST segments, but this can introduce additional requirements and complexities.

Cold Survival Considerations and Epoxy and Bond Considerations – An important issue is that acrylics used to hold multi-layer insulation (MLI) and epoxies used to bond nearly everything have glass transition temperatures that can impact their strength or cause other problems like contamination. These are typically in the 240 – 220 K range. To deal with this, cryo strength and contamination testing is needed. In addition, every bond and joint will not only need to be analyzed for room temperature launch loads, but also for cryo strength margins. Likely this means considerable testing for cryo material strength at the proposed temperature which was a cause of cost and complexity on JWST.

Heater Power – The biggest advantage for cold operation of the telescope is the fact that this would reduce the needed heater power at L2. Our studies have indicated a well-insulated mirror would need about 20-30 Watts to maintain room temperature at L2 so total power just for mirrors on a 12 meter telescope will be approximately 1.5 kW and the backplane could require as much or more (still under study). This is a large power consumption but not undoable (for reference, HST uses 2800 Watts). In addition, strides are being made in solar array efficiency and it may be that the mass and cost of the arrays in this timeframe are no larger than other large observatories.

Shock – Cryo shock is an important consideration because at cold temperatures the shocks are not absorbed as well. For JWST, shock has played a key role in driving the launch restraint mechanism selection which has been challenging, and drove extensive cryo shock testing. With this experience, the issue could be reduced but will still be a complexity driver depending on how cold an operating temperature is chosen.

Less significant factors:

Composite Stability and Complexity – For totally passive systems, backplane CTE for stability is a similar issue to that for mirrors. However, one not only needs to consider stability but also cryo stress and cryo distortion of the backplane itself. On JWST, cryogenic temperatures drove the backplane schedule in a large way. Every joint type and bond had to be assessed for cool-down stresses (in addition to launch loads). Both stability and thermal distortion had to be modeled in the design and then verified through cryogenic testing. The CTE of every tube needed to be measured and statistical studies done to assess backplane stability. A whole technology was needed to develop the 50-K-stable backplane material. Since there is a huge database and experience with room temperature composites, going cold and especially a temperature that is not room temperature or 50 K could require extensive material testing and possibly even new laminate design.

One way to mitigate backplane stability (and stability only) is to use edge sensors or laser metrology in a loop with a segmented DM to mitigate segment jitter. Segment motions due to thermal changes can be controlled with feedback to segment actuators. Our goal is to not need edge sensors but we are making this a high priority to develop. If a metrology solution is developed, thermal stability will prove less important than dynamic stability, which would favor a SiC backplane solution. For this reason, composite stability and complexity may not be a major driver in this trade although having the possibility of a low CTE composite option at room temperature is desirable to maintain. In addition, the likely edge sensor technologies have a room temperature heritage (capacitive and laser metrology technologies) so going cold might complicate this problem.

Cryo Thermal Testing – Anything cold will need to be tested at cold temperatures which can take extra time and add complexity. This includes thermal balance testing and verification of all electrical connections where impedances and phase vary with temperature.

System Optical Testing – In general it is important to test an optical system at operating temperature. This is for system WFE, alignment, wavefront sensing and control, etc. So if the telescope is cold, room temperature optical testing will likely not be sufficient. The system testing of JWST was a major cost and complexity driver.

Cryo Lubricants – At some temperature, typical warm lubricants will need to be replaced. This can also mean bearings need to be revisited. While cryo lubricants do exist, cryo actuators are more complex and generally more expensive.

Demonstrated Mid-frequency and Roughness – UV and high contrast systems require very tight controls on both mid-frequency wavefront and surface roughness errors. To this end, glass mirrors like ULE[®], Fused Silica, and Zerodur[®] have been used on most UV and EUV telescopes including Hubble and Fuse. Polishing of Si-clad or chemical-vapor deposition (CVD)-clad SiC can also achieve good surface roughness, although CVD SiC is harder to polish. Another solution for SiC is to embed actuators for higher control authority.

The Long Wavelength Limit of LUVUOIR

Michael Werner

Initially the long wavelength limit of ATLAST* was set at 1.8 μm with a stretch goal of 2.5 μm . This choice was driven in large part by the perception that working at longer wavelengths necessarily requires a cooled telescope, and by the cost and complexity of that cooling.

However, it is easy to show that this perception is a misconception, and that a large space telescope >8 m in size, say, can do marvelous science from 2.5-to-5 μm even if it operates at a nominal temperature of 270-to-290 K. For many purposes, of course, colder is better, but for some important science drivers for ATLAST/LUVUOIR, particularly in the exoplanet area, the telescope temperature does not matter.

Of course, it is known from work on the ground that important infrared observations can be done with a large telescope working at the high background levels encountered from a warm telescope operating within the atmosphere. However, taking that same warm telescope and putting it into space provides the following advantages:

- Access to the entire infrared spectrum, a good bit of which is blocked out from the ground by the very molecules one might hope to study in exoplanet atmospheres
- Radiometric stability, which will facilitate achieving the high precision [far in excess of 100 ppm] required for transit and eclipse spectroscopy of exoplanets
- Higher sensitivity, a consequence of the absence of atmospheric absorption, emission, and turbulence and the routine achievement of diffraction-limited performance
- Clear skies and long observations, which guarantee that a particular transit or eclipse can be observed if it is accessible, with no worries about clouds, rain, or snow, and observed for many hours if needed without worrying about morning twilight. This is very important because a particular system may have a transit only a few times per year.

A group from JPL, GSFC, and STScI have taken a serious look at the exoplanet science which could be done from 1-5 μm on a LUVUOIR without cooling. We focus on exoplanets because exoplanet studies are certain to be a major part of the rationale for any LUVUOIR type system in the near future. We focus on 1-5 μm because that spectral band is rich in molecules, including CO, CO₂, H₂O, and CH₄, which have potentially interesting biogenic implications. Note that the strongest band of CH₄, which has been suggested as a biomarker in circumstances where O₂ and O₃ yield ambiguous results due to possible degeneracies, lies at 3.4 μm . Of course, with more time and greater resources, one could examine a wider range of long wavelength limits [note that radiation from 5-8 μm is absorbed in the Earth's atmosphere by water vapor, so extending the wavelength range to 8 μm has considerable appeal] as well as the benefits of cooling the telescope [our large space telescope will want to cool radiatively and will have to be heated to maintain a temperature of 273 K]. Finally, we note that millions of sources seen at 3.4 and 4.6 μm in the WISE survey, could be studied at resolving power $R \sim 200$ by a warm space telescope of 8m+ diameter.

*In this memo, we use LUVUOIR and ATLAST more or less interchangeably, although we recognize that they are in fact not necessarily identical; ATAST is one possible realization of LUVUOIR

Exoplanets orbiting the brightest stars will always be the most attractive targets, and will often put us into a regime where the main source of noise is the stellar photon noise rather than the background noise. In this limit, it is easy to show that a ~9.2-m diameter space telescope operating at 295 K will outperform the much colder James Webb Space Telescope, as is shown in the figure below.

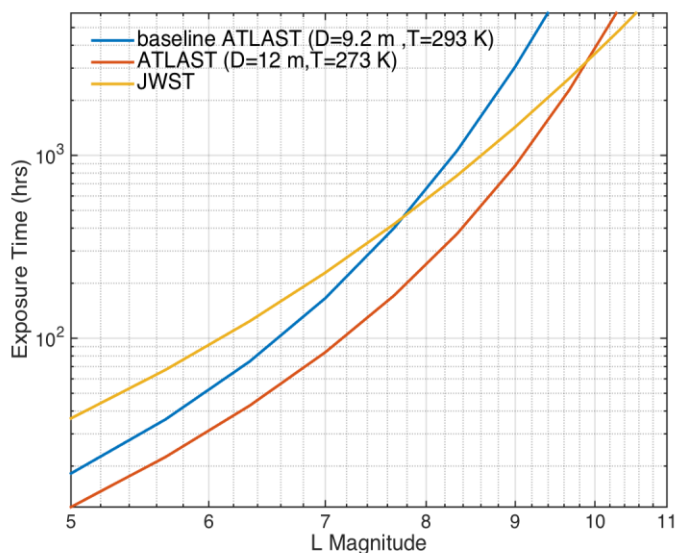


Figure: The time taken for three telescope configurations to detect at 5σ a small (10 ppm at $R = 200$) and narrow feature at $4 \mu\text{m}$, as a function of the stellar magnitude at that wavelength, by transit spectroscopy. The configurations are baseline ATLAST, the larger and somewhat cooler “stretch goal” ATLAST, and JWST. As suggested above, ATLAST is more sensitive than JWST for bright host stars, with the 12-m ATLAST telescope taking $\sim 4\times$ less time to make the same observation, as is to be expected in the stellar photon limited case. The JWST curve is based on the predicted performance of NIRCAM; the ATLAST curve on the instrument described by Werner *et al.* in the SPIE Journal of Astronomical Telescopes and Instruments

This figure is taken from a paper by Werner et al to be published in the special issue of the SPIE Journal of Astronomical Telescopes and Instruments devoted to ATLAST. This paper also contains an elaboration of the scientific arguments for extending the wavelength range of ATLAST to $5 \mu\text{m}$. It also presents a design concept for a small prism spectrometer which could provide the measurement capability required to achieve the performance simulated above. In this concept, the infrared starlight reaching the focal plane of the warm telescope is carried by an optical fiber to the slit of the spectrometer, which is mounted some 10 m away on the telescope backup structure in a manner which allows it to cool radiatively to the temperature required for satisfactory performance of its detector arrays, which are based on current JWST HgCdTe technology.

To conclude, there are substantial scientific benefits to be gained by extending the wavelength range of LUVUOIR/ATLAST to $5 \mu\text{m}$, even if the telescope is not cooled below room temperature. We have shown that this can be done with little or no impact on the rest of the system.

UV Coatings and Short-wavelength Cutoff

Matthew R. Bolcar

Enabling the LUVUOIR mission's compelling ultraviolet (UV) science goals, while also maintaining broadband capabilities to support the exoplanet science mission and other general astrophysics observations, will require a high-performance broadband reflective coating. Of the common metallic mirror coatings (gold, silver, aluminum), only aluminum is capable of providing high reflectivity into the UV at wavelengths as short as 90 nm (see Figure 1). However, almost immediately upon exposure to air (even at very low pressures), an oxidation layer forms on the surface of aluminum-coated mirrors that dramatically reduces its UV performance. Protective overcoats (usually a fluoride such as LiF, MgF₂, or AlF₃) are used to arrest the oxidation once it has begun, and protect the aluminum layer from further oxidation. These overcoat layers themselves can also impact the reflectivity of the mirror at the shortest wavelengths. Current technology development efforts are focused on improving deposition processes to maximize protected aluminum coatings at wavelengths between 90 – 150 nm, while maintaining high reflectivity at long wavelengths through the visible and near-infrared.

The current state-of-the-art in protected aluminum coatings is aluminum with a single, thin layer of MgF₂ (see Figure 1). This is the coating used on the Hubble Space Telescope, and provides excellent reflectivity at wavelengths greater than ~120 nm. Below 120 nm, the reflectivity sharply drops to less than 20%.

Aluminum protected by LiF provides reflectivity greater than 50% at wavelengths as short as 100 nm, below which it too drops off sharply. It is important to also note that LiF is a hygroscopic material that deteriorates when exposed to water vapor. Mirrors coated with LiF would need to be held under a constant dry purge during the entire integration and test phase, as well as launch. This would prove extremely challenging for a system as large and complex as LUVUOIR.

Figure 1 shows two theoretical curves for an aluminum mirror protected by AlF₃. The first is a theoretical best-case in which no oxide layer has formed on the Al undercoat. This is hard to achieve in practice as the undercoat is usually exposed to air for at least a brief time while coating materials must be swapped in the deposition chamber. The second curve shows the theoretical performance assuming a 3 nm layer of oxide has formed between the Al undercoat and the AlF₃ overcoat. Both coatings show improved performance below 100 nm compared to either MgF₂ or LiF, as well as better performance at higher wavelengths.

Technology development efforts are currently underway to achieve the AlF₃ theoretical performance shown in Fig. 1, as well as improvements to the coating deposition processes, including both physical vapor deposition (PVD) and atomic layer deposition (ALD). New techniques that allow the overcoat to be deposited immediately after the deposition of the base Al layer will reduce the thickness of the oxide layer that forms, or prevent it all together. Process improvements will also help increase the reflectivity of the overcoat layer, as well as its uniformity across the mirror surface.

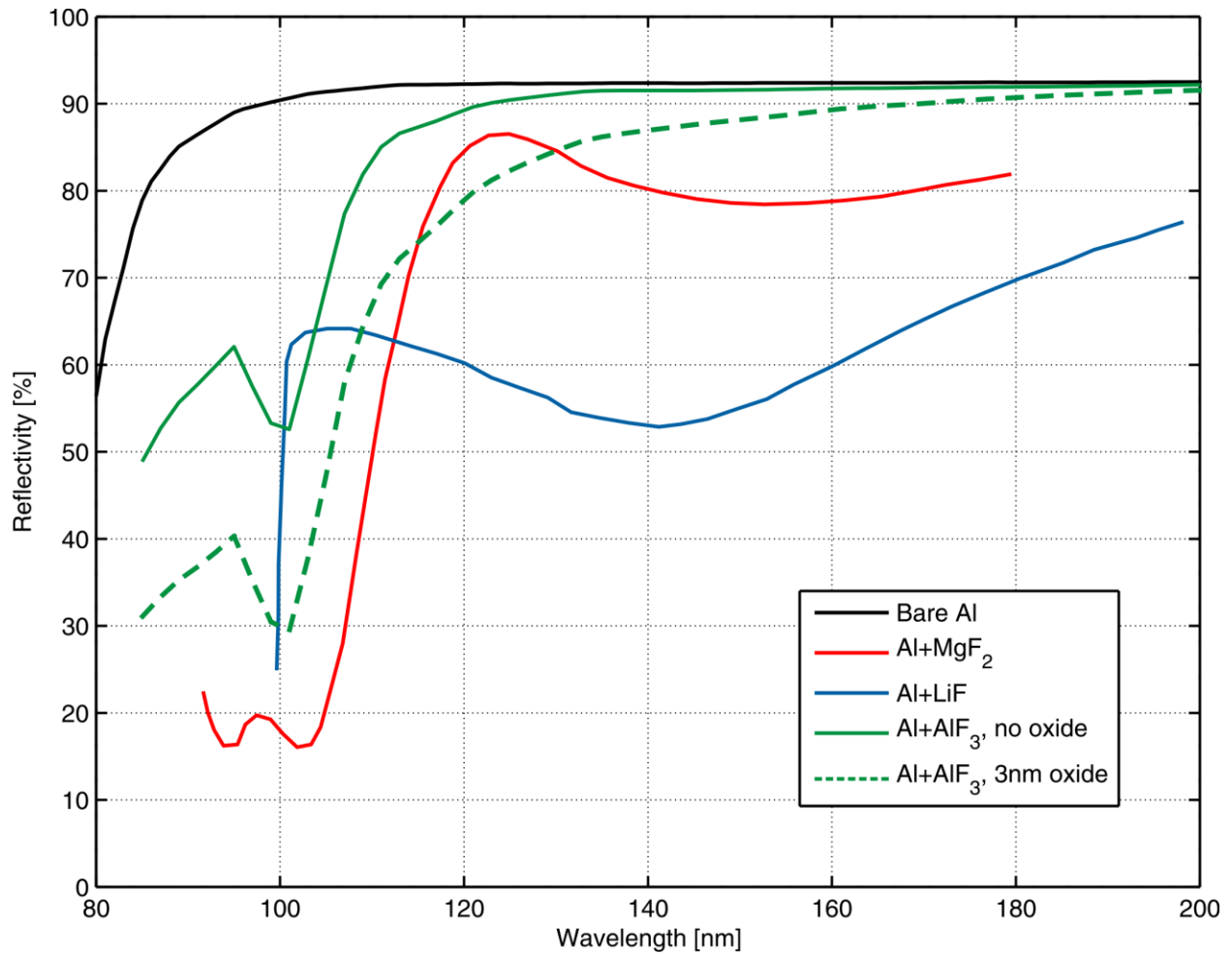


Figure 1 – Theoretical and demonstrated performance for various Aluminum coatings. The theoretical, un-oxidized bare Al performance is shown in black. Demonstrated performance for MgF₂ and LiF overcoats are shown in red and blue, respectively. Finally, theoretical performance for an AlF₃ overcoat is shown in green for two scenarios: without an interstitial oxide layer (*solid*) and with a 3 nm interstitial oxide layer (*dashed*). This figure was adapted with permission from J. Hennessy, *et al.*, “Performance and prospects of far ultraviolet aluminum mirrors protected by atomic layer deposition,” *J. Astron. Telesc. Instrum. Syst.* 2(4), 041206 (2016).

Detectors and Cooling Technology for Direct Spectroscopic Biosignature Characterization

Bernard Rauscher and Avi Mandell

The search for life on other worlds looms large in NASA's 30-year strategic vision, and several mission concept studies are underway that would use UV-Optical-IR space telescopes equipped with a coronagraph or starshade to characterize potentially habitable exoEarths (e.g. LUVVOIR, HabEx). Because of different overall system design considerations, different solutions may turn out to be optimal depending on whether a mission is coronagraph or starshade based. Our aim in this note is to discuss a short list of detector technologies that we believe to be potentially capable of biosignature characterization for either coronagraph or starshade missions.

Once a rocky exoplanet in the habitable zone has been found, biosignature characterization will be the primary tool for determining whether we think it harbors life. Biosignature characterization uses moderate-resolution spectroscopy, $R = \lambda/\Delta\lambda > 100$, to study atmospheric spectral features that are thought to be necessary for life, or that can be created by it (e.g. H₂O, O₂, O₃, CH₄, CO₂). Even using a very large space telescope, biosignature characterization is extremely photon-starved. The emerging technologies for ultra-low-noise detectors fall into two broad categories: (1) low noise detectors (including "photon counting") that are compatible with passive cooling and (2) true energy resolving single photon detectors that require active cooling.

Table 1: Strawman Detector Characteristics for Biosignature Detection

Parameter:	Goal:
Operational Bandpass	0.4 - 1.8 μm (need) 0.4 - 5 μm (goal)
Read Noise	$\ll 1 e^-$
Dark Current	$< 0.001 e^-/\text{pix}/\text{s}$
Spurious Count Rate	Small compared to dark current
Quantum Efficiency (Peak)	$> 80\%$ over bandpass (conventional) $> 50\%$ over bandpass (energy resolving)
Format	$> 2\text{K} \times 2\text{K}$ (conventional) $> 30 \times 30$ (energy resolving)
Spectral resolution	$R = \lambda/\Delta\lambda > 100$ at 1 μm (energy resolving only)
Other	Rad-hard, minimum 5-year lifetime at L2. Non-cryogenic operation strongly preferred

Today's State of the Art

The most mature VISIR detector candidates are semiconductor based. These include silicon EMCCDs for the visible and HgCdTe photodiode and avalanche photodiode (APD) arrays for the VISIR. These technologies are attractive because of their comparative maturity, low risk, and the possibility that their performance might be “good enough” for biosignature characterization, even if they do not function as single photon detectors.

EMCCDs – Electron multiplying charge coupled devices (EMCCD) are widely regarded as the most mature detector technology for visible wavelength biosignature characterization today. For this reason, a $1K \times 1K$ pixel EMCCD has been selected for the WFIRST coronagraph's imaging camera and integral field spectrograph.

Advantages: They are operational now, and are being space-qualified for use in WFIRST. Significant investment will be made as part of this process, making the subsequent TRL level attractive for risk reduction.

Disadvantages: A major concern with the current EMCCD design for biosignature characterization on LUVVOIR is radiation induced performance degradation. This may include decreased charge transfer efficiency, increased clock induced charge (CIC), and decreased pixel operability.

HgCdTe Near-IR Photodiode Arrays – HgCdTe is today's most mature material for astronomical near-IR instruments. By adjusting the relative amount of Cd in the semiconductor material, it is possible to tune the cutoff wavelength from about $1.7 \mu\text{m}$ out to $5 - 10 \mu\text{m}$ while still achieving performance that enables low background space astronomy.

Advantages: HgCdTe arrays have substantial heritage for NASA astronomy, having been used in JWST, Euclid, WFIRST, etc. When cooled sufficiently, the dark current of today's $2.5 \mu\text{m}$ cutoff flight grade HgCdTe arrays already achieves the $< 0.001 \text{ e}^- \text{ s}^{-1} \text{ pix}^{-1}$ that is needed for biosignature characterization.

Disadvantages: The read noise floor of the existing generation of HgCdTe photodiode arrays is a few e^- RMS per pixel, higher than what is needed for biosignature detection, and significant work is needed to understand exactly where the read noise and dark current originate and why.

HgCdTe APD Arrays – HgCdTe APD arrays are a promising technology that initially entered astronomy for comparatively high background applications including adaptive optics and interferometry and wavefront sensing and fringe tracking. More recently, they have been used at the telescope to provide diffraction-limited imaging via the “lucky imaging” technique.

Advantages: The gain in APD arrays is built into the pixels before the first amplifier, they promise photon counting and potentially even single photon detection if “dark current” can be reduced to acceptable levels. With an appropriately optimized fabrication process, the HgCdTe itself is potentially capable of the same quantum efficiency (QE) performance as the JWST arrays.

Disadvantages: “Dark current” is the most significant obstacle to using APD arrays for ultra-low background astronomy today. The $\sim 10-20 \text{ e}^- \text{ s}^{-1} \text{ pixel}^{-1}$ gain corrected “dark current” that has been reported is almost certainly dominated by glow from the readout integrated circuit (ROIC). This dark current may be reduced with optimization of the ROIC.

Maturing Technologies

Today's EMCCDs, HgCdTe hybrids, and HgCdTe APD arrays are not single photon detectors in the context of biosignature characterization. All would add significant noise and thereby reduce mission exoEarth yields below what could be achieved with a noiseless detector. On the other hand, superconducting MKID and TES arrays already function as single photon detectors today. However, the use of these superconducting detectors by LUVUOIR is contingent upon the development of ultra-low vibration cooling.

Transition-edge sensor (TES) microcalorimeter arrays – In a microcalorimeter, the energy of an absorbed photon is determined from the temperature rise of the detector. The energy resolution of such a detector is set by thermodynamic noise sources in the detector and amplifier noise.

Advantages: Thermal sensors simultaneously detect individual photons and use the thermal signal to measure photon energy. For the designs discussed here, the minimum photon energy is well separated from the system noise, so the probability of dark events are near zero, and the read noise manifests itself as the limit to the energy resolution of the system.

Disadvantages: The energy resolution scales with temperature, so for VISIR applications with $R > 100$ the detectors must be operated in the 5 – 50 mK regime.

Microwave kinetic inductance devices (MKID) – An MKID detects absorption of photons in a superconductor by a change in kinetic inductance.

Advantages: MKIDs are theoretically energy resolving detectors with zero dark count rate. In addition to high sensitivity, MKIDs have a natural means of multiplexing; systems have been demonstrated for simultaneous readout of up to 4000 MKID pixels.

Disadvantages: Operating temperatures are around 1 K. Other, non-fundamental sources of MKID noise also exist, and are the subject of active research. Current resolving powers are $R \sim 10$ at 0.4 μm . Improving VISIR MKIDs to $R = 100$ faces a significant challenges.

Ultra-Low-Vibration Detector Cooling – In order to take advantage of super-conducting energy resolving detectors, detector cooling down to > 1 K must be achieved, using a low-volume and space-qualified technology with a low-vibration and low-energy profile. Stored cryogen systems have been used in the past to provide cooling to observatories and instruments with near zero vibration, but they are impractically massive for missions with lifetimes greater than five years, and have largely been replaced by mechanical cryocoolers. Cryocoolers are far lighter and have lifetimes limited primarily by their control electronics.

Linear compressor cryocoolers: Almost all flight cryocoolers launched to date are based on linear motor-driven piston compressors with non-contact clearance seals. These devices, originally developed in the 1970s and 80s at Oxford University, have virtually unlimited lifetime. They also have inherently high vibration at their operating frequency, typically 20 to 70 Hz, which unfortunately is in a range that often contains important telescope and instrument structural mode frequencies. Many flight cryocoolers use a second, co-aligned piston and control electronics to provide active vibration cancellation along the axis of motion, but cancellation is imperfect, partially because the piston force couples into other degrees of freedom.

Low Vibration Cryocoolers: Because of the known problems with the vibration from linear-piston cryocoolers, alternative coolers with much lower exported vibration force in the critical 0 – 200 Hz band have been developed. Two examples are Joule-Thompson expansion

coolers with sorption-based compressors (called sorption coolers here) and reverse Brayton cycle coolers using miniature turbine compressors and expanders (called turbo-Brayton coolers here). In both cases, the flow is continuous, rather than oscillating, and the compressors can be mounted meters away from the instruments. These coolers are compact and low-vibration, but reaching the required level of cooling for ultra-low-noise detectors may be impossible.

Sub-Kelvin Coolers: The effectiveness of cooling by the expansion of helium gas drops off rapidly below 1 K, and other physical phenomena must be used to reach deep sub-Kelvin temperatures. In terrestrial laboratories, dilution refrigerators are most commonly used to reach temperatures as low as 0.002 K; however, no zero-g version has been demonstrated. Another option is magnetic coolers, or Adiabatic Demagnetization Refrigerators (ADRs). ADRs have no moving parts and are generally considered to be zero-vibration devices. However, the stresses in the magnetic components may generate disturbances at the relevant level and frequencies.

This note is based on work published in Rauscher, *et al.*, “Detectors and cooling technology for direct spectroscopic biosignature characterization,” *J. Astron. Telesc. Instrum. Syst.* **2**(4), in press.

Ultraviolet Detectors for Cosmic Origins and Exoplanet Science with LUVOIR

Kevin France and David Schiminovich

The LUVOIR Surveyor is envisioned as the ‘Space Observatory of the 21st Century’. With 10 – 40 times the geometric collecting area of the *Hubble Space Telescope*, highly sensitive and multi-plexed instruments, LUVOIR is poised to provide transformative scientific measurements of a broad range of astrophysical objects, from the interaction of galaxies with the large-scale structure of the Universe to the frequency of potentially inhabited planets in the solar neighborhood. Ultraviolet imaging and spectroscopic capabilities are central to the majority of the key scientific goals of LUVOIR, from quantifying the flows of matter between galaxies and the intergalactic medium to understanding how the host star’s UV radiation regulates the atmospheric photochemistry on these habitable planets.

Carrying out high-precision ultraviolet astronomy across such a wide range of sources requires detector systems working below the atmospheric cut-off (90 – 400 nm) with low-noise and/or photon-counting capability, high quantum detection efficiency, large format size, and high temporal resolution. Ideally, all of these characteristics would be encompassed in a single detector, but multiple technologies may be required to accomplish LUVOIR’s suite of science investigations.

We present an overview of UV detector technologies so the LUVOIR STDT and NASA can make informed recommendations for directed technology investment in the near- to intermediate-term future to support first generation UV instrumentation for LUVOIR. We note that with the goal of serviceability, some technologies that are less mature today may indeed be optimized by the time second generation LUVOIR instruments are proposed, and as such a long-term, but adaptable, technology maturation plan would be desirable for UV detectors.

Microchannel Plate Devices – Micro-channel plates (MCPs) with “solar-blind” photocathodes, low dark rates, and zero read noise have a rich flight heritage on astronomy, heliophysics, and planetary science missions. MCP-based detectors are inherently photon-counting, can be ruggedized for 10+ year lifetimes in space, are scalable to large formats, and offer relatively high quantum efficiency at short UV wavelengths ($\lambda < 130$ nm). However, MCPs have limited dynamic range for bright objects that require instrument safety protocols, do not regularly support high-S/N observations ($S/N > 100$) owing to fixed pattern noise, and experience issues with long-term “gain-sag” (burn-in at locations of prolonged high illumination).

Charge Coupled Devices and sCMOS – Charge coupled devices (CCDs) can be δ -doped to improve UV performance and anti-reflection coatings can be optimized to offer high QE over a selected bandpass. CCDs have flight-heritage on astrophysics suborbital missions as well as solar missions at shorter UV wavelengths. The large dynamic range and flat-field characteristics are well-suited for high S/N UV observations. CCDs are moving to larger formats and advancements in electron-multiplying CCDs (EMCCDs) offer the prospect of ~zero read noise photon-counting operation. CCDs have yet to demonstrate simultaneous broadband UV response and solar-blind operation (e.g. for FUV imaging without a pre-filter); testing/optimization of these devices for radiation hardness in an L2-like environment is an active area of research. Other silicon-based technologies such as low-noise scientific complementary metal-oxide-semiconductor (sCMOS) are now being optimized for the UV using similar processing techniques as those being used for

CCDs, and require similar investigation into radiation hardness and low temperature operation. sCMOS detectors may offer new options in terms of addressability and dynamic range for photon-counting.

Advanced Concepts – Less mature UV detector technologies such as microwave kinetic inductance detectors (MKIDs), offer the possibility of energy resolution at the pixel level. Uncertainties in the scalability to significant pixel/spaxel counts and cryogenic operation currently limit the utility of these devices for LUVUOIR, but these issues may be quantified and possibly overcome with additional technology investment.

Challenges unique to UV – Key technology challenges that remain unique to the UV involve boosting efficiency and reducing noise, along with several other issues linked to these goals.

Quantum Efficiency: UV sensitive detectors have quantum efficiencies at or below 20-50% within the band, leading to the possibility that future technologies may provide factors of up to 2-5× improvement in overall UV throughput. Some UV sensor technologies have a comparable or higher QE in the visible, raising potential “red leak” issues that may require additional filtering. A related challenge is the low transmittance of UV band-pass filters, which limits options for efficient red-blocking or band selection.

Noise: The sky background is several magnitudes fainter in the UV than in the visible which presents both an opportunity and a challenge. The opportunity is the exploitation of a low-background window for the study of faint objects. For example, for broadband FUV observations, the sky background is 28.5 mag/sq. arcsec, or fewer than ~1 photon per resol for 10-30 min exposure times on a 10-m LUVUOIR, even less for narrowband observations or spectroscopy. Taking full advantage of this low background requires detectors that do not themselves limit faint observations, motivating low noise or photon-counting technologies, with read noise and/or dark current typically lower than required for standard broadband visible observations. These same photon-counting detectors may also have limited dynamic range, particularly in the large formats required for LUVUOIR. Dynamic range is a related challenge that needs to be addressed by all technologies being considered.

Improving performance in these areas can significantly impact science return. The required exposure time to reach a given S/N for a particular target in a sky-background-limited observation scales as $t \sim QE$, and increases to $t \sim QE^2$ in the detector dark current-limited regime, motivating efficiency gains. Similarly, the required exposure times decrease linearly with improvement in dark current and/or read noise, down to the very low sky-background limit. No single technology leads performance in all three areas (efficiency, read noise and dark current), at this point the optimal UV detector is likely to be application or instrument-specific.

Table 1: UV detector targets for LUVUOIR and a comparison with the state-of-the-art in laboratory and flight technology (adapted from Bolcar et al. 2016).

Parameter:	Goal:	State-of-the-Art:	
Operational Bandpass	90 nm – 400 nm	90 nm – 300 nm	MCP
		90 nm – 400 nm	EMCCD
		TBD	sCMOS
Read Noise	0	0	MCP
		N/A for multi. mode	EMCCD
		0.8 – 1.0 e ⁻	sCMOS
Dark Current	0	0	MCP
		> 0.005 e ⁻ /resol/hr	EMCCD
		> 0.005 e ⁻ /resol/hr	sCMOS
Spurious Count Rate	≤ 0.05 counts/cm ² /s	0.05 counts/cm ² /s	MCP
		TBD	EMCCD
		TBD	sCMOS
Quantum Efficiency (Peak)	75% (Far UV – Near UV)	45-20% FUV - NUV	MCP
		30-50% FUV - NUV	EMCCD
		TBD	sCMOS
Resol Size	≤ 10 μm	20 μm	MCP
		20 μm	EMCCD
		10-20 μm	sCMOS
Dynamic Range (Max. Count Rate)	≥ 10 ⁴ Hz / resol (as needed)	40 Hz / resol 5 MHz global	MCP
		Readout dependent	EMCCD
		10 ⁵ Hz / resol	sCMOS
Time Resolution	≤ 100 ms (as needed)	<< 1 ms	MCP
		< 10 ms	EMCCD
		< 10 ms	sCMOS
Format	≥ 8–16k pixels per side with high fill factor	8k × 8k	MCP
		3.5k × 3.5k	EMCCD
		3.5k × 3.5k	sCMOS
Radiation Tolerance	Good	Good	MCP
		TBD	EMCCD
		Good	sCMOS