Enabling Future Space Telescopes:
Mirror Technology Review and Development Roadmap

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Executive Summary

Mirrors are a fundamental enabling technology for future space-based telescopes ranging from UV/OIR to Far-IR/Sub-MM. Space mirror technology includes the materials used to make the mirror substrates; the processes used to handle, fabricate, and test the mirrors; the mechanical systems used to support the mirrors; and the processes used to certify flight qualification of the mirror systems.

This white paper has three objectives: to summarize the current state of the art for space mirror technology; to discuss future possibilities and potential challenges which mirror technology pose to future space telescope missions; and to propose a mirror technology development roadmap as a function of the science mission priorities.

This white paper requests that the Astro2010 Committee recommend a sustained and dedicated technology investment to develop methods for solving the most significant technical challenge for future space telescopes: how to fabricate and flight-qualify low-cost, high-quality large-aperture mirrors.

In addition, this paper suggests that the mirror technology development effort be part of a sustained and cross-discipline development program. We highly recommend developing space mirror technology alongside similar efforts in space structures, optical coatings, control mechanisms, and detectors. All of these technologies are needed for a successful telescope system, and their development needs to be coordinated. This program should be conducted as an on-going activity because it can take 6 to 10 years (or more) to mature a candidate technology from TRL-3 to TRL-6. The total cost for each technology development effort should be 10% to 20% of the anticipated cost if the component was procured using existing technology.

Specific technologies to be developed include replication of low CTE glass, such as ULE for UVOIR and possibly Far-IR/Sub-mm telescopes; replication of SiC mirrors for Far-IR/Sub-mm telescopes; polishing of segmented mirrors to the edge of the physical aperture to minimize diffraction effects; polishing of lightweight mirrors to minimize quilting effects; thermal control of mirrors to maintain precision figure tolerances; active sensing and controlling phasing of a segmented mirror; active wavefront sensing and control (WFSC) of a segmented mirror; and characterizing gravity sag of large mirrors as well as very low-stiffness mirrors to produce zero-g surface figures.

[1] This work is based on research performed by the author while at the University of Arizona.

Background

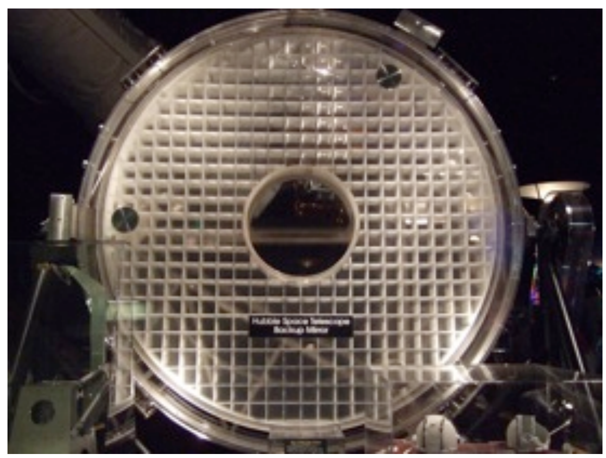
Mirrors are a fundamental enabling technology for space based telescopes. Primary mirror size and quality is directly traceable to telescope performance. Every engineering advance in space mirror technology has resulted in improved science productivity.

For the past 30 years, the limiting factor on mirror size—and telescope capability—has been the mass and volume constraints imposed by the launch vehicle's payload faring. The Hubble Space Telescope's (HST) overall payload volume of 4.3 by 13.2 meters and 11,110 kg of lift capacity was specifically tailored for the Space Shuttle's payload capacity of 4.6 by 18.3 meters and 16,000 kg. Similarly, NASA's next generation observatory, the James Webb Space Telescope (JWST), is sized to fit within an Ariane V. In addition to the restrictions imposed by the launch vehicle, constraints such as stiffness requirements, fabrication capacity, thermal performance, and the need for maintenance-free operation are other factors that can affect mirror diameter.

As the astronomy community drives the need for more powerful telescopes, the engineering community needs to work within these constraints to supply astronomers with the larger-aperture observatories that will enable advancement in astronomy.

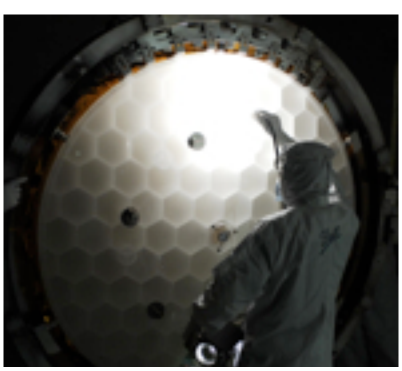
State-of-the-art mirror technology currently on orbit

Although it has been on orbit since 1990, HST still has the largest primary mirror is space and therefore represents the state-of-the-art in large aperture UV/optical telescopes. The telescope is diffraction limited at 500 nm, and the requirement that it operate in the visible was an important constraint on the telescope's design. The HST's primary is made out of ULE glass and is 2.4 meters in diameter and about 46 cm thick. The mirror is essentially a giant sandwich: it has a front and back sheet with supporting ribs in the center, all of which were fused together in a furnace. The mirror has an approximate mass of 800 kg, giving it an areal density (mass/optical surface area) of 180 kg/m^2. The optical surface is polished to 6.3 nm rms, and the telescope structure has exceptional stiffness and thermal stability.



The HST backup (and uncoated) primary mirror, on display at the Smithsonian Air & Space Museum.

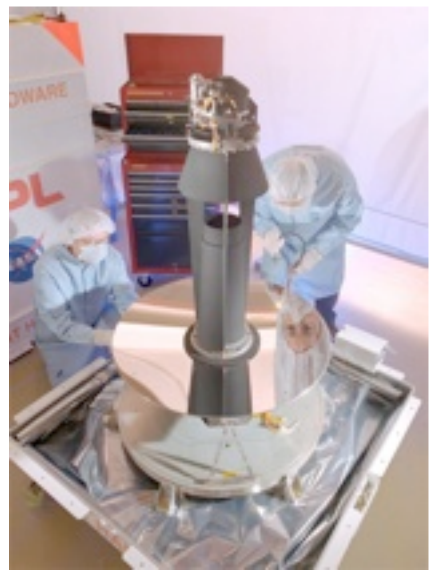
The next largest and most recent glass-mirror space telescope is the Kepler Observatory: it successfully entered orbit on 6 Mar 2009. Kepler's primary mission is to identify stars which may have Earth-like planets [Koch 1998]. Similar to HST, the Kepler primary uses a ULE sandwich architecture. However, at 1.4 meters in diameter, the mirror is smaller than HST.



The Kepler primary mirror. Image courtesy NASA and Ball Aerospace.

It's interesting to note that the launch dates of HST and Kepler are separated by nearly 20 years of technology development, yet both mirrors are made from the same material and share a similar geometry. Glass is the legacy material for mirror substrates, and there are several reasons why it performs so well: the material is thermally stable; it can be engineered into a stiff structure with minimal residual stress; and the face sheet can be polished to a high-quality optical surface. In the case of the HST, the mirror is essentially a light-weighted version of the mirrors that have been used in ground-based telescopes for the last hundred years. The HST primary mirror is the direct result of a mirror technology development effort begun in 1964—26 years before launch—to develop lightweight, thermally-stable mirrors. As a result, low CTE glasses such as ULE were developed along with processes to make lightweight glass mirrors.

While glass has been the traditional substrate of choice, other materials have been used. One example is the Spitzer Space Telescope (SST), which has an 0.85 meter beryllium primary mirror. Launched in 2003, the SST is a general-purpose observatory that is diffraction limited at 5.5 microns and operates at 4K. Beryllium offers several advantages when used as a mirror substrate. One of the most significant advantages is that Be has a large specific stiffness (or stiffness-to-mass ratio): this ratio is five times greater than ULE and 6 times greater than aluminum [Yoder 1993]. Beryllium's superior rigidity means that it can be used in mirror substrates that take up less volume than a ULE substrate designed for the same mission. In addition to a high specific stiffness, Be has a near-zero coefficient of thermal expansion (CTE) when used below 100 K which makes it an ideal material for cryogenic mirrors.



The assembled SST. Photo courtesy NASA/JPL-Caltech.

For all three examples mentioned above, it is worth noting that all of these mirrors share two features in common:

> **The mirrors are monolithic.** Each primary is made out of a single piece of material; they are not segmented.
>
> **Their diameters are less than 2.5 meters.** Each was designed to fit within the existing fleet of launch vehicles.

State-of-the-art mirror development in the near future

While monolithic mirrors have been the dominant paradigm for space telescopes, NASA's planned James Webb Space Telescope (JWST) will be the first in a new generation of space observatories to use a segmented primary mirror. The science requirements call for a 6 to 8-meter aperture that is diffraction-limited at two microns and operates below 50 K. The planned launch vehicle—an Ariane 5—accommodates a maximum payload width of 4.5 m, so the only way to fit a 6 meter-class telescope into a 4.5 meter faring is to use a segmented primary mirror.

Conceptual drawing of the JWST telescope and sunshade. Image courtesy NASA.

JWST will have a 6.5 m aperture which is comprised of eighteen 1.5 meter hexagonal beryllium segments. The telescope will be diffraction limited at 2 micrometers, and the error budget requires that each mirror segment have a surface figure of 25 nm rms. Compliance with this requirement was demonstrated on the Advanced Mirror System Demonstrator (AMSD) and will soon be demonstrated on the JWST Engineering Development Unit. As of March 2009, all JWST segments have been cast, machined to near net shape, and are in various stages of polishing. Two segments have completed initial polishing and are at NASA Marshall undergoing cryogenic testing. Overall, the fabrication process is proceeding as expected for such a difficult task. Challenges are being discovered and overcome, but there have been no insurmountable problems and none are expected at the current level of maturity.

The JWST primary mirror is an ambitious undertaking, especially when compared to ground-based observatories that have segmented primary mirrors. Both the Keck and the Hobby-Eberly telescopes use 10 meter-class primary mirrors with semi-active control. However, both of these systems depend on significant structural mass to provide stability for the optical surface: each mirror has an areal density of about 2000 kg/m^2 (compared to 50 kg/m^2 for the JWST).

It should be noted that JWST would likely not be possible without the development of O-30 Beryllium. (The I-70 Be used in SST's primary is too inhomogeneous.) Starting in 1990 (23 years before the currently scheduled launch of JWST), the Air Force started developing O-30 Be. Its homogeneous material properties enables the fabrication of 1.5 meter class mirrors.

Technical challenges associated with scaling existing architectures

While the industrial infrastructure may be physically capable of fabricating larger mirrors (by building larger ovens, bigger mandrels, etc), the basic rules of static mechanics are often nonlinear with diameter [Baiocchi 2004]. In these cases, simply scaling the mirror diameter up by a factor of two—while maintaining the same aspect ratio—may reduce its mechanical or thermal performance, and the resulting mirror may be incapable of meeting the mission requirements.

One of the most important criteria is mirror stiffness. A primary mirror must be rigid enough to maintain an accurate surface figure throughout the entire mission cycle: it must be stiff enough to be manufactured to specification, survive launch, and maintain an accurate surface figure on-orbit.

A useful first-order approximation is that the stiffness for a solid, plate-like substrate is proportional to t^2/D^4, where t is the substrate thickness and D is the mirror diameter [Bely 2003, Nelson 2006]. This is an important relationship to understand because it provides insight into the amount of additional material required to maintain stiffness.

As an example, suppose that a 0.5-meter mirror prototype (substrate and support structure) currently exists, and it is suggested that the manufacturing process is easily scaled such that a 2.0-meter class mirror could be fabricated. The 4X increase in mirror diameter means the substrate will be 256 times less stiff if the same thickness is maintained. The engineers have three options: they can use the mirror in a longer wavelength regime mission, where the reduction in presumed surface accuracy (due to a lack of stiffness) is acceptable; they can increase stiffness by increasing the support structure stiffness; or they can increase stiffness by increasing substrate thickness (by a factor of 8X, in this example). Increasing the thickness by 8X will also increase the areal density by a similar factor.

Areal density is another important factor in space mirror technology, but recent experience suggests that it should be not the primary metric. One lesson that NASA learned when evaluating potential mirror technologies for JWST is that areal density may not be the most important criteria for a space mirror. While AMSD successfully demonstrated the ability to manufacture 1.3 meter mirrors with areal densities of 18 kg/m^2, when it came time to insert these mirrors into the JWST architecture, it was discovered that they would not survive the launch loads because they were not stiff enough. It was necessary to add 10 kg/m^2 of mass, bringing their areal densities up to 28 kg/m^2.

Complexity is another important criterion to consider when evaluating future mirror options for astrophysics missions. While an Earth observation system may require a mirror with high authority control—given the mechanical and thermal dynamics of its orbit and mission profile—an astronomical observatory may not. Astronomical space observatories typically take long exposures and slew slowly between observations. Additionally, SE-L2 is a very gravitationally and thermally stable environment. Thus, while actively-controlled mirror technology is available, its suitability for a potential astrophysics mission needs to be considered carefully. If a degree of active control *is* necessary, then the reliability and failure mechanisms should be investigated. If one active control fails, how will the mission be affected? What would happen if all of the mirror controls were to fail?

Areal cost is a practical metric that warrants consideration. The areal cost of the Hubble primary in 2008 dollars was $12M/m^2, and the estimated areal cost for the JWST primary is $6M/m^2. This cost reduction is the direct result of a mirror technology development effort begun in 1996 [Stahl, 2007].

While this cost reduction has been beneficial, even more is needed. For example, scaling the current JWST mirror technology up by 2X to a 13 meter aperture would result in a primary mirror cost of $0.75B, and scaling up to a 26 m system would result in a primary mirror cost close to $3B. Clearly, to make large telescopes a reality, the cost of mirror fabrication must be reduced by at least an order of magnitude.

Thermal performance is another useful criterion upon which future mirror technologies should be judged. The coefficient of thermal expansion (CTE) is an important consideration, especially for mirror substrates that contain different materials. If the CTE mismatch is significant, the mirror will need additional sensing and control hardware to compensate for the bimorph effect. This adds additional mass and complexity.

Thermal conductivity is another component of thermal performance. As structures become lighter, the substrate can become so thin that it cannot radiate heat quickly enough, and proper thermal management becomes a dominant problem. In the end, the benefits realized by using a thinner substrate may be superseded by performance risk and the need to mitigate complexity and program cost.

Practical example: scaling the JWST architecture to future mission needs

When looking ahead to future telescopes beyond JWST, there are two obvious questions:

- What would it take to convert the JWST architecture into a UV/optical observatory that is diffraction limited at 500 nm?
- What would it take to scale the JWST architecture to a 13 meter aperture?

The first question assumes that the diameter remains the same, but that the telescope system requirements are scaled to be diffraction limited at 0.5 micrometers. To obtain a first-order approximation on the parameters required to achieve this, the current JWST specifications can simply be divided by four (corresponding to changing the diffraction limited wavelength from 2.0 to 0.5 micrometers).

Parameter	JWST spec	Spec needed for 'visible' JWST
Wavefront sensing & control error residual error	40 nm rms	10 nm rms
Surface figure error	25 nm rms	6 nm rms
Actuator step size	7.5 nm	1.9 nm
Wavefront error due to structural stability	60 nm rms	15 nm rms
Telescope pointing stability	7 mas	1.6 mas

Some of these parameters suggest there would be significant challenges involved in developing a 6.5-m segmented telescope in the visible regime. The two most significant are:

- **Surface figure error.** A 6 nm rms figure error represents a λ/83 error across a 6.5 meter aperture. To provide some context, the final mirror for the 8.2 meter Very Large Telescope (VLT) was polished to a surface figure error of 7.8 nm rms [Geyl 1999]. In addition, the supported Subaru mirror has a surface error of less than 14 nm rms [Kaifu 2000]. Both of these mirrors are solid meniscus substrates, which is similar to the mirror geometry used by JWST. Assuming these mirrors represent the state-of-the-art in large optics fabrication for ground based-telescopes, a surface error of 6 nm rms for a space observatory is an aggressive target requirement.

- **Structural stability.** The structural stability for a visible telescope is four times tighter than for JWST. To first order, the stiffness of the primary could be improved by a factor of four by making the primary mirror twice as thick. However, the areal density will also increase by a factor of two. Furthermore, this stability will also be impacted by the optical bench structure and secondary mirror support structure.

As this example shows, there is a good reason why a segmented 6.5 meter-class, UV/visible wavelength telescope hasn't been launched into space—or even demonstrated on the ground: there are several technical challenges associated with achieving the required performance parameters.

Scaling the JWST architecture to a 13 meter aperture introduces a different set of technical challenges. Using the method outlined in the previous section, scaling JWST by 2X will result in a 4X loss in stiffness, assuming that the aspect ratio is maintained.[2] This reduction in stiffness will likely mean that the system is no longer diffraction-limited at 2 micrometers. In addition, the areal density is double that of the 6.5 meter mirror, or roughly 100 kg/m^2 (JWST's primary mirror assembly has an areal density of approximately 50 kg/m^2 while the areal density of just the mirror substrate is about 30 kg/m^2). In order to achieve a stiffness equivalent to the original mirror, the thickness should be increased by an additional 2X, resulting in a final areal density of about 200 kg/m^2. The mechanical implications of scaling from 6.5 to 13 meters cannot be overstated! It's also important to note that these rules apply to *any* existing architecture, whether the substrate is made out of glass, Be, SiC, or any other material.

While reduction in stiffness is the most dramatic effect of scaling, there are additional effects to consider. One example is edge effects. The current JWST segments are separated by a 3 mm air gap and are

[2] Maintaining the aspect ratio means that mirror thickness scales linearly with the diameter. In this example, we are doubling the size of the aperture, so the thickness will double, as well. The aspect ratio (diameter/thickness) does not change.

polished to within 7 mm of the segment's edge. This results in a 15 mm gap between segments, which contributes to diffraction and decreased optical throughput. If the 6.5 meter architecture is scaled up, these edge effects may scale and further hinder telescope performance.

Also, these scaling effects don't just affect the on-orbit performance; they will complicate operations on the ground during the fabrication process. One of the lessons-learned from the University of Arizona NGST Mirror System Demonstrator (NMSD) is that handling large mirrors becomes an increasingly difficult problem with increased mirror size [Baiocchi 2004]. As the mirror diameter doubles, the amount of additional preparation and hardware needed to simply move the mirror around the optics shop becomes a significant engineering challenge. In addition, ground testing becomes more challenging because the gravity sag will be 4X worse.

The trade space

Independent of science priority, there is a clear hierarchy of telescope technology maturity and complexity which directly translates into cost and risk. For example, on-axis systems are easier than off-axis systems, and monolithic systems are easier than segmented systems. However, these guidelines should not be taken out of the application's context. For some applications, off-axis or segmented systems are the appropriate geometry needed to accomplish the mission. This section discusses two fundamental technical trades that drive the technology requirements.

Before discussing the technical trades, however, it is important to acknowledge the single largest external technology driver: the launch vehicle. Because the launch vehicle is such an important driver on mirror geometry, the path forward will depend on the availability of future launch vehicles.

> **Ares V.** NASA is currently developing the Ares V vehicle to support cargo requirements associated with human travel to the Moon and Mars. The Ares V's 10 meter fairing is projected to have an 8.8 meter dynamic payload diameter and the capability to launch approximately 65,000 kg to a Sun-Earth L2 (SE-L2) transfer orbit. The Ares is anticipated to be available to launch large space telescopes in the early 2020 decade [Stahl 2009].
>
> **EELV**. The current US space-lift capability is the Air Force's Evolved Expandable Launch Vehicle (EELV), e.g. Delta-IV and Atlas-V. There are many different versions of these vehicles, and each has a different capacity. The largest, the Delta IVH, has a 5 meter fairing with a 4.5 meter payload diameter and the capability to launch approximately 9,400 kg to SE-L2.

It's important to note that each platform would allow for a unique path forward: the Ares would emphasize large aperture technology development with less concern about mass, while the EELV would emphasize technologies that use the existing launch vehicles more efficiently. Keeping these constraints in mind, the following paragraphs outline some of the technical trades that drive the mission requirements.

<u>Monolithic v. Segmented</u>. The fundamental telescope geometry trade is between monolithic and segmented mirrors. In general, a monolithic aperture will produce a cleaner, more uniform, and more stable PSF than a segmented aperture. Additionally, a monolithic aperture will provide diffraction limited performance down to shorter wavelengths than a comparable segmented aperture. In general, a monolithic aperture is the geometry of choice for UV/OIR applications. By contrast, a segmented aperture is suitable for spectroscopic and for IR to Far-IR/Sub-mm applications. For very large apertures, segmented geometries are the only path forward.

As mentioned above, the launch vehicle's capabilities affect the path forward for both geometries, although in different ways. The monolithic aperture is constrained in volume by the launch vehicle's faring size, while the segmented geometry is constrained in mass by the lift capacity. The monolithic potential maximum (circular) aperture is 4 meters for the EELV and 8 meters for the Ares V [Stahl 2008].

Mass v. Stiffness. The second fundamental trade is between mass and stiffness. As previously discussed, a stiff telescope is required to achieve UV/OIR performance. A stiffer telescope will be more mechanically and thermally stable, and the only way to achieve stiffness for a passive telescope is through structural depth and mass. Thus, a large aperture telescope requires a large and massive support structure. To be fair, some of this mass and volume can be replaced with complex, active isolation and control, but this adds to the mission risk because the technology is not as mature. However, as a general rule, there is an optimum stiffness for any given telescope aperture which can be derived from its required diffraction limit. Similarly, the stiffer the primary mirror, the easier it is to achieve a very smooth surface figure. For example, UV/OIR and exo-planet missions require a surface figure of less than 10 nm rms with no periodic structure or quilting. Such surface figures have recently been achieved on solid meniscus mirrors in ground-based observatories [Geyl 1999, Kaifu 2000]. Lightweight 'egg-crate'-style mirrors always demonstrate quilting effects and generally do not achieve the same level of surface figure error. Finally, the difficulty in handing, fabricating, and testing low stiffness space mirrors is a primary cost driver.

During the 1990's, JWST Pre-Phase A mirror technology development efforts were completely driven by the mass side of this trade with limited consideration made to stiffness. This is because the NGST (JWST) project desired an 8-m class 50 square meter collecting aperture telescope. However, existing launch vehicles are mass constrained and the mass allocation for the primary mirror assembly (PMA) was approximately 1000 kg (including the mirror's support hardware). This allocation led to an areal density requirement of 15 to 20 kg/m^2. NASA's Advanced Mirror System Demonstrator (AMSD) program demonstrated mirrors at that areal density, but when this mirror technology was integrated into JWST, it was discovered that they had insufficient stiffness to survive the launch load environment. A redesign increased their areal density to 28 kg/m^2. When the mirror segment support structure is included, the total areal density for the JWST 6.5 meter (25 square meter area) PMA is approximately 50 kg/m^2 for a total mass of 1250 kg [Stahl 2007].

Unless the mass capacity of future EELVs increases, it is reasonable to assume that any future telescope launched on an EELV will have a mass budget for the primary mirror assembly of 1250 to 1500 kg. For a 4-m monolithic aperture this results in a target areal density of 100 to 120 kg/m^2 for the PMA (recall that the HST PM was 180 kg/m^2 and the HST PMA was 240 kg/m^2). However, it's important to note that such a 4 m monolithic mirror will be 7X to 10X less stiff than HST. In addition, for an 8-m class segmented aperture with 50 m^2 of collecting area, the areal density drops to 25 to 30 kg/m^2 and the stiffness is 100X less stiff than HST.

The mass capacity of the Ares V greatly relieves these constraints. Based on the Ares V's ability to launch approximately 65,000 kg to SE-L2 it is reasonable to allocate up to 25,000 kg for the primary mirror (PM) and 30,000 kg for the entire primary mirror assembly (PMA) [Stahl 2008]. For an 8-m monolithic aperture, this allows for an areal density of 500 to 600 kg/m^2 which is virtually identical to the areal density found in ground based telescopes. There is a similar benefit for segmented geometries. For example, the current JWST 50 kg/m^2 areal density technology can be scaled to a 600 square meter collecting aperture telescope (26 m diameter). Of course, at four times the diameter of JWST, such a telescope would be 256X less stiff and would thus operate at a much longer diffraction limit.

Based on this discussion, we recommend the following general paths forward:

- If a science mission requires a 4 m or smaller aperture, mission planners should use a monolithic mirror and launch on an EELV.
- If the science requires a 4 to 8 meter aperture, use a monolithic mirror and launch on an Ares V. However, if the Ares V fails to materialize, then fall back to a segmented mirror concept.
- Finally, if science requires very large apertures, plan on using a segmented mirror launched on the Ares V.

However, regardless of which approach is selected, mirror technology development is required to enable these concepts.

Technology development roadmap

With a few exceptions, a common mirror technology development roadmap enables all potential future space telescope concepts, regardless of whether these missions are UV/OIR or Far-IR/Sub-mm. The starting point for this roadmap should be the 2006 NASA Advanced Telescope and Observatory (ATO) Capability Roadmap (CRM) report to the National Academy [Feinberg, 2007; Stahl and Feinberg, 2007]. It must be noted that this report did not consider the impact of a potential large capacity launch vehicle in the future. Therefore, one of its recommendations was to continue the effort towards lower areal-density mirrors. If one assumes availability of the Ares V, this recommendation can be relieved. However, the other investment recommendations are still valid: the community should invest in technologies that enable smoother surfaces across the full physical aperture and/or reduce areal cost by 10X. It's important to note that relieving the areal density challenge makes all of the other mirror technology issues much easier to achieve.

As reported in the ATO CRM, the most significant mirror technical challenge for a large aperture Far-IR/ Sub-mm telescope is areal cost. To address this challenge, investment is required in technologies such as mirror replication or casting.

For a monolithic UV/OIR telescope, the primary technical challenge will be to achieve the required on-orbit surface figure. In general, this will be easier for an 8-m solid meniscus glass mirror than a 4-m lightweight glass mirror. The technology path for a 4-m lightweight glass mirror will be to demonstrate an ability to polish an AMSD-like ULE mirror to 5 nm rms. (The existing AMSD mirror was polished to 20 nm rms.) Additionally, alternative mirror substrate technologies should be examined if they can provide a 5 nm rms surface figure at the 4-m scale for a lower areal cost than AMSD (about $5M/m^2). However, given that a 4-m mirror only has 12.5 m^2 of area, this investment should be limited to less than $10M. In this case, the existing AMSD technology may be acceptable for the mission requirements. Once the ability to achieve a 5 nm rms surface has been demonstrated, it is necessary to scale that capability from 1.3 meters to 4 meters. As discussed earlier, stiffness will be the major challenge. Finally, both the 4-m and 8-m monolithic mirrors will require engineering risk-reduction activities to demonstrate that current state of the art engineering practices (which allow 1.4 to 2.4 meter-class mirrors to survive launch) can be scaled to the 4-m to 8-m class. As part of this scaling demonstration, it will be necessary to calibrate these mirrors' on-orbit gravity sag release.

For a segmented UV/OIR telescope, there are multiple technical challenges. These challenges are compounded if extremely low areal density is required. The primary technical challenge is in developing techniques that allow for quick replication of mirror segments that will reduce risk and cost. Rapid replication of ULE for UV/OIR telescopes and SiC for FIR/sub-MM telescopes is an example of applicable technology development. Many of the technology improvements discussed for monolithic systems will also benefit segmented geometries: reduced areal density and cost, improved surface finishe, improved thermal control, and better characterization of gravity sag.

Conclusion

Independent of science priority, mirrors are a fundamental enabling technology for future space-based telescopes ranging from UV/OIR to Far-IR/Sub-MM. As the astronomy community looks ahead to the next decade, it is important that the engineering community continue to develop the tools needed to push telescope technology forward. To do this, a sustained, dedicated, and cross-disciplinary investment program in mirror technology development is required. This program should develop methods to solve the most significant mirror technical challenge for potential future space telescopes: how to fabricate and flight-qualify low-cost high-quality large-aperture mirrors.

This paper summarizes the current state of the art for space mirrors, outlines some of the most important issues which the astrophysics community should consider as they move forward, and recommends a potential technology development roadmap based on lessons-learned from previous technology development efforts.

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