MIRROR COATING TECHNOLOGY AND INFRASTRCTURE PLANS FOR HABEX AND LUVOIR NASA CONCEPT MISSIONS

CORRESPONDENCE

WITH THE

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Prepared by David A. Sheikh, ZeCoat Corporation

dsheikh@zecoat.com; ph. (424) 254-6002

The ideas, opinions, and views presented in this White Paper are solely those of the author and may not represent the views of other collaborators or organizations.

Dear Colleagues,

The purpose of this White Paper is to convey my plan to develop the FUV-broadband reflective coating technology and new coating infrastructure needed to support NASA's HabEx and LUVOIR concept missions. We are currently installing new coating facilities and we expect to achieve TRL-6 for the new coating technology by the mid-2020's.

ZeCoat Corporation is currently renovating a decommissioned US ARMY steam plant near St. Louis, Missouri, and we are converting it to a vacuum coating facility capable of coating very large optics. The building renovation is scheduled for completion near the end of 2019 and we plan to begin relocating from our California facility at that time. The new coating facility, located within America's Central Port, has two large river-barge ports with full-service on/off-load amenities. A future NASA monolithic mirror, a large spacecraft structure, or a vacuum chamber of virtually any size, may be transported to and from this facility by barge. With a 9-meter ceiling height, the new facility can comfortably house a 6-meter vacuum chamber.

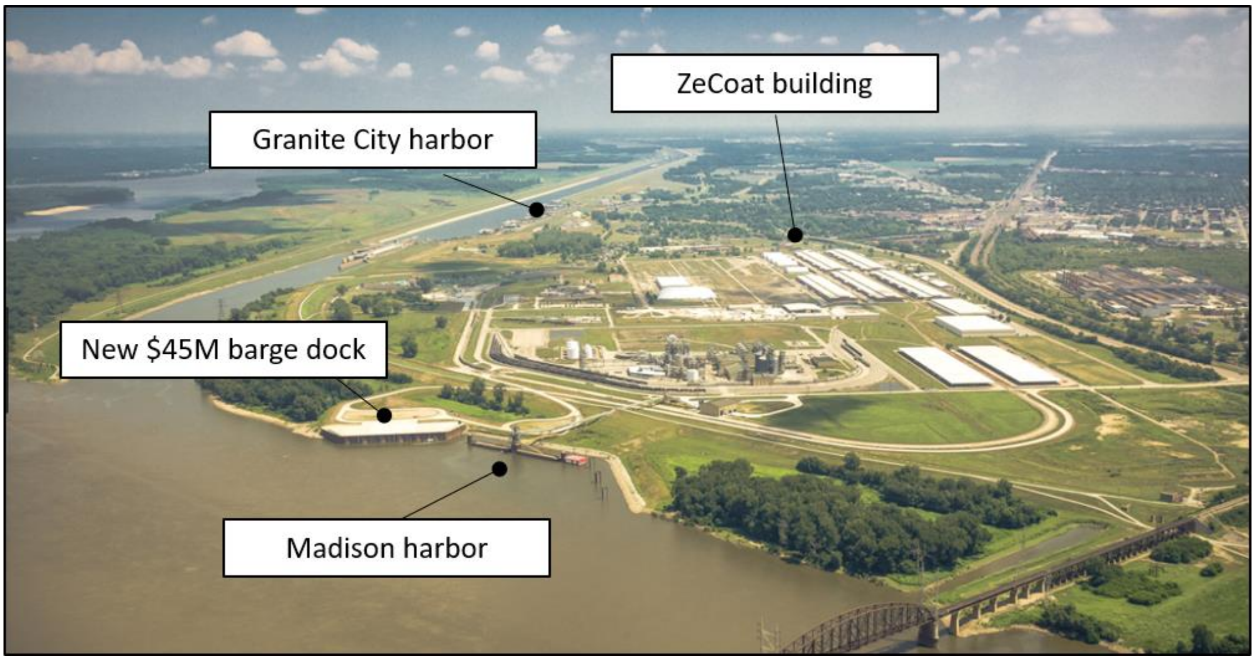

Figure 1 – America's Central Port's 1,200-acre campus in Granite City, Illinois, and future location of ZeCoat Corporation

Advancing new broadband coating technology to TRL 5 by 2021

In 2018, ZeCoat Corporation, in collaboration with researchers at GSFC and JPL, were awarded a 3-year NASA APRA grant to develop scalable reflective coating processes to achieve TRL 5 for large FUV-quality broadband mirrors by 2021. The coating processes are based on evaporated aluminum with a protective metal-fluoride overcoat. The coating materials and processes are similar to those used on HST and FUSE, with significant improvements. Figure 2 shows the measured reflectance vs. wavelength for HST, FUSE, and ideal aluminum. Table 1 shows the reflectance goals for the APRA research, which are nearly equivalent to ideal aluminum for wavelengths beyond 120-nm. Researchers at GSFC have demonstrated very high reflectance FUV coatings on small mirrors, and we will now scale their so-called, "three-step process" for much larger mirrors.

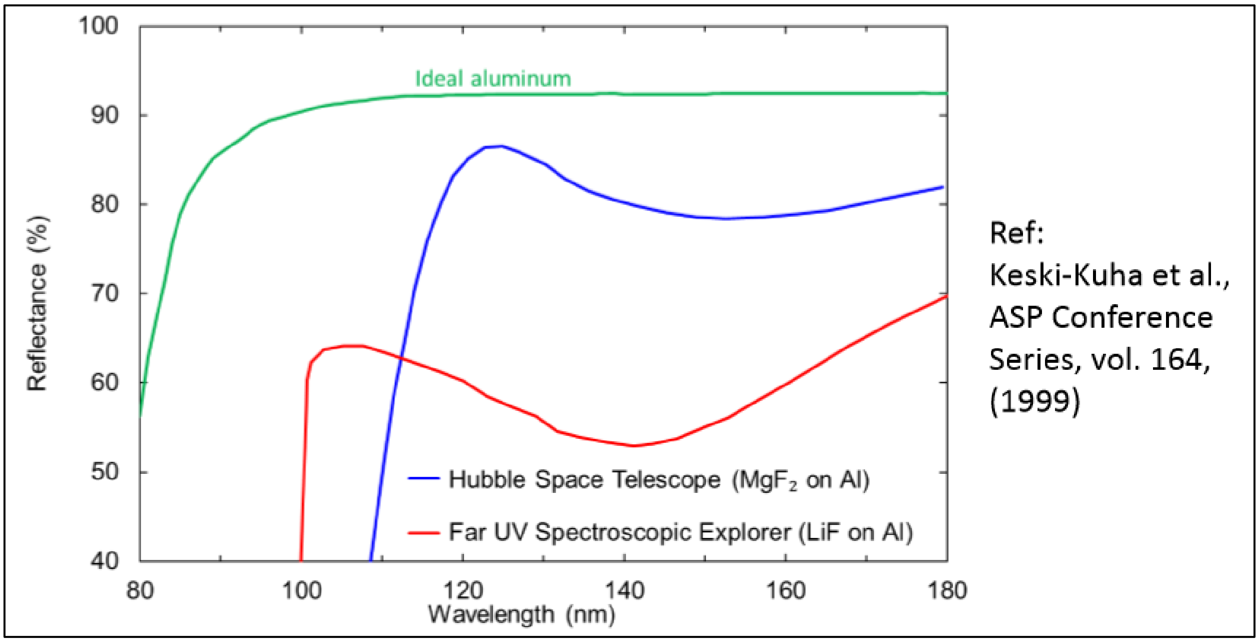

Figure 2 – Measured reflectance for HST and FUSE mirrors

Table 1 – APRA Coating Metrics

	APRA Goals for TRL 5
Reflectivity; 90-nm to 105-nm	>50%
Reflectivity; 90nm to 120-nm	>70%
Reflectivity; 120-nm to 2500-nm	>90%
Reflectance uniformity 90-nm to 2500-nm over mirror coating area	<1%
Coating contribution to wavefront error	< 9-nm (PTV)
Mirror size	2-m scaleable to 8-m

The APRA development work is in-progress at ZeCoat's 2.4-meter vacuum chamber facility in Torrance, California. By 2020 we will demonstrate a scaled process over a 2.0-meter coating area. This mirror size is large enough for most of the segmented telescope designs proposed for LUVOIR. We expect to achieve TRL 6 for 2-meter mirrors by 2023. With private financing, we will install a larger 6-meter coating chamber as early as 2023, capable of uniformly coating a large monolithic HabEx primary mirror, 4.5-meters in diameter, and we expect to achieve TRL 6 for large monoliths by 2025. Figure 3 summarizes ZeCoat's planned TRL progression for the LUVOIR and HabEx concept missions.

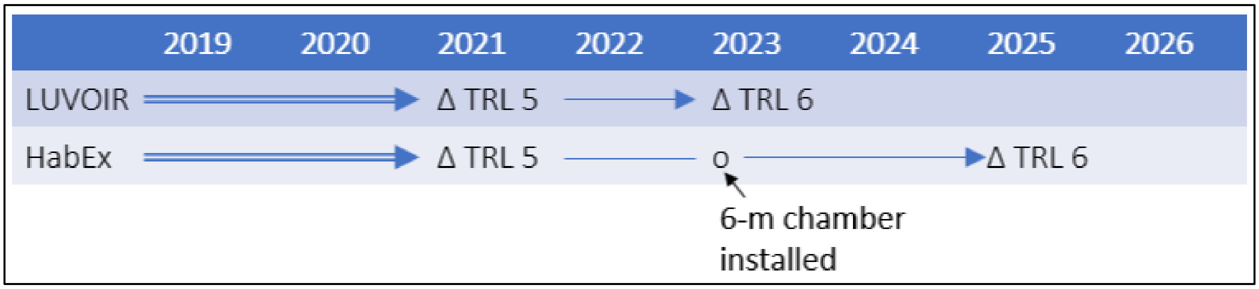

Figure 3 - TRL progression for large broadband mirrors

The following abstract is from our 2018 APRA proposal, which is currently in the 4th quarter of development:

> *This proposal, "Precision Optical Coatings for Large Space Telescope Mirrors" addresses the need to develop and advance the state-of-the-art in optical coating technology. Improvements are needed to coat the large astronomical mirrors planned for advanced NASA mission concepts such as LUVOIR and HabEx. ZeCoat has recently acquired a large vacuum chamber 2.4-meters in diameter, which will be upgraded with the necessary tools to uniformly coat optics up to 2-meters in diameter.*
>
> *ZeCoat Corporation, in collaboration with co-investigators at GSFC and JPL, will demonstrate a broadband reflective coating process for achieving high reflectivity from 90-nm to 2500-nm over a 2-meter diameter coating area. We propose using a new battery-driven coating process to make the aluminum reflector, and a unique motion-controlled coating technology for depositing protective layers. We will advance the technology and manufacturing infrastructure to meet the reflectance and wavefront requirements of both HabEx and LUVOIR. We will test the coating in a simulated space environment, and we expect to advance the TRL from 3 to 5 in 3-years.*

A project overview is provided in PowerPoint charts in this link, http://www.zecoat.com/images/APRA_Mirror_Technology_Days.pdf

Our technology development plan for FUV-quality, broadband coatings can be broken into two general categories; aluminum coating development and protective fluoride coating development. Table 2 shows a TRL comparison, which details the TRL's for several relevant coating processes.

Table 2 - Technology Readiness Comparison

Mirror Size	Process	TRL at end of 2018	TRL at end of 2021	Notes
< 1-meter	GSFC 3-step process	TRL-9	NA	Successfully flown on NASA missions; currently limited to small mirrors less than 1-meter. Baseline process for ZeCoat APRA work
Up to 2-m	ZeCoat Aluminum	TRL-3	TRL-5	Developing new battery-powered coating technology
Up to 2-m	ZeCoat MgF2 or LiF/AlF	TRL-4	TRL-5	TRL-9 motion-control coating system scaled to larger size (deposition technology successfully used to silver-coat 1.44-m Kepler primary, 1.3-m MCAT)
Up to 5.0-m	ZeCoat aluminum	TRL-3	TRL-5	To move beyond TRL 5 requires a full-scale 6-meter chamber capable of uniformly coating mirrors up to 5-meters in diameter
Up to 5.0-m	ZeCoat MgF2, or LiF/AlF	TRL-3	TRL-5	To move beyond TRL 5 requires a full-scale 6-meter chamber capable of uniformly coating mirrors up to 5-meters in diameter

ZeCoat's Battery-powered coating process for depositing uniform aluminum films

Previous work at GSFC, JPL, and elsewhere has shown that some keys to making a highly reflecting aluminum films in the FUV are; (1) high evaporation rates over 100-A/second, which leads to less absorbing and less scattering aluminum films, (2) low chamber pressures, which reduces aluminum reaction with trace background contaminants, (3) minimizing the angle of deposition onto the mirror substrate.

To achieve a high aluminum deposition rate and a uniform film over a very large coating area, our approach is to assemble an array of small resistive evaporation sources and power each source with an individual lithium-ion battery-pack. Our math model shows that a 4.5-meter mirror can be quickly and uniformly coated with a hexagonal array of 367 evaporation sources distributed over a 6-meter diameter area. Our coating experiments show that we will need about a half megawatt of battery-power for a few seconds to energize the coating array. During the next two years, we will demonstrate the process and experimentally verify our model using an array of evaporation sources.

For a smaller LUVOIR segment, our analysis shows for example, that we can uniformly coat a 1.5-meter segment with as few as thirty-seven aluminum evaporation sources and only 70-kW of array-power. We are currently building the (37) evaporation sources for a demonstration next year.

MgF_2 deposition process based on ZeCoat's motion-controlled coating technology

Over the past 19-years, the author has developed a motion-controlled coating system, which utilizes a moving evaporation source and crystal microbalance to uniformly coat a rotating substrate. In 2007, the original version of this system was used to silver-coat the Kepler Space Telescope primary mirror at Surface Optics Corporation. Over the past decade at ZeCoat Corporation, the software algorithm, computer system, and mechanical hardware have all been improved substantially, and we are obtaining coating uniformity at least 3x better than what was achieved for Kepler. Exceptional coating uniformity is essential to meet the stringent wavefront requirements, and coating reflectance uniformity requirements, of future space telescope mirrors.

In our APRA development effort, we will use this motion-controlled system to deliver a precise volume of metal-fluoride on top of the aluminum reflector to protect it from oxidation. Due to the nature of the deposition method, our motion-controlled process is readily scalable to any size mirror, limited only by the size of the vacuum chamber. Figure 4 shows a photo of NASA's 1.3-meter (900 lb.) MCAT primary mirror after coating (November, 2018) with an UV-enhanced silver recipe similar to the one used on Kepler.

Figure 4 – ZeCoat's 2.4-meter motion-controlled vacuum coating system is large enough to coat segments up to 2-meters in diameter (1.3-meter MCAT primary mirror shown in photo)

Scaling up from 2.4-meter chamber to 6-meter diameter coating chamber

We believe scaling our coating processes from a 2.4-meter chamber size to a 6-meter chamber size is a relatively low-risk endeavor, which is why we can offer this capitalization via private financing. We expect our 6-meter coating chamber will look very similar to the 2.4-meter chamber shown in figure 4. The 6-meter cylinder will be placed horizontally, with the primary mirror hung from an arch and facing in the downward direction during coating. The chamber will be manufactured in two cylindrical halves (6-meters diameter and 3-meters long), and will joined by welding after delivery to the coating facility. These large chamber pieces are the maximum size that may be transported as a “super-load” on US freeways. TRL 6 for a scaled coating technology cannot be completely achieved until a full-size chamber is installed, and a coating made from the chamber is tested, and spaceflight-qualified via radiation testing, etc. For these reasons, we plan to design and build a larger coating chamber in the near-term, to reduce schedule, risk, and costs.

Conclusions

A brief summary of our plans for advancing coating technology development in support of LUVOIR and HabEx, and installing new coating infrastructure have been presented. We believe ZeCoat’s strategic decision to build a new coating facility with river-barge access will help enable the swift and economical realization of new heavy-launch, space-based telescopes during the next decade.