

Zenith: Defense Advanced Research Projects Agency's liquid mirror telescope program

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ABSTRACT. Astronomy and Space Domain Awareness are limited by the size of available telescope optics, the cost for which scales steeply due to the exquisitely ground and polished primary mirrors, typically made of glass or other lightweight substrates. Liquid mirrors (LMs) may break this unfavorable cost scaling. When rotated at a constant angular velocity, it has been shown that fluid surfaces take the form of a paraboloid, which can function as a primary mirror. However, current LMs cannot slew or tilt off-zenith due to gravity, greatly limiting the viewing area in the sky. To overcome these limitations while also enabling low-cost, very-large-aperture telescopes, the Defense Advanced Research Projects Agency launched the *Zenith* program. Zenith is developing entirely new LM design-for-build approaches that can create large optical surfaces without rotation and maintain the optical quality during tilt and slew by correcting transient liquid surface aberrations in real time. The development of these new designs is being supported by multi-physics models, materials, surface and field controls, and structures. We discuss key and fundamental aspects of four new design and modeling approaches for this new class of LMs, and the software and simulation tools developed by the Zenith program to design tiltable and size-scalable liquid mirrors.

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1 Introduction

In the quest to map the universe, Hubble Space Telescope¹ and James Webb Space Telescope (JWST)² represent historic inflection points in Deep Space Observation technology owing to

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their size and unprecedented manufacturing precision at scale. HST has a 2.4-m diameter circular, monolithic mirror made from glass coated with aluminum and magnesium fluoride; JWST has a 6.6-m hexagonal, 18-segment mirror made from beryllium coated with gold.¹ JWST's 25 m² collection area allows detection of faint infrared light of galaxies 13 billion light-years away. The flatness precision required to achieve this imaging capability is equivalent to a hexagonal mirror scaled to the size of the United States with its highest peak no taller than 2 in.³ The science return of JWST⁴ has the astronomical community looking to leverage this remarkable technological feat to build even larger telescopes in the coming decade by incrementally advancing the traditional mirror fabrication paradigm. Larger apertures serve not just the scientific community; Space Domain Awareness (SDA) in geostationary orbits (GEO) is currently choked by insufficient imaging resolution limited by the telescope mirror size, as shown in Fig. 1.⁵

As space-based telescopes become larger and more costly and time-consuming to fabricate, they also face heightened operational risk from damage by collisions with micrometeoroids and orbital debris.^{6–9} In recognition of obstacles to future scalability and survivability, investigation of different approaches that allow faster construction of larger and lower-cost and damage-resilient telescopes, assembled either on the ground or in space, has commenced.¹⁰ Diffractive lenses¹¹ and fluidic telescopes^{12,13} are two such alternative approaches.

When rotated at a constant angular velocity about a vertical rotation axis, the equipotential surface of a fluid takes the form of a paraboloid. This is the principle behind present-day liquid mirror telescopes (LMTs): light incident upon a reflective liquid surface spinning at a constant angular velocity converges at an effective prime focal point. Cabanac et al.¹⁴ demonstrated a 3-m diffraction-limited spinning LMT made of mercury for orbital debris observations. The cost of a liquid mirror is estimated to be two orders of magnitude less than a glass mirror.¹⁵ For example, the cost of the 4-m diameter International LMT is ~\$2 million,¹⁶ whereas the estimated cost for the optical telescope assembly of a 4-m conventional telescope is \$341 million for space application and \$11 million for ground application.¹⁷ Parametric cost models developed at NASA¹⁷ indicate that the cost of the optical assembly for traditional telescopes made from ground and polished solid mirrors increases very rapidly with the overall mirror diameter (as 1.7th power of the effective diameter), and the cost of a segmented mirror is similar to the cost of a monolithic mirror of the same effective diameter due to the higher cost of the structure for the segmented mirrors. Liquid mirror (LM) approaches hold promise for breaking these traditional telescope-scaling paradigms.

Laird et al.¹⁸ first showed that combining a ferrofluid shaped by a magnetic field with a surface-deposited metal liquid-like film (MELLF) made from a silver colloid could be used to build a deformable LM. Brousseau et al.^{15,19} demonstrated a residual root mean squared (RMS) wavefront error of less than 0.05 μm with a 100-mm diameter (laboratory scale) ferrofluidic deformable mirror shaped by an array of ~91- to 3-mm-diameter magnetic cores placed

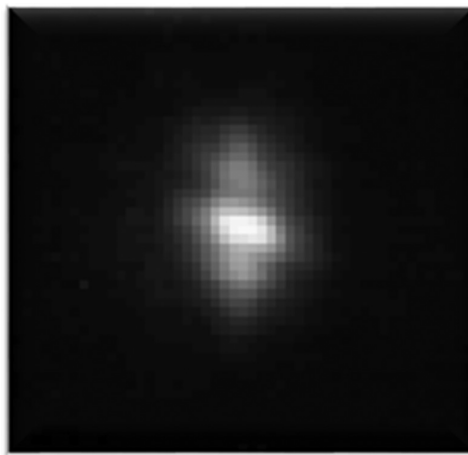


Fig. 1 Image of GEO satellite GE-23 from the second largest optical telescope on Earth (10-m Keck II, with adaptive optics).⁵ Despite the large imaging aperture, the satellite is still unresolved, revealing the limitation of aperture size for SDA.

beneath the liquid and a superimposed larger steady circumferential magnetic field generated by a Maxwell coil. The 4-m diameter International Liquid Mirror Telescope in Davasthal, India saw first light in April 2022.²⁰ The mirror spins at 7.5 rpm to create a parabolic mirror shape. Limited by gravity, the liquid mirror has a field of view of 0.36-deg around the zenith.

In general, fundamental limitations such as not being able to tilt LMTs has limited their utility to the astronomical and space domain awareness communities. Traditional LMTs can only point straight upward (zenith-restricted) and are, therefore, limited to isotropic sky surveys. Any application of tip or tilt results in the liquid sloshing out and the imaging capability of the telescope being lost. The need for spin-rotation or thrust-for-gravity to form a coherent liquid mirror surface also restricts the space deployment of LMTs. Due to the necessity for spin, segmented mirrors, which are the standard for large space-based telescopes, are not possible with LMTs.

Recent work has opened new paths for potentially implementing tiltable liquid mirrors. Wang et al.²¹ investigated ferrofluid-infused microporous surfaces subjected to a magnetic field and demonstrated combined magnetic and capillary actuation and control of a ferrofluid through an engineered capillary microchannel and more complex flow paths. They also showed that a droplet can be magnetically forced to maintain its shape while tilting up to 90 deg in the presence of gravity. Caillasse et al.²² showed that ultrathin adherent reflective films of homogeneously self-assembled silver nanoparticles (AgNPs) can be generated *in situ* by exposing an aqueous solution containing a silver precursor and a photogenerator to ultraviolet light for a few seconds. Khan et al.²³ demonstrated how the interfacial tension of liquid metals can be reversibly controlled by applying voltage. Eaker and Dickey²⁴ investigated reversible shape changes of gallium-based LMs upon applying a voltage and reviewed four methods of LM actuation: electrocapillarity, continuous electrowetting, electrowetting-on-dielectric (EWOD), and electrochemically controlled capillarity. EWOD does not require the LM to be immersed in an inert electrolyte and may be scalable and easy to fabricate. Ren et al.²⁵ demonstrated focal length control of a liquid lens using a servo motor to induce hoop compression on the convex lens and thereby induce curvature change. Li et al.²⁶ achieved a similar result using a piezoelectric motor. Corning's Varioptic^{®27} liquid lens uses an electrostatic field to control the curvature, and therefore focal length, of a liquid lens. This change is effected in ~10 ms by changing the applied voltage. In summary, these advances offer proofs-of-concept for tiltable, slewable, scalable, and segmentable millimeter-scale LMs using capillary, electrostatic, and magnetic forces.

The present work explores the scalability of these concepts to the meter-scale LMs and the challenges therein, built upon the research advances described above. In this paper, we report on four non-spinning, tiltable, and slewable LM prototype development initiatives, from teams led by General Atomics (GA), General Electric (GE), Lockheed Martin (Lockheed), and Honeywell Aerospace Technologies (Honeywell). All four efforts strive to prove the feasibility of a scalable liquid mirror. The proof-of-concept hardware development is backed by a robust modeling and simulation (M&S) effort. Under funding from the Defense Advanced Research Projects Agency (DARPA), the "Zenith" program's near-term (33-month) goal is to demonstrate through hardware and M&S, a liquid mirror with the following characteristics:²⁸

- optical aperture diameter of at least 0.5 m and a focal length in the range of 1 to 10 m
- liquid system that covers the entire LM aperture and that has specular reflectivity of greater than 0.65 at a reference wavelength of 550 nm
- out-of-plane tip and tilt angles of greater than 10 deg
- 0 to 1 deg/s slew rate
- wavefront error, correctable to a sixth of a wavelength RMS error across the entire effective aperture during slew and at rest at a reference wavelength of 550 nm.

The vibration environment and real-time fluid control must permit this level of wavefront error rejection, which is expected to be the pacing technical challenge. Each of the four design concepts is a new and unique build concept for a 0.5-m aperture LM system, supported by multi-physics analysis and M&S. Successful designs may be scaled up to the 1-m and larger sizes in future phases of the program. As Zenith is the first ever undertaking to realize a tiltable LM system, a 10-deg tilt capability was chosen as an achievable and meaningful first step for showing

the feasibility of achieving even greater angles. Also, choosing a smaller tilt angle would enable rapid precipitation of key challenges encountered in maintaining optical quality during tilting, allowing for faster design iteration.

2 Approaches to a Tilttable, Slewable, and Scalable LMT

The need to spin traditional liquid mirrors has previously limited their scaling to Very Large Telescope sizes. Instead of the liquid mirror surface scaling unfavorably in cost, the size of the required torque motor would instead scale unfavorably. To advance this state-of-the-art, Zenith LMT systems are designed to not use spin.

Figure 2 and Table 1 summarize the approaches to extend the research discussed in Sec. 1 at the coupon scale to the 0.5-m prototype scale and beyond. This paper presents advances made in phase 1 of the Zenith program.

These four methods use a combination of reflective liquids development, mirror surface metrology and control, system-architecture development, newly developed physics-based M&S capabilities, and laboratory tests. These include:

1. A capillary-actuated, electromagnetically controlled liquid surface. The liquid contains reflective and magnetic nanoparticles. The lead organization is GE, with the University of Laval and Raytheon Technologies Research Center²⁹ as team members.
2. An electromagnetically driven and controlled ferrofluid surface with a reflectivity that is achieved through the use of nanoparticles. The lead organization is Lockheed Martin, with the University of Arizona³⁰ as a team member.
3. An electrostatically driven and piezoelectrically controlled mirror design with liquid metal as the optical fluid. The lead organization is GA.³¹
4. A permanent magnetic controlled mirror design with two immiscible liquids containing reflective and magnetic nanoparticles, which will spontaneously phase separate. The lead organization is Honeywell, with Georgia Institute of Technology and Soter Technology³² as team members.

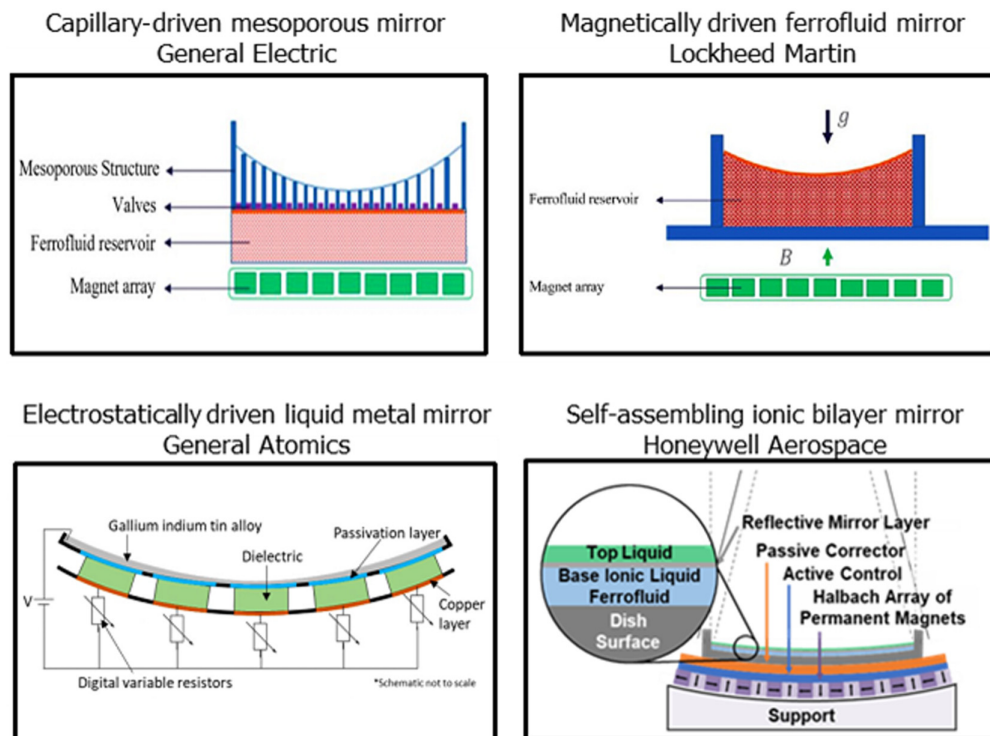


Fig. 2 DARPA Zenith program is advancing LM design-to-build 0.5-m mirror concepts that implement magnetic, capillary, electrostatic, and piezoelectric control of ferrofluids and liquid metals. Schematics are not to scale.

Table 1 Comparison of the key attributes of the four LM technologies that were investigated.

	GA	GE	Lockheed Martin	Honeywell Aerospace
Forces controlling mirror surface	Electrostatic, surface tension, viscous, gravitational	Magnetic, capillary, surface tension, viscous, gravitational	Magnetic, surface tension, viscous, gravitational, capillary (optional)	Magnetic, surface tension, viscous, gravitational
Liquid system	Mercury layer	Ferrofluid layer, reflective nanoparticles layer	Ferrofluid layer, reflective nanoparticles layer	Ferrofluid layer, reflective nanoparticles layer, protective layer
EM system	Electrodes	Electromagnets, Helmholtz coils	Electromagnets, permanent magnets	Halbach array, passive magnetic correctors, active magnetic field control
Surface control	Voltage, piezoelectric transducers	Electromagnets	Electromagnets	Magnetic field controls, tilting of the liquid container
Spin-stabilization (Rotation)	None	None	None	None

All methods seek to base the formation of an imaging surface and shape on field control of a working liquid, without the use of rotation or thrust, for the first time. Approaches (1), (2), and (4) investigate the scaling of these concepts both experimentally and using new simulation tools, with reflective ferrofluids or bilayer ionic liquids. Approach (3) investigates the feasibility of scaling up the EWOD behavior shown^{23,24} by a non-reflective gallium–indium–tin liquid alloy at the droplet level, to a half-meter scale LM, using experiments and newly developed simulation tools, and mercury as the working fluid.

Sections 2.1–2.4 summarize each of these methods and the work accomplished to date.

2.1 Mercury Liquid Mirror Based on the Electrowetting-on-Dielectric Approach

This approach is an electrostatically driven and piezoelectrically tuned segmented LM system, with a mirror diameter of 50 cm. The liquid metal chosen for this design is mercury, which is conductive but also has LMT heritage from previous work on the NASA Orbital Debris Observatory.¹⁴ Figure 3 shows a schematic of the concept. Additional details may be found in Ref. 32.

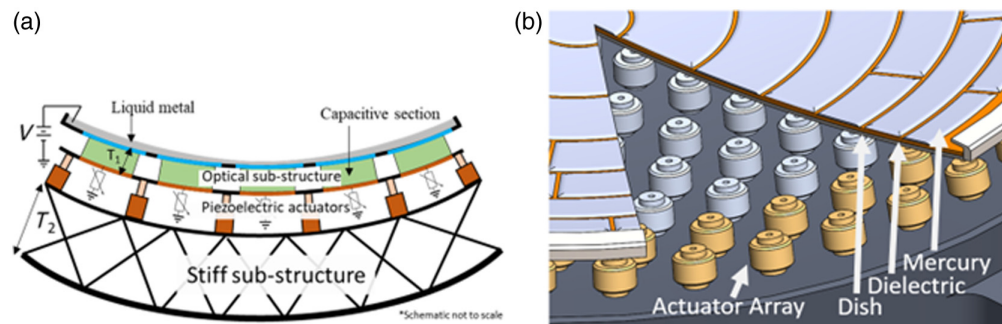


Fig. 3 Liquid mirror design based on the EWOD approach. (a) Schematic showing the key sub-systems of the liquid metal-based mirror and a conceptual implementation in a telescope, and (b) CAD drawing showing mirror segmentation, paraboloid dish, and piezoelectric actuator array used for fine control of the mirror surface. Figures courtesy GA.

The mirror substrate is a curved (paraboloid) dish to match the required mirror curvature. The substrate is coated with a dielectric material to aid in the spreading of mercury and the adhesion of mercury to the substrate. The design relies on the EWOD principle, i.e., the ability of a thin film of mercury to spread when voltage is applied at the top surface of the mercury layer, and the bottom of the substrate is grounded. The design compels the top surface of the mercury to assume the desired mirror shape before correction through uniform spreading due to the EWOD effect and through conformation to the curved shape of the substrate.

The mirror design is segmented, as shown in Fig. 3. The segment size is determined by the largest mercury mirror that can be made by the EWOD principle. The substrate is supported on a stiff sub-structure with an intermediate actuator layer, as shown in Fig. 3(b). During slew and at rest, the mercury surface in each segment needs to create a high optical quality surface and conform to the curvature prescription. All the segments need to be maintained in phase during operation to enable diffraction-limited imaging by the entire mirror aperture. This is to be accomplished by a combination of global and local actuators and by a combination of piezoelectric and DC-motor-driven actuators in the actuator layer. Closed loop wavefront error control of the mercury mirror surface will be implemented using a wavefront sensor and the suite of actuators.

To investigate electrostatic field strengths, adhesion to the substrate, and other conditions necessary for achieving a stable contiguous mercury film on a dielectric substrate, a custom test apparatus with a built-in glove box and fume hood has been built (Fig. 4). This experimental setup safely supplies high electric fields while the mirror substrate is tilted up to 10 deg along two axes. Initial experiments are focusing on flat dielectric substrates and substrates in the form of a container. Testing with this setup is ongoing. The competing requirements of liquid spreading and adhesion crucially depend on the properties of the dielectric layer between the mercury and the substrate.

To develop a baseline mirror design, the multi-physics simulation of mercury spreading on a dielectric substrate is in progress, using analytical models and COMSOL. Models include the effects of gravity, liquid viscosity, liquid surface energy, and interfacial friction, in addition to coupling electrostatics with the fluid mechanical response. Most simulations were performed in 2D; full 3D simulations have long computational run times. Eventually, 3D simulations will be required to model tilting and slewing.

Figure 5 shows one example of results from a mercury-spreading simulation. In this example, the profile of a mercury droplet is shown in half (symmetric) at 0.5 s after the application of voltage between the droplet and the substrate, with a layer of dielectric in between. The results show that a mercury droplet with a size (radius) of 2.5 mm at zero voltage expands to 5.8 mm under 800 V of applied voltage. Simulations are in progress to compute the profile when the substrate is tilted from 0 to 10 deg.

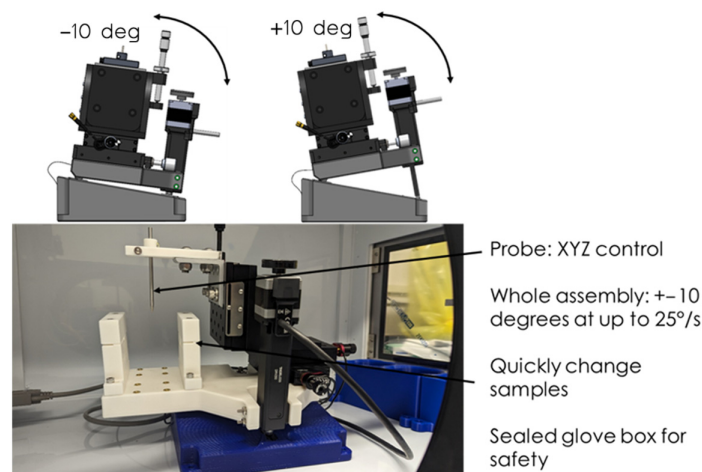


Fig. 4 Test apparatus for investigating electrostatic wetting on dielectric (EWOD) effects to create a large-area mercury mirror.

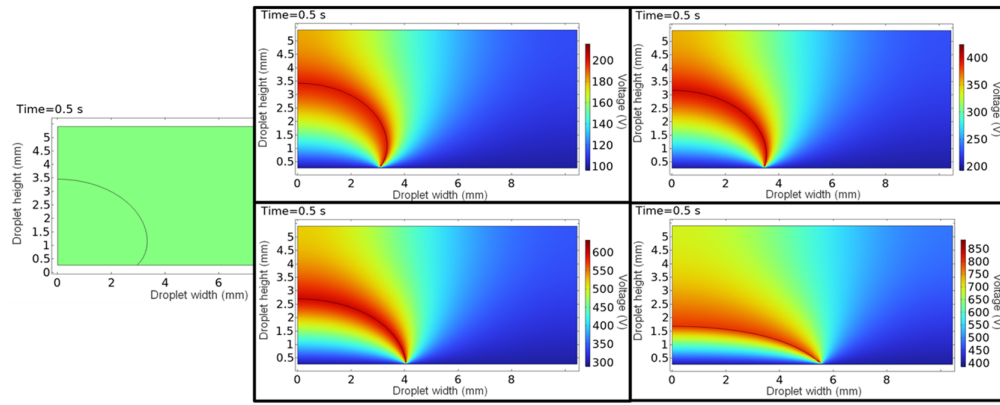


Fig. 5 Representative COMSOL simulation of the electrostatically induced mercury droplet profile versus applied voltage. The profiles are shown 0.5 s after the voltage is applied and when a steady state is reached.

Simulations of the piezoelectric actuator array to control the substrate shape of the half-meter diameter LM are being performed, using ANSYS and ZEMAX. Given actuator properties such as stiffness and tip size, the number of actuators, the substrate material and thickness, and deformations of the substrate can be calculated. Simulation results are then used to optimize the actuator subsystem. The ANSYS mechanical analysis provides the substrate profile and sag between actuators. The dish surface shape from ANSYS is used as input to ZEMAX, which performs the optical wavefront error computation for the substrate.

A typical simulation output showing deformation and wavefront error of the substrate is shown in Fig. 6. For these results, the substrate is assumed to be of optical quality.

Prior work in the literature on EWOD modeling of mercury was limited to millimeter (mm) scale droplets. One of the accomplishments of this effort has been the development and expansion of a mercury spreading and adhesion model to a centimeter (cm) scale. The modeling tools may be applied to liquid metals other than mercury. The code base developed by the GA team is discussed in Sec. 3.1.

Some operational attributes of the liquid mirror based on the EWOD approach were considered. The dielectric layer between the mercury and the ground plane was seen to limit the lifetime of the test coupons during testing. It was assumed that pinholes through the coating shorted to the substrate and thus prevented further electrostatic adhesion. Future work would

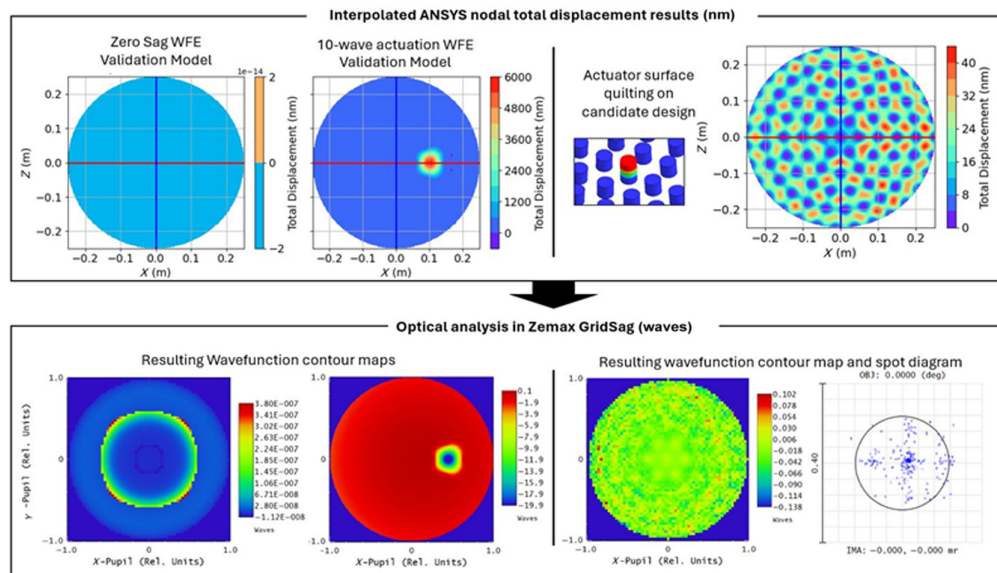


Fig. 6 Modeling flow that takes ANSYS deformation/sag output and provides it to ZEMAX, which computes wavefront error.

focus on analyzing the pinhole initiation and optimizing the coating process. The EWOD design is not expected to generate significant thermal loads at the mirror surface because the electrostatic adhesion process requires high voltage, not high current, and thus the waste heat generated is expected to be minimal. Much of the required distortion of the dish is expected to be mechanical and stable once set in place. Evaporation is not expected to be a significant factor. At room temperature, mercury will very slowly evaporate but the use of only pure mercury in the design means that cells can be refilled without worry of disturbing any mixture or layering requirements. The vibration and settling concerns for the segmented mercury dish design in the EWOD approach are expected to be similar to those of existing mercury rotating mirrors except for vibration sources derived exclusively from the rotation of the dish.

The cost of the system is expected to be comparable to, but somewhat greater, than existing mercury telescopes. Costs for similar components, such as mercury, pumps, and safety handling from existing rotating telescopes, will carry over. However, synchronous motors and air bearings would be replaced by high-voltage power supplies and large, commercial stepper motors, and piezoelectric actuators. It may be noted that the number of actuators scales linearly rather than quadratically with radius in this design. The optical metrology sub-system implements mature, commercial technology, so this aspect would be expected to scale in a similar manner as previous, large-format telescopes.

2.2 Capillary-Assisted and Magnetically Controlled Ferrofluidic Approach

This approach is a capillary-force assisted and magnetically controlled LM system, with a mirror diameter of 50 cm. The liquid chosen for this design is a two-component liquid system, typically 2- to 5-mm thick, comprising a ferrofluidic layer with a top reflective layer. Ferrofluids are made of a suspension of magnetic nanoparticles in a suitable solvent. Ferrofluids have very low reflectivity in visible wavelengths. To form a mirror, a MELLF layer containing AgNPs and organic ligands is applied to the top of the ferrofluid layer.¹⁵ The MELLF combines the property of high reflectivity of silver and liquid-like behavior that allows it to form a thin uniform layer on the ferrofluid surface that can be controlled by the magnetic field. Figure 7 shows a schematic of the concept. Additional details may be found in Ref. 29.

This approach is being investigated by a team from GE Vernova Advanced Research, with the University of Laval. The magnetically controlled ferrofluid development builds on work done by Brousseau et al.,^{18,19} which demonstrated a 23-mm optical aperture ferrofluidic deformable mirror.

Figure 7(a) shows the first design of a LMT with wavefront error diagnostics. Figures 7(b) and 7(c) show the design schematic for the capillary-assisted magnetically controlled ferrofluidic mirror. A paraboloid mesoporous dish provides the basic mirror shape to the liquid surface, which is then controlled by a magnetic sub-system consisting of an underlying electromagnetic coil array and circumferential Helmholtz coils. The Helmholtz coils simplify the liquid surface response function. The deformation at the liquid surface increases with the applied magnetic field. When the magnetic field exceeds a critical value (typically 80 Gauss in some cases;¹⁵ for comparison, the Earth's magnetic field is less than 0.67 Gauss), spikes appear on the liquid surface. The design ensures the magnetic field remains below this so-called Rosensweig instability limit.³³

Capillaries serve two purposes—dampening the fluid motion during tilt and slew and delaying the formation of the Rosensweig instability. Submerged in the ferrofluidic layer is a capillary

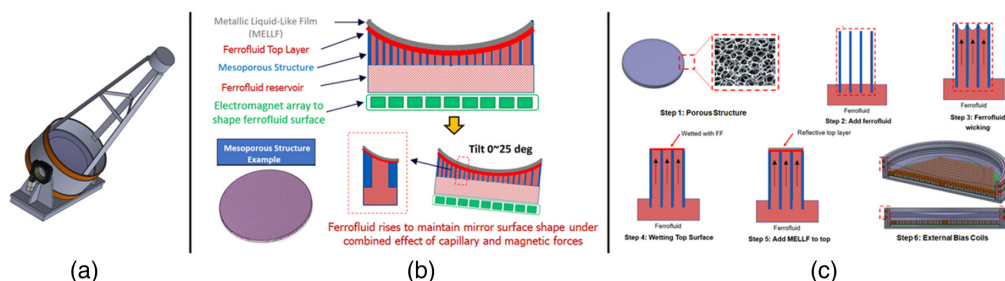


Fig. 7 Schematic of a capillary-assisted magnetically controlled ferrofluidic mirror and telescope.

("mesoporous") structure that combines capillary forces with magnetohydrodynamic forces to control the optical surface of the MELLF layer in the presence of tilt and slew. The typical pore size is $50\ \mu\text{m}$ in diameter. Figure 7(c) shows the curved substrate for the ferrofluid mirror and the bias coils of the electromagnets underneath. The ferrofluid rises through the capillaries, and a reflective MELLF layer is formed on top of the ferrofluid surface above the capillaries. Two types of capillary structures are being investigated: structures with random-sized pores (foam) and structures with uniform-sized (machined) holes. Different material classes for the capillary substrate and the height and diameter of the capillary channels are being actively optimized for the liquid mirror application.

Thermal expansion was analyzed for the porous plate. For a 1°C increase in the temperature of a steel plate, the 784-mm diameter increased by $10\ \mu\text{m}$ ($5\ \mu\text{m}$ radially). In the vertical direction, the plate thickness grew by 0.4 to $0.5\ \mu\text{m}$. Similarly, the thermal expansion of an actuator coil was analyzed. For free/natural convection [$5\ \text{W}/(\text{m}^2 \cdot \text{K})$ convective heat transfer coefficient] and a heat generation of $0.9\ \text{W}$ per coil, the coil was found to reach 79°C at a steady state. This would, in turn, result in the coil growing in height by $30\ \mu\text{m}$.

The liquid system developed by GE Vernova Advanced Research is a custom ferrofluid with a submerged porous structure (which aids in controlling the liquid mirror surface) and a custom MELLF layer, which gives more than 65% reflectivity. Figure 8 shows the picture of the liquid surface and a wavefront error map of the surface at rest showing $\lambda/7$ RMS uncorrected wavefront error measured at $633\ \text{nm}$ ²⁹ while at rest.

The core aspect of the liquid system design is the use of a low vapor pressure hydrophilic ferrofluidic system, coupled with slight hydrophobic AgNPs,³⁴ allowing their self-aggregation at the liquid–air interface due to a combination of hysteretic and electrostatic factors. Once applied, the nanoparticles spontaneously self-assemble at the surface of the ferrofluid, forming a mono film of nanoparticles. Once the surface is saturated with nanoparticles, any excess particles are injected into the volume, forming folds on the film.³⁵

MELLFs are known for self-healing in the liquid–liquid interface, that is, the systems can be completely disturbed followed by complete and spontaneous recovery of their structure and properties.³⁶ In the liquid–air interface (liquid mirror), this self-healing ability is partially maintained, and mixing of the MELLF and ferrofluid is only observed upon significant mechanical mixing. Provided that the system is mechanically stable, degradation of the two liquid systems occurs by separate mechanisms already described in the literature: surface oxidation of the AgNPs for the MELLF layer,³⁷ and agglomeration and destabilization of magnetite nanoparticles suspension in the case of the ferrofluid.³⁸ In both cases, previous results have shown that custom ferrofluid and MELLF do not experience significant degradation for at least 70 days.³⁹

Vibration of the liquid system is a fundamental concern for system performance. It is well known that the surface of a liquid inside a cylindrical container is sensitive to vibrations. However, when the liquid depth to container radius ratio is small, viscous effects tend to dominate, and sloshing is highly reduced, both in terms of spatial amplitude and temporal frequency. In previous work on ferrofluid deformable mirrors, a liquid depth-to-container radius ratio of ~ 0.02 was used, and the experiments showed that the sensitivity to vibrations was minimal.

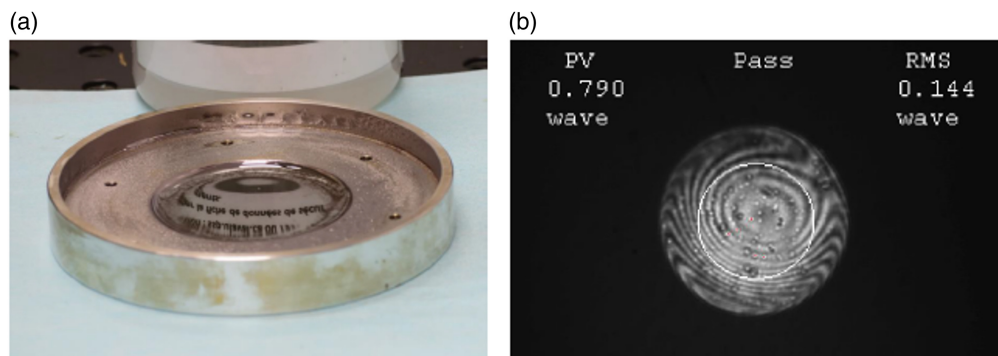


Fig. 8 GE liquid mirror with ferrofluid and MELLF²⁹ (a) and measured surface wavefront quality while at rest (b).

Moreover, when the ferrofluid deformable mirror is under use, the magnetic field from the actuators also acts as a stabilizing effect. In fact, in most of the experiments on magnetic liquid mirrors, it was found that the air flows coming from the ceiling ventilation of the lab were a bigger problem than vibrations. These air flows were found to be easily minimized by installing a Mylar film of optical quality over the ferrofluid container. Installing such a Mylar film has proved to be successful even for a liquid mirror of 6 m in diameter.⁴⁰

The ferrofluid shape is controlled by an electromagnet subsystem, which consists of an underlying electromagnetic (EM) coil array and two Helmholtz coils, as shown in Fig. 9. The Helmholtz coils produce a strong and uniform magnetic field throughout the ferrofluid. An array of electromagnets under the mirror substrate carry out fine control of the ferrofluid surface shape, working in the linear regime of magnetic field versus current. The major advantage of this linearization is that one can use the same proven algorithms that are used with solid deformable mirrors. The magnetic field of the Helmholtz coils is at least 10× larger than the magnetic field from a single EM coil, which indicates that the design is within a linear regime. The surface response, linearized with a strong and uniform magnetic field from the Helmholtz coil, can be 50 to 100× the field strength generated by a single EM coil.

The response of the ferrofluid surface for different coil arrangements has been modeled to optimize the magnet sub-assembly. COMSOL simulations have been verified against analytical solutions (see Sec. 3.2). Figure 10 shows the influence function of an electromagnet on the ferrofluid surface calculated both analytically and with COMSOL, showing good agreement between the two. Modeling of the field generated by the magnets has yielded an optimized number of electromagnet coils. Power dissipation from the Helmholtz coils has been found to be small and insensitive to the wire gauge used for the 50-cm mirror design.

A full suite of analytical models is being developed for this LM approach. This includes (1) magnetic field modeling; (2) magnetohydrodynamic modeling; (3) fluid dynamics modeling including gravity, capillary effect, and physical motion of the mirror; and (4) controls system modeling.

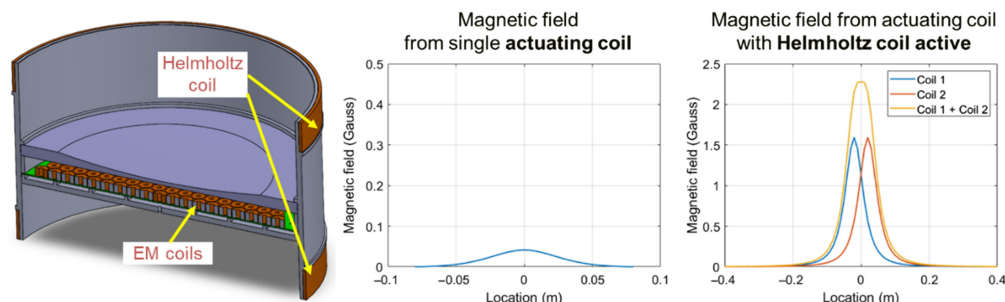


Fig. 9 Modeling of representative designs combining Helmholtz and EM coil arrays ensures that the mirror surface response is in the desired linear regime.

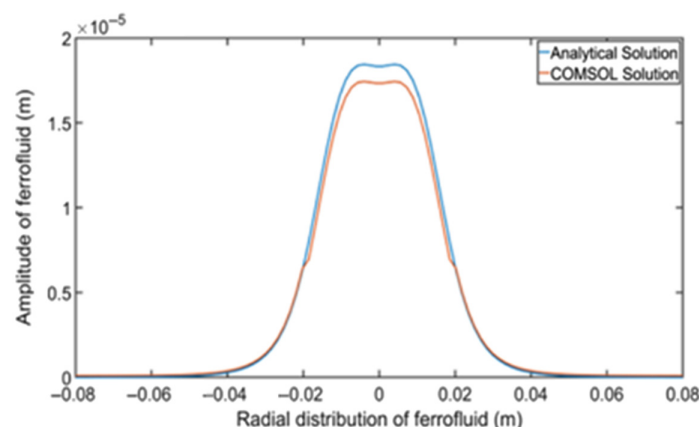


Fig. 10 Comparison between analytical modeling and COMSOL simulations.

A multi-input multi-output control system has been designed for a 7-unit cell system consisting of ferrofluids and the electromagnet coils underneath the fluids. The objective of the controller is to regulate the deformation of the liquid mirror at desired locations while mitigating the impact of system tilt. The maximum deformation in the closed loop system was observed to be 25 nm in the simulations performed in MATLAB/SIMULINK, and this is a significant improvement from 5.3- μm deformation without closed-loop wavefront control. While developing the system dynamic models, a linearized system and the superposition of individual actuators have been assumed, and the active control can be performed with a closed loop rate of 8 Hz.

Telescope primary mirrors must achieve and maintain very tight optical tolerances, typically some tens of nanometers or less. Conventional telescopes achieve this, at a high cost, by precise ultrafine polishing, and with complex support structures. LMs, on the other hand, have mechanical tolerances that are three orders of magnitude lower. They achieve and maintain surfaces of optical quality simply due to the natural equilibrium of fluid under gravitational and inertial forces. Therefore, liquid mirrors are much easier to fabricate and can be considerably lighter than their rigid counterparts. For example, the cost of the deformable mirror in work performed by Brousseau et al.⁴¹ was estimated at about \$100 per actuator, including materials, electronics, and machine shop time. About 70% of the total cost was from the commercial off-the-shelf analog output cards used at the time. For commercial deformable mirrors having similar characteristics, the cost is usually about \$500 to \$1000 per actuator.

Ionic liquids have negligible vapor pressures and thus do not evaporate in a vacuum. It has been shown⁴² that there are commercially available ionic liquids that solidify at 175K. Furthermore, it has been shown that the ionic liquid can be coated with silver. Ionic liquids are organic compounds, and there are more than 10^6 simple ionic liquids and 10^{18} ternary ionic liquid systems.⁴³

Despite the wide availability of ionic liquids, the design of an appropriate liquid system for space applications is still an issue. For instance, there is extensive research on ferrofluidic systems based on ionic liquids, but most of these studies have focused on hydrophobic ionic liquids.⁴⁴ The lack of highly hydrophilic ionic liquids has been a restricting factor to test its potential as a substitute for the ethylene glycol based ionic liquids for realizing space applications. Furthermore, the deposition of the self-assembly nanoparticles is part of a complex thermodynamic phenomenon that, to our best knowledge, has been poorly studied under such environmental conditions. Thus, although the main limitations are the materials, especially the ferrofluid, extensive testing would still be required to confirm its feasibility for space applications. The code base developed by the GE Vernova team is discussed in Sec. 3.2.

2.3 Magnetically Controlled Ferrofluidic with a Porous Wicking Structure Approach

This approach, led by Lockheed Martin, is a magnetically controlled ferrofluidic liquid system for a liquid mirror diameter of 50 cm. The liquid system chosen for this design is a commercially available ferrofluid, which gives the surface shape, and a custom MELLF layer on top, which gives the desired reflectivity. The MELLF contains gold nanoparticles to give high reflectivity for visible wavelengths. A porous wicking structure submerged in the liquid to give additional control of the surface layer against gravity is an option. Figure 11 shows a schematic of the concept. Additional details may be found in Ref. 31.

A fluid reservoir with a liquid retention film at the bottom contains the ferrofluid. The liquid-retention substrate is curved to match the desired mirror prescription. A magnet subsystem containing an array of electromagnets is positioned underneath the ferrofluid layer to control the shape and achieve wavefront error correction of the fluid surface. A porous wicking structure submerged in the ferrofluid, as shown in Fig. 11, is an option being actively traded. The role of the capillary wicking structure is to reduce required fluid volume, increase liquid surface stability, and increase liquid surface area scalability. Preliminary modeling results suggest that the wicking structure may not be needed in a 50-cm diameter mirror design. The ferrofluid extends above the wicking structure. The shape and the figure of the liquid are maintained by a combination of the magnetic force (from the magnet subsystem), surface adhesion force, and optional capillary force.

After carrying out trade studies for the liquid system, a commercial ferrofluid with low vapor pressure and high viscosity has been chosen. For the MELLF layer, experiments were carried out

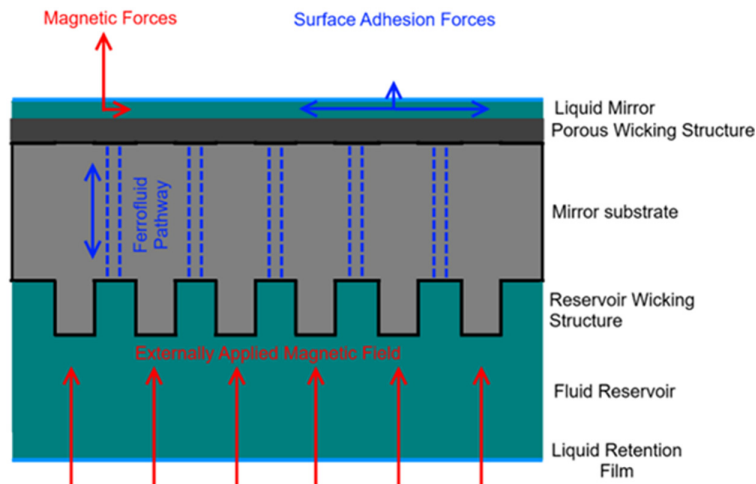


Fig. 11 Schematic of the magnetically controlled ferrofluidic with a porous wicking structure approach.

using silver and gold nanoparticles of various sizes, shapes, and concentrations. Ligands were optimized to make the MELLF compatible with the ferrofluid and to increase the lifetime of the liquid system. The application process of the MELLF on top of the ferrofluid layer was optimized. As a result, a sub-scale reflective liquid system that can be controlled by a magnetic field was developed.

Experiments were conducted to study the physical and optical characteristics of ferrofluids in magnetic and gravitational fields. The experimental setup is shown in Fig. 12. A sample holder was designed to hold the ferrofluid and a permanent magnet. The sample holder is tilted using optical stages. The surface profiles are measured using interferometry and X-ray computed tomography (CT scan). The interferometer had a field of view of $494 \times 494 \mu\text{m}$. As shown in Fig. 12, the shape of the ferrofluid sample and the surface roughness did not change appreciably when the sample holder was tilted between 0 and 10 deg. The CT scan showed surface perturbations due to Rosenzweig instability at two edges of the ferrofluid sample. Figure 13 shows the measured ferrofluid surface roughness values in the 2 to 5 nm RMS range at applied magnetic field strength values between 0 and 250 G.

Preliminary measurements indicate a surface roughness <5 nm RMS within this field of view in the presence of a magnet. As shown in Fig. 13, the shape of the ferrofluid sample and

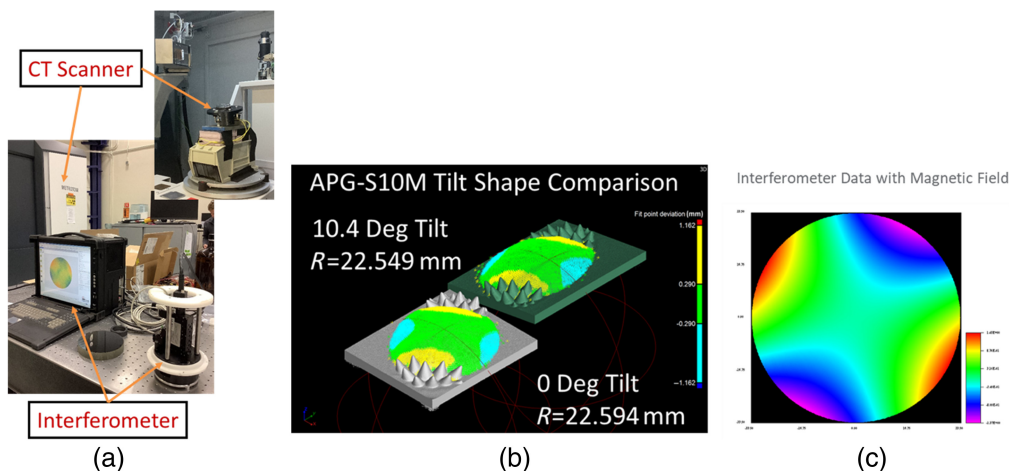


Fig. 12 (a) Experimental setup to investigate the applicability of interferometry, X-ray CT, and a Keyence Microscope, to characterize the shape and smoothness of LM surfaces, (b) demonstration of ferrofluid curvature maintenance at 10-deg tilt while under the control of a permanent magnet. The onset of the Rosenzweig instability at two regions is also imaged, and (c) interferometric data is obtained in the upright (no tilt) position.

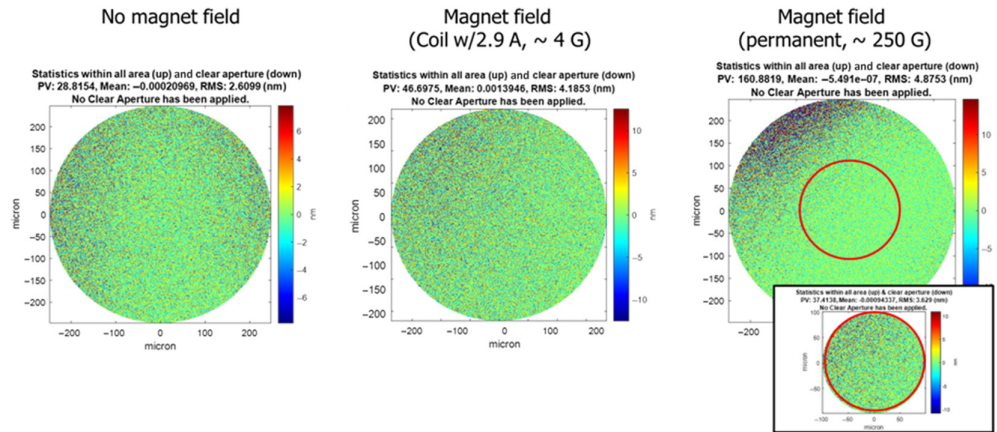


Fig. 13 Interferometric surface roughness measurements as a function of magnetic field strength.

the surface roughness did not change appreciably when the sample holder was tilted between 0 and 10 deg. The Lockheed Martin/University of Arizona approach is designed to employ EM coil arrays to achieve surface tunability and stability and deliver the required wavefront performance. A parabolic shell design with a combination of permanent magnet arrays and wicking structures collectively addresses the rotational and off-axis requirements. These elements will provide both EM and capillary forces to help maintain a thin, conformal layer of ferrofluid that can be reshaped and manipulated via active coils to achieve the final, desirable optical wavefront error of $\frac{1}{4}$ wave at 550 nm. To address off-zenith ferrofluid creep and linear gradient compensation for small wavefront errors, optical interferometry techniques, in particular, adaptive nulling will be used to bridge the gap between large and final errors.

In the M&S effort, magnetic field profiles in the ferrofluid have been calculated for linear coils. The ferrofluid surface profile has also been calculated using an arrangement of coils to impart the desired shape. For linear coils, the field is mostly parallel to the coil axis and is maximum at the ends. Basic model predictions aligned well with test data from the small-scale experiment described above. The equations for the surface shape function have been analytically derived (see Sec. 3.3).³⁰ An effort is underway to incorporate the analytical model into finite element simulations.

The LM surface figure may be highly temperature-dependent owing to the multi-physics interplay of bulk forces (gravity and viscous), surface tension, and capillary and magnetic forces across the curvature of the ferrofluid and reflective layers. With respect to the mirror surface interacting with the backing structure, heating, and power dissipation of the individual coils, coefficient of thermal expansion changes in the parabolic backing shell, thermal gradient between backing and surface, and fluid evaporation effects also must be taken into account. A first-order analysis assumed standard temperature and pressure operating conditions for the system. Further analysis will be needed to determine temperature margins for maintaining wavefront control both from temperature changes in the fluid as well as the effects of mechanical expansion on the backing structure.

2.4 Magnetically Controlled Self-Assembling Ferrofluidic Ionic Liquid Bilayer Approach

This approach is a magnetically controlled self-assembling ferrofluidic LM system that uses a liquid bilayer structure with reflective and magnetic nanoparticles, with a mirror diameter of 50 cm. The liquid system comprises a base ionic liquid that contains magnetic particles and is ferrofluidic, a liquid with reflective nanoparticles, a second liquid that caps the reflective layer, and reflective nanoparticles held at the liquid–liquid interface that serves as the optical surface of the mirror. Figure 14 shows a schematic of the concept. Additional details may be found in Ref. ³².

The mirror surface shape and optical quality of this LM system are controlled by permanent magnets with passive magnetic correctors and active magnetic control. A key feature of the concept is its self-assembling nature. This ferrofluidic ionic LMT is constructed from two immiscible non-volatile liquids containing spatially segregated reflective and magnetic nanoparticles,

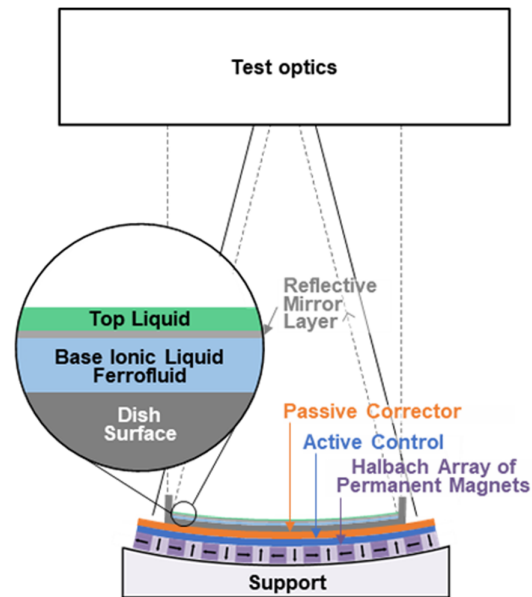


Fig. 14 Schematic of a self-assembling ferrofluidic ionic LMT.

positioned by a Halbach array of permanent magnets. The substrate is curved to match the optical prescription of the primary mirror. When the base ferrofluidic ionic liquid, the reflective nanoparticles, and the top liquids are mixed and allowed to settle, the layers separate, and the reflective layer is driven to the interface between the two layers. The top layer of the substrate also plays a role in spreading and retaining the liquid system. Selection of non-volatile liquids avoids fluid loss to the atmosphere or to space through evaporation that would result in measurable changes in the position of the mirror surface on timescales relevant to mirror calibration and imaging. Self-assembly is a major advantage as if a mirror has been disrupted by impact or other events, it can self-heal and reform the reflective surface. The presence of the top liquid extends the life of the mirror by preventing reflective particle aggregation that is otherwise observed when a nanoparticle mirror layer is placed at a fluid surface.

Processes to prepare magnetic particles for suspension in ionic liquids as well as to produce the reflective layer have been developed and tested experimentally at a small scale. Experiments have been conducted to study the spreading behavior of ionic liquids on various substrates. The reflectivity of test reflective layers on ferrofluid has been measured for several design choices. Progress has also been made toward developing commercially sourced liquid pairs that with the custom reflective particles produce reflectivity in excess of 65% at 550 nm. Figure 14 shows a diagnostic setup in which the reflected light from the mirror is focused and analyzed at the focal plane of a telescope.

The primary figure control of the ionic ferrofluid is accomplished with a Halbach array.³² The Halbach array creates a magnetic equipotential surface away from the array and parallel to the top plane of the array.⁴⁵ Preliminary ferromagnetic modeling led to the design and construction of a 10" × 10" Halbach array prototype with 400 half-inch cubic magnets, as shown in Fig. 15. The magnets were commercially procured and measurements showed only 2.5% maximum variability in the magnetic flux density across the lot. The test showed that the assembly requires controlling deformations within the array due to strong magnetic forces in the vertical direction. The fabricated Halbach array demonstrated the ability to hold a ferrofluid and its surface at a tilt angle of 90 deg, also shown in Fig. 15. The figure shows that a beaker containing a commercial ferrofluid is held horizontally against gravity by the Halbach array, and the fluid continuity is maintained by the magnet.

To investigate and validate the influence of as-built Halbach arrays on the LM surface quality and other test conditions that cannot be easily captured by modeling, a custom test apparatus with an interferometric system was built (Fig. 16). The setup characterizes mirror wavefront error while tilting up to >10 deg. It uses a circular optical bench with a steel baseplate in its center for placing and positioning a dish containing a liquid mirror sample (Fig. 15). A Halbach array can

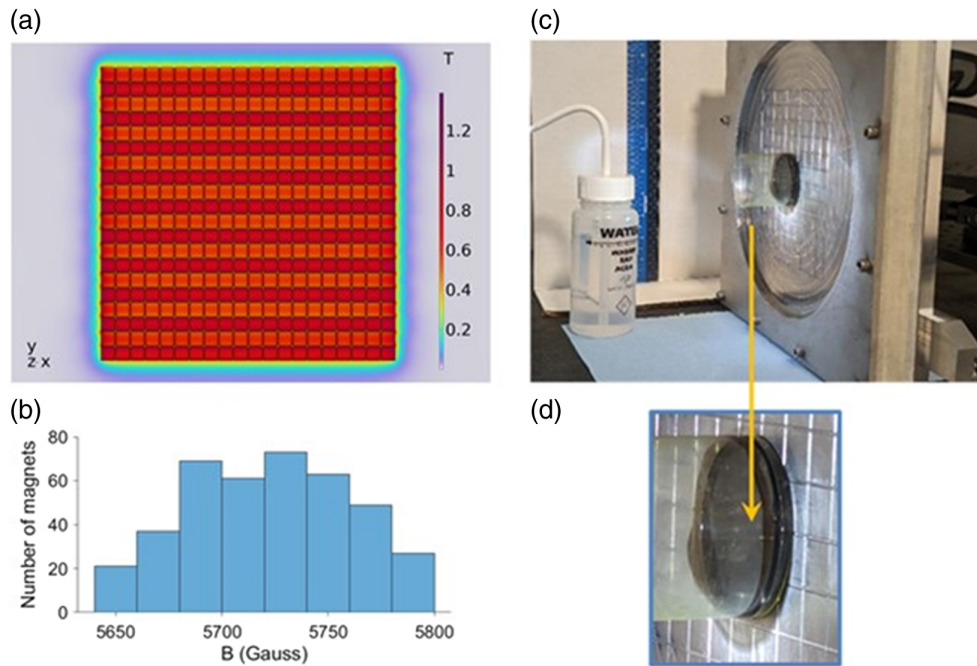


Fig. 15 Assembled Halbach array (a), statistics of magnetic induction of commercially procured magnets (b), a beaker containing ferrofluid held horizontally with a vertically oriented Halbach array (c), and an enlarged view of the magnetic fluid at 90-deg tilt angle to the vertical (d).

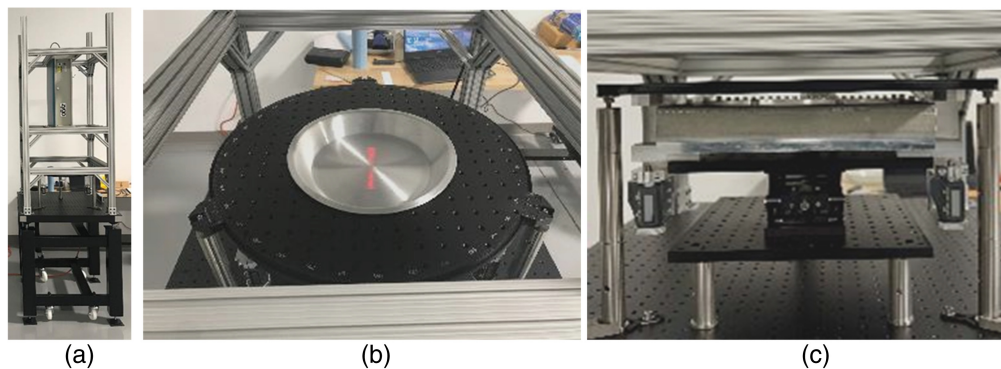


Fig. 16 Interferometric test set up to measure the optical quality of the ionic liquid-based mirror (a), (b) and test set up shown with Halbach array (c).

be positioned precisely underneath an LM sample, exploring the influence of distance (and field strength) on mid-frequency wavefront error, and on global wavefront error under tilt. Tests are ongoing to understand design implementation issues and to anchor experimental results in M&S.

The Halbach array shown was designed using a custom model. Figure 17 shows the computed Kelvin body force magnitude and magnetic field from an array of 400 magnets. This model was also used to estimate the mid-frequency wavefront error induced in the LM, which is then used to design tailored passive magnetic correction added on top of the Halbach array to further reduce magnetic field variations and enhance magnetic control.

Both analytical and finite element models have been developed to predict ferrofluidic behavior and optical surface aberration in the presence of gravity. Simulation results have shown that tilting off-axis requires active control or compensation. A separate 2D analytical model that integrates a model of a Halbach array and ferrofluid and COMSOL showed that the Halbach array magnet size impacts global and mid-frequency wavefront error in opposite directions, i.e., the global wavefront error (from tilt) is minimized by large magnets, whereas the mid-frequency

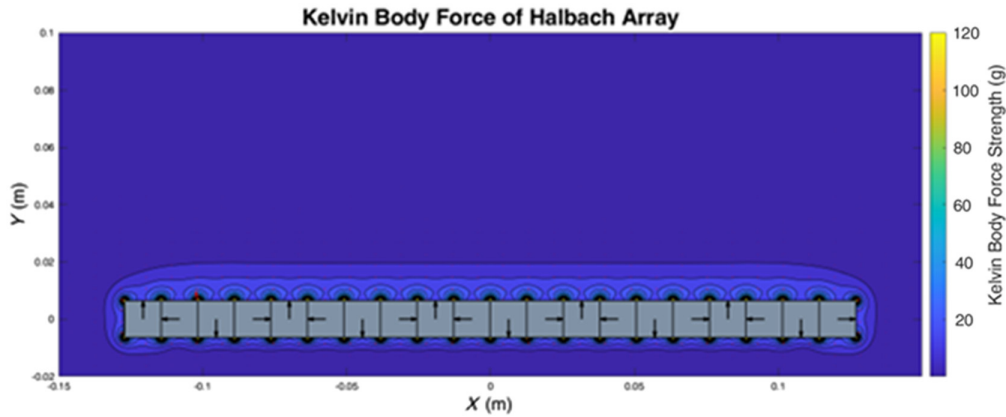


Fig. 17 COMSOL simulation of a linear Halbach array of permanent magnets generating a flat magnetic force field on a ferrofluid layer.

wavefront error (from array periodicity) is minimized by small magnets. A key finding is that mid-frequency wavefront error is independent of tilt, so global and mid-frequency wavefront error can be controlled separately. Representative results from physics-based modeling are shown in Fig. 18.

Early identification of key design trades was achieved through an analytical approach, followed by finite element analysis simulations to evaluate complex scenarios. This analysis showed that smaller magnet wavelengths favor surface ripple control but increase errors when tilting. Larger magnet wavelengths are better not only for tilting control but are also easier to manufacture. The team has identified a need for active control to effectively mitigate excess low-spatial frequency surface deformations resulting from tilt, and design iterations are ongoing.

The Zenith program requires mirror control during slewing, and thus, the fluid viscosities are selected to minimize the impact of dynamics, both due to slewing and due to vibrations induced by the pointing control system of the telescope/mirror mounting. Because the ferrofluid is subject to $O(100\text{ N})$ magnetic settling forces, surface wave energy dissipation per cycle increases by a factor greater than two⁴⁶ due to its dependency on $g^{1/4}$, where g is acceleration due to gravity on Earth. In addition, the effective shear viscosity coefficient of the fluid is $\sim 5\%$ higher than for a non-magnetic liquid under the same conditions.^{34,47} Together, these factors produce smaller, faster-decaying surface waves than with traditional LMTs.

Preliminary modeling has indicated that the fluid surface will require active control at the level of $\sim 100\text{ }\mu\text{m}$ to correct for the global wavefront error induced by tilting off-zenith by the required 10 deg. Although the expected operating environment of the ground-based telescope is expected to be relatively benign, i.e., a moderate range of temperatures and rates of temperature

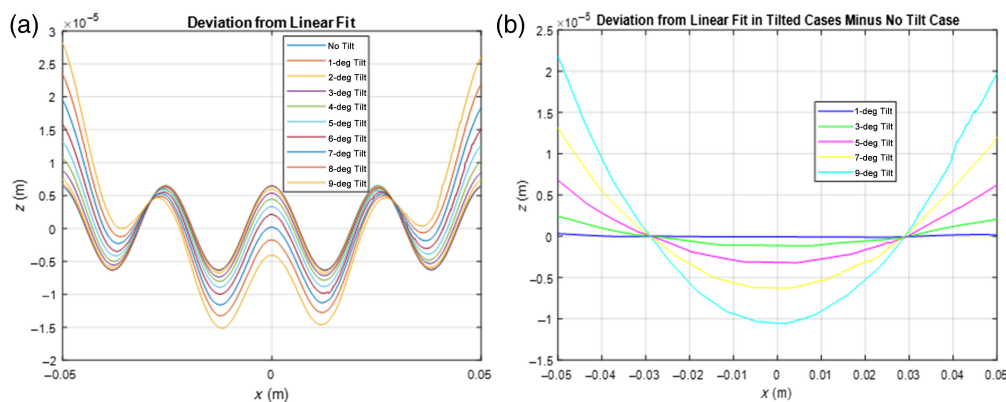


Fig. 18 Representative results from physics-based modeling: (a) sum of global and mid-frequency wavefront error for different tilt angles, (b) leaves only global wavefront error only, after subtraction of mid-frequency wavefront error for no tilt.

change, some active control authority can be allocated to correcting for these environmental changes.

In terms of a potential application to a future space-based telescope, in addition to the benefits of the self-assembling bilayer fluid system mentioned above, the active control required to correct for the deformation of tilting off-zenith under gravity is reduced. Active control may still be retained at a much lower level to compensate for thrust, the microgravity environment, and variations in the thermal environment.

The code base developed by the Honeywell team is discussed in Sec. 3.4.

3 Availability of Liquid Mirror Modeling Codes

An important part of the Zenith program vision was to create the capability for the broader astronomy community to investigate, validate, build, and proliferate tiltable LMTs for civil and commercial use. As the utility of current LMTs is limited by the small viewing area at the zenith, tiltable Zenith LMTs may greatly enhance the utility of LMTs in general while offering significant cost benefits over traditional glass optics at large aperture sizes. The simulation tools developed to validate these designs may be useful to the astronomy community for designing future liquid mirror applications.

All four Zenith teams have developed open-source coding tools, together with in-code comments and instructions for use. This section describes those code bases.

3.1 General Atomics Code Base

The code base and documentation developed by GA³¹ contains an M&S documentation file and the computer code bases in four areas: (1) physics modeling, (2) mechanical modeling, (3) controls system modeling, and (4) fundamental modeling. The M&S documentation file contains the physical properties of the LM components and design variables and describes in detail the analytical framework and the underlying physics. The analysis is applicable to liquid metals other than mercury as well. It also provides an overview of all four code bases and detailed operating instructions.

In this code base, fluid dynamics is combined with electrostatics in COMSOL multiphysics. The modules used for the simulation are computational fluid dynamics laminar flow, mercury/air interface, electrowetting, and electrostatics. The evolution of the liquid mercury surface on a curved surface is simulated under a gravity load environment using a basic electrowetting model with surface tension, viscosity, and coefficient of friction as parameters. The original goal was to model a monolithic 50-cm diameter curved mercury surface held in place by electrostatic forces. However, the model did not converge even after running for a long time. An alternate segmented aperture design was developed with small containers of mercury forming segments of a 50-cm diameter curved mirror. This design can be simulated using an electrowetting model and under various slewing conditions. The residual uncorrected surface form error of $+/- 50 \mu\text{m}$ was observed for a multi-container configuration over a 45-mm radius. The ANSYS model carries out deformation analysis of the mirror substrate under gravity load and in the presence of piezoelectric actuators that are used for shape control. The control simulation provides voltages to be applied to the piezoelectric actuators for substrate shape control. Finally, the fundamental modeling codes provide contact angles and voltages necessary for wetting various dielectric layers between mercury and the grounded substrate.

3.2 General Electric Code Base

The code base and documentation developed by the GE team²⁹ contains a M&S documentation file and the computer code bases in three areas: (1) analytical models, (2) COMSOL Multiphysics models, and (3) controls models. The M&S documentation file contains the physical properties of the liquid mirror components and the design variables, and it describes in detail the analytical framework and the underlying physics.

The analytical models compute the influence function for single coils, the magnetic field generated by Helmholtz coils and EM coils, 1D and 2D simulation of the influence of coil design parameters, and magnetic field calculation of a tilted coil.

The 2D COMSOL model includes a simulation of ferrofluids interacting with porous media and Helmholtz and EM coils. In the numerical model, the LM consists of three layers: a reservoir (ferrofluid) layer, a capillary (porous) layer, and the top surface of the ferrofluid layer. It is assumed that the reflective MELLF layer with any protective layer on top conforms to the ferrofluid surface and does not impart any additional surface deformation. The ferrofluid in the reservoir rises up in the porous media due to the capillary force and extends above the capillary structure to form a top surface layer. The magnetic field is calculated for the given magnet array design. The magnetic force term in the ferrofluid is computed. The magnetic force term along with gravity is included in the Navier–Stokes equation for fluid flow. The laminar condition is approximated due to the low velocity of the ferrofluid under nominal operating conditions.

To model the porous media and the top layer, Darcy's Law is applied in conjunction with the phase transport equation as the fluid flow represents a two-phase flow consisting of air and ferrofluid. Darcy's Law is coupled with the phase transport equation by setting the mass source term in Darcy's Law equal to the sum of the mass source terms for each individual volume fraction. The inputs to the model include ferrofluid properties, operating current for the magnets, geometrical parameters of the design, porous media properties, and gravity. Porous media properties are added to the COMSOL code. Capillary and Bond numbers are then calculated. The 2D model shows the time-dependent flow of ferrofluid through the porous media and is checked against analytical results. 2D analysis for magnetic field calculation was extended to a 3D COMSOL code. Time-dependent top surface profile results can be obtained for various slewing conditions. Work is ongoing to check the simulation results against laboratory tests and to generate more accurate surface deformation results by employing finer grid sizes.

The control model computes surface deformation at various locations in the mirror due to the applied current at a single EM coil. This analytical model computes the cumulative deformation of the LM surface using the superposition of transfer functions due to all EM coils. For the control model in this version of the code, a unit cell is defined as consisting of a ferrofluid without a porous structure and an electromagnet actuator. The MATLAB code produces Bode plots and Step response plots of the unit cell's dynamic operation. The bandwidth of the unit cell for step function input can be computed for open and closed-loop operations.

3.3 Lockheed Martin Code Base

The Lockheed Martin code base and documentation³⁰ contain an M&S documentation file and code that can be used to study magnetic fields for various coil magnet designs. The documentation file describes the analytical framework for the liquid mirror system, including the calculation of the magnetic field for various magnet geometries, the response of the ferrofluid to the magnetic field, and simplified code optimization by the order of magnitude calculations of effects such as surface tension and viscous damping.

The MATLAB code calculates the magnetic field using Maxwell equations for a magnet arrangement. Given the magnetic field, it calculates the magnetic force on the ferrofluid.

The documentation presents the equations to be solved for the mirror design and points out computational difficulties in solving them. The difficulties arise primarily due to the large aspect ratio of the fluid bed (diameter to thickness), the fluid-to-air boundary determined by nonlinear differential equations, mirror dynamics, and the need to determine the liquid surface location to $\sim 1/40$ th-wavelength accuracy, whereas the liquid thickness is few thousand times the wavelength. This creates a challenging setup.

Several useful observations are made to guide future modeling development. The first is that creeping (or Stokes) flow can be assumed. Considering the surface tension force, it was concluded that surface deformations < 1.75 mm in lateral scale would be smoothed out. In this design, Rosensweig instability is predicted to occur at a much lower magnetic field than the saturation magnetization of the ferrofluid, with an operating point in the linear magnetization regime. For the case of a nonmagnetic top reflective layer, the surface deformation is predicted to be $(\text{liquid thickness}/(4f\#))$, where $f\#$ is the f -number of the LM. For example, for a mirror with $f\#$ of 5 and liquid thickness of 1 mm, the surface deformation under tilting conditions is predicted to be 50 μm .

3.4 Honeywell Aerospace Technology Code Base

The Honeywell Aerospace Technologies' code base and documentation developed by the Honeywell team³² contain two M&S documentation files and the computer code bases.

The M&S documentation files contain documentation on modeling relating the ferrofluid surface profile to the magnetic field conditions and device design. They also document the Optical model and are tied to the 2D analytical model for ferrofluid deformation. The Kelvin body force expression is derived expression is derived for the ferrofluid in equilibrium in the presence of a magnetic field. Considering gravity and magnetic force, the momentum conservation equation is derived for the ferrofluid interface. The magnetic field is calculated using Maxwell equations.

Making further assumptions such as the use of low-density ferrofluid for which magnetic susceptibility $\ll 1$ and the surface tension force is comparatively small, it was shown³² that the ferrofluid interface is determined by the equipotential lines (considering magnetic and gravity forces).

The next task is to determine the equipotential lines for any specific Halbach array configuration. The unit cell of a Halbach array is a set of four magnets rotated with respect to one other. The unit cell can be repeated indefinitely. This configuration gives rise to a flat magnetic field on one side and nearly zero magnetic field on the opposite side. An analytical expression for the magnetic field has been derived and implemented in MATLAB. The magnetic field is linear with magnetization and decreases exponentially from the top surface of the Halbach array. An analytical expression for the ferrofluid surface amplitude and the total body force potential were derived. The body force potential gives the ferrofluid surface profile assuming it follows the equipotential line. The analysis was extended to derive an expression for the critical magnetization field for the onset of Rosensweig instability, which forms a serrated surface pattern. This analytical framework is the basis for the code bases described below.

The analytical expression for the ferrofluid surface amplitude was solved using MATLAB to produce the mid-frequency wavefront error as a function of saturation magnetization and magnet height/wavelength ratio. This includes assumptions such as the absence of edge effects, saturation magnetization much less than the magnetic field strength, and the use of a commercial ferrofluid. Several plots relating various design factors help in determining the optimum operating conditions in terms of saturation magnetization, ferrofluid height, and magnet spacing.

The Halbach array code generates the magnetic flux density and Kelvin body force for a 2D flat Halbach array. The spherical global tilting code produces the equipotential fluid surface for a 2D spherical Halbach array, assuming an ideal Mallinson³² magnetic field. The equipotential surface is calculated as a function of tilt angle, which was then used in the optical code.

The analytical model cannot be used for a curved Halbach array with discrete magnets. A more accurate 3D COMSOL model was developed for the curved liquid mirror.

The documentation files also contain information on the calculation of the optical performance of the liquid mirror of this design. The input to the model is the result of the MATLAB 2D spherical global tilting code described above. The 2D results can be analyzed using a 3D Zernike fitting process. The input to the model is the height profile of the ferrofluid surface as a function of tilt. Tip/tilt and curvature are first removed to see the mid-frequency ripple due to the Halbach array. The mid-frequency ripple was found to be independent of the tilt angle. Assuming the ripple can be corrected to a 1% residual level using passive magnetic correctors, simulated passively corrected curves can then be generated.

In the optical model, the piston, tilt, and curvature are first removed from the equipotential surface obtained from the 2D spherical global tilting code. This gives the global wavefront error. The rest of the code carries out "what if" analyses to determine what is ideally possible. The code calculates residual wavefront error versus radial location as a function of tilt after numerically fitting and removing coma and spherical aberration terms. The residual error is the uncorrected mid-frequency error. The code then can carry out another "what if" exercise to remove periodic error in the residual wavefront to yield 10-nm RMS residual error and the associated point-spread function.

The baseline design assumption is that 99% of the mid-frequency errors can be corrected by passive magnetic correctors.

These code bases for tiltable LMTs are being made publicly available. The code bases are hosted on GitHub and Box and may be obtained at no cost until December 2025 by sending an email request to zenith@darpa.mil.

4 Summary

The Zenith program is investigating four approaches to developing half-meter and larger-scale LMTs. The liquid mirror in three of these approaches is based on a ferrofluid combined with a MELLF, and a fourth approach employs liquid mercury as the mirror material. As the telescope must be able to tilt and track and slew while imaging, spin-stabilization is excluded. This has led to the design and implementation of other, new means of controlling a diffraction-limited imaging-quality mirror surface, i.e., by using a combination of magnetic, electrostatic, and capillary means. The sloshing behavior of liquids when the mirror is in motion is being addressed through viscosity control and the use of porous media. The absence of centrifugal forces also requires the development of new substrate material surfaces/coatings that statically ensure wetting and adhesion. New formulations of ferrofluids, MELLFs, and optional protective coatings for MELLF are being actively developed. The processes for the repeatable formation of the liquid system, application of the MELLF layer, and replenishment of the liquid system during long-term operation are also in development. The objective is to enable next-generation LMs and LMTs that are tiltable and have an optical quality imaging surface that can be maintained for long periods without defects or instabilities.

Alongside the development of successful recipes for 50-cm-scale non-rotating LMs, the development of custom control systems required to maintain high-quality imaging capability at rest and during tilt and slew is in progress. The non-alignment of gravity and the optical axis during tilt results in non-uniform surface wavefront error distribution. The liquid sub-system, the shape, and surface control sub-system (magnetic or capillary or electrostatic or some combination thereof), *in situ* mirror metrology sub-system (interferometry, deflectometry, etc.), along with real-time closed-loop adaptive optics control of the wavefront error of the mirror must all be integrated into an operational LMT system.

The Zenith program is addressing these challenges. A set of openly available M&S tools has been developed to enable the future development of large-diameter LMTs. The modeling and simulation tools (tiltable liquid mirror codes) are available on request.

Disclosures

The authors declare that there are no financial interests, commercial affiliations, or other potential conflicts of interest that could have influenced the objectivity of this research or the writing of this paper.

Code and Data Availability

All data in support of the findings of this paper are available within the article.

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Biographies of the authors are not available.