Honeywell

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Proposal Title	Self-Assembling Ferrofluidic Ionic Liquid Mirror Telescope
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TABLE OF CONTENTS

2.0 PROPOSAL SUMMARY

Honeywell, in partnership with Georgia Institute of Technology and Soter Technology, is pleased to propose the demonstration of a self-assembling ferrofluidic ionic liquid mirror (FILM) telescope concept constructed from two immiscible ionic liquids (ILs) containing reflective and magnetic nanoparticles (NPs) positioned by a Halbach array of permanent magnets (Figure 1-1).

The system is scalable and self-healing and can be deployed without applied acceleration or rotation. The Halbach array overcomes the force of gravity for a ground-based liquid mirror, which allows tilting off-axis and slew with imaging quality wavefront error (WFE) levels.

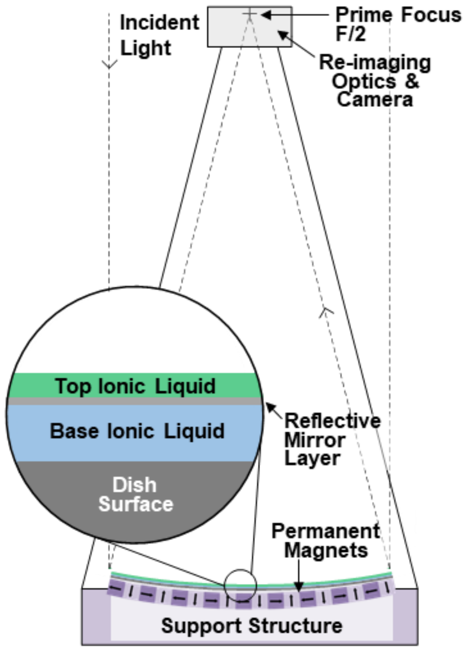

Figure 1-1. Concept for the Self-Assembled Ferrofluidic LMT.

Phase I of the proposed program leverages existing modeling and simulation (M&S) tools, IL fluid development facilities, and interferometric fluid mirror test equipment to demonstrate the FILM technology concept through modeling and laboratory efforts into a PDR-level design for a 0.5 m FILM demonstration. Phase II refines the modeling tools and fluid system and culminates in a demonstration of the 0.5 m FILM. The same team is capable of developing the Phase III 2 m non-segmented and 1 m segmented telescope designs with on-sky demonstrations, including the M&S of a 20-50 m FILM telescope.

3.0 GOALS AND IMPACT

3.1 The Self-Assembling FILM Telescope

The FILM will employ a Halbach array to position a reflective ferrofluid layer as the base layer for the mirror. These tessellar magnetic structures provide a ferromagnetic force potential parallel to the surface of the array.[1,2] By tuning the position of the magnetic assembly, the liquid surface is forced to adopt the desired shape. Because the ferrohydrodynamic force is orders of magnitude larger than gravity, the latter becomes a disturbance that can be compensated by means of magnetic or other actuators to allow tilt or slew without disrupting the mirror. An illustrative simulation of the Kelvin force field $M\nabla H$ produced by a N52 neodymium array is shown in Figure 3-1 for a diluted 1:10 volume solution of the commercially available [Ferrotec EMG-700 water-based ferrofluid]. 2D-homogeneous forces one order of magnitude above the gravity level are induced at ~1 cm from the magnet and decay following an exponential law of the form $F \propto e^{-ky}$. Lateral components are at least one

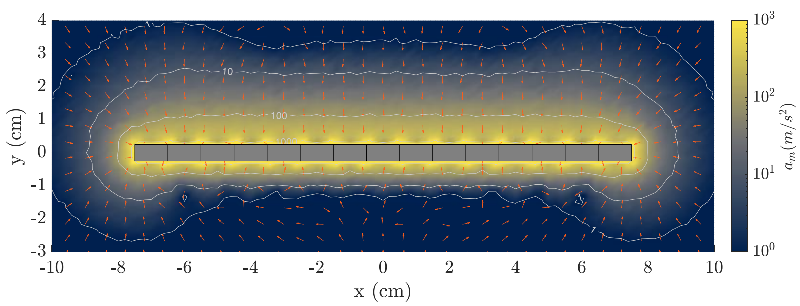

Figure 3-1. COMSOL Multiphysics simulation of a linear Halbach array of permanent magnets generating a flat magnetic force field on a ferrofluid layer.

order of magnitude weaker than the vertical force. A physical demonstration of control of the ferrofluid by a Halbach array against the force of gravity is shown in Figure 3-2. Halbach arrays have been proposed for use in biomedical applications[3] and low-gravity electrolysis[1,4] but have not yet been applied to the control of ferrofluid interfaces. Unlike previously proposed magnetic control methods,[5] Halbach arrays can be easily scaled and tuned to compensate for external disturbances.

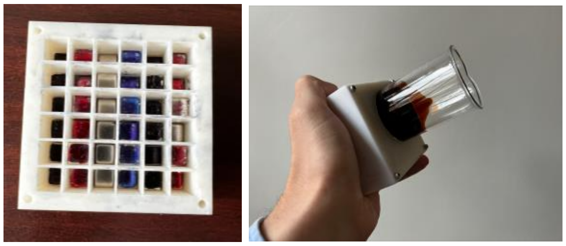

Figure 3-2. Laboratory Demonstration of a Halbach Array Controlling a Ferrofluid Against Gravity.

For the reflective materials system to be controlled by the Halbach array, Honeywell proposes to create a self-organizing bilayer liquid mirror that is both a ferrofluid and reflective (Figure 3-3). The liquids are held in place and shape within the mirror by use of the magnetic array, hydrophilic materials, and the high surface tension and high viscosity of the liquid.[6] The metal liquidlike films (MELLF) approach first proposed by Yogev *et al*.[7] and also demonstrated by others[8,9] will be adapted by replacing the organic and aqueous liquids with two mutually immiscible ILs, and by adding magnetic NPs in addition to reflective particles. Magnetic NPs have previously been demonstrated in IL[10] and in non-IL mirrors using the MELLF approach.[11] In the proposed fluid system, the surface modified magnetic NPs are preferentially wetted by and suspended in the lower liquid. The reflective surface is formed by surface modified metallic NPs (e.g. silver) that are not well-wetted by either liquid and will therefore organize at the interface between the two liquids. The two immiscible liquids will spontaneously phase-separate, and the equipotential lines of the magnetic field will ensure that the liquid follows the desired, nominally parabolic, shape. Wetting effects will aid in spreading the liquids on the dish, while repulsive interactions between the NPs will stabilize dispersions.[12,13] Minimizing the volume of the upper liquid will improve reflectivity and help to anchor this liquid in place.[11]

Choice of an IL bilayer to hold the ferrofluidic and reflective materials offers significant advantages. Selection of non-volatile ILs avoids fluid loss to the atmosphere through evaporation. Use of ILs builds on an enormous library of commercially available ILs[14] and on Honeywell expertise in IL selection, handling, and system design, including an ongoing NASA-supported program.[15] Existing test facilities and capabilities for IL systems include development of new ILs and full chemical and physical characterization. ILs can be cooled to preserve functionality before rapid slewing because, for most ILs, viscosity increases upon

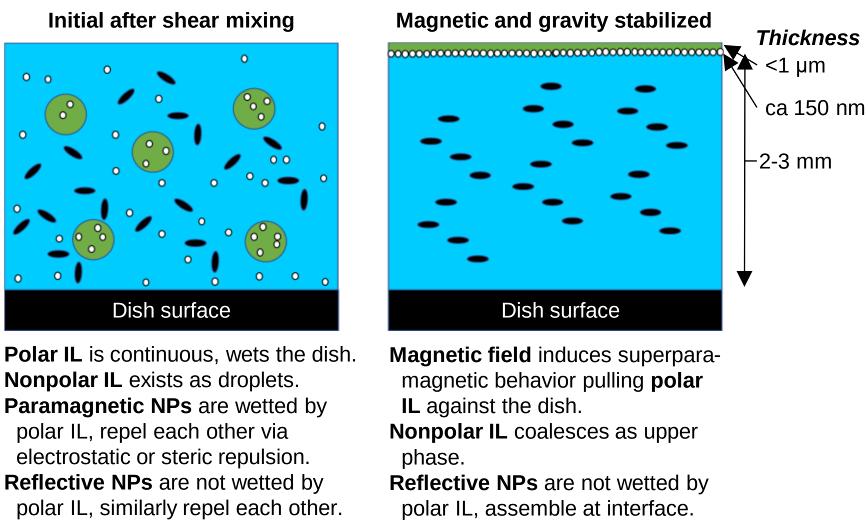

Figure 3-3. Proposed fluid system for the Self-Assembling FILM.

cooling to generate a glass without crystallization. Self-assembly is a major advantage, since, if a mirror has been disrupted by impact or other events, it can self-heal and reform the reflective surface.

The FILM design includes a roughly parabolic magnetic substrate composed of permanent magnets and covered by a thin layer of the fluid system positioned about 1 cm from the Halbach array. Development will leverage existing Soter Technology capabilities in design, analysis, fabrication, and nanometer level measurement on λ/10 liquid mirrors (Figure 3-4).

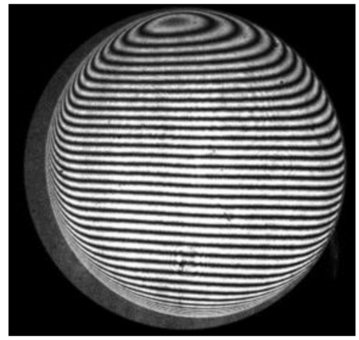

Figure 3-4. A Soter Technology interferometric measurement of a 100 mm dia. LM surface. Edge artifacts aside, this is the λ/10 surface.

3.2 Comparison to Other Liquid Mirror Technologies

3.2.1 Ferromagnetic surface control alternatives

Ferromagnetic control of the liquid brings flexibility and robustness to the design of the FILM since it allows the telescope to be operated off-zenith and without rotation or acceleration to hold the liquids in place. Bringing the liquid to an optically appropriate position against gravity and without spinning is only possible with the aid of a different force. Three alternatives to the ferrofluidic approach may be considered: **surface tension, electrostatic forces, and electromagnetic polarization**. For the former to work, the Bond number $\mathrm{Bo} = \rho g l^2/\sigma$, with $\rho, \sigma, g,$ and l being the density and surface tension of the liquid, gravity, and characteristic length, respectively, must be much smaller than one. The resulting capillary length of 2.5 mm for water (Bo = 1) implies that a conceptual LM exploiting capillary action would need to be subdivided into <2.5 mm tiles to hold the liquid against gravity. In the unlikely case where this was possible, the meniscus profile errors induced by uncertainties in the contact angle (bounded by ~0.5º in the measurement process alone,[16] not to mention atmospheric liquid contamination effects[17]) would reach >10 μm, making this approach unfeasible.

Electrostatic forces can control deformable membrane mirrors,[18,19] so replacing the reflective membrane by a liquid metal like gallium might be proposed. The Coulombic force acting between two parallel conductors may be then computed through the well-known expression $F_e/A \sim \epsilon V^2/2d^2$ to prove feasibility. However, induced charges accumulate at the surface of conductors, bringing the internal electrostatic field to zero, so only the innermost surface would be attracted to the fixed electrode. Because the force at the bulk is zero and the Bond number is computed along the largest characteristic dimension, the liquid metal would slide under the force of gravity. If a thin liquid metal layer on top of a liquid was used instead, the system would become unstable and collapse due to the null dielectrophoretic force acting on the intermediate dielectric.

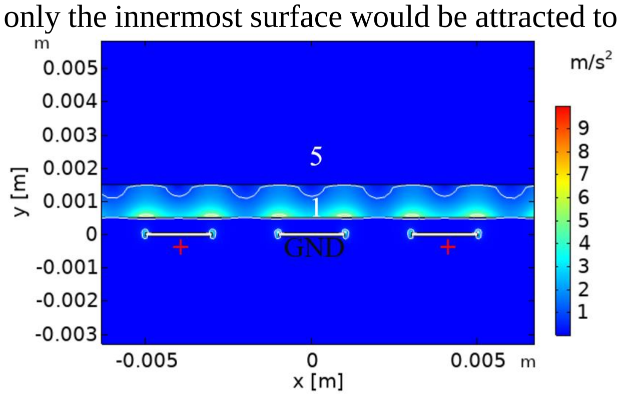

Figure 3-5. Hypothetical dielectrophoretic acceleration maps and contours (m/s²) induced by a 2D +5 kV / GND alternating 2 mm electrode array on a 1 mm water layer in air, <u>not intended for use in the FILM</u>.

The **electromagnetic polarization** force arises when liquids are exposed to inhomogeneous electric or magnetic fields.[20] The electric case (*dielectrophoresis*) has been considered since the 1960s for propellant positioning[21] or microfluidics.[22] However, electrically polarized liquids superimpose their own field and, as a result, modify both the magnitude and direction of the dielectric force.[23,24] For instance, the dielectric force imposed on water by a 2D array of alternating 5 kV / GND 2 mm electrodes reaches 250 m/s^2 at 1 mm from the array but drops to just 5 m/s^2 when a 2 mm liquid layer is considered (Figure 3-5). The decrease of the dielectrophoretic force needs to be compensated with a significant increase in the electrode potential difference, which leads to arcing and conduction pumping,[25,26] wider electrode separation, and large spatial frequency waves. These waves are unavoidable due to the difficulty to tune the dielectric response of the liquid, a problem that is overcome in this proposal by controlling the particle concentration of ferrofluids instead.

3.2.2 Fluid system alternatives

As an alternative to the self-assembled fluid system proposed, reflective ferrofluids containing only a single liquid layer have been suggested with either magnetic particles coated in reflective material[27] or reflective particles appended with magnetic particles.[28] However, these approaches are incapable of achieving sufficient wavefront error. Concentration of a reflective ferrofluid until the surface of the fluid has the required close packed reflective particle layer would require a likely achievable custom NP design with silver:maghemite mass ratio of ~220; however, the overall solids content of the fluid would be ~90 wt%, which is much higher than demonstrated stable suspensions[29] and would result in solids settling. The large amount of reflective NP material required can only be supported at an interface. Yet another approach has involved vapor deposition of the reflective material on a liquid surface but can only be done once, so the self-healing and self-assembly advantages of the FILM approach are lost.

3.3 Project Deliverables

Project deliverables will include the M&S codes, quarterly technical reports, phase completions reports, and a CUI protection plan as specified in BAA S1.G with further detail provided in the SOW. Project-specific deliverables will also include design, build information, procedures, and test data for the Halbach array, fluid system, demonstration hardware, and test equipment.

3.4 Technology Transition

The FILM technology is directly applicable to implementing large low-cost ground-based telescopes for orbital debris tracking which drives relatively high slew rates and a moderate field of view. We will also explore and report on other applications, such as ground based astronomical telescopes and/or ground optical terminals for ground to space optical communications. In addition, we plan in Phase II to explore and report on the potential for FILM technology for space-based telescopes for various applications. Low vapor pressure ILs are well suited to a space application, and operation of the FILM technology is expected to be simpler without humidity or gravity present (for example a 20x lighter magnet array will be required).

As a major supplier of components for space systems (see Sec. 7.0), Honeywell has a commercial interest in the LMT technology for potential downstream applications such as:

1) The development of large space-based LMTs payloads for imaging of spacecraft in GEO orbit for US DOD applications.
2) The development of LMT payloads for future space-based astronomical observatories, such as the next large US space telescope. Honeywell has completed a Phase 0 study for a 1m class space astronomy survey mission called CASTOR for the Canadian Space Agency (https://www.castormission.org/about), where LMT could apply.

3) The FILM technology may prove useful in smaller scale optics, such as small configurable mirrors for use in wavefront correction in optical Intersatellite link (OISL) communications systems. The technology transition to such applications will be explored even if the ambitious goals of the DARPA Zenith program for larger mirrors are not met.

4.0 TECHNICAL PLAN

Honeywell intends to follow the program structure as outlined in section IID of the BAA. The sections below describe the technical challenges and proposed solutions during Phases I, II, and III. Planned laboratory testing in Phase I utilize existing test capabilities available at all three partners' facilities to mitigate risk in Phase II. Since the authors have already developed M&S tools for ferrofluids, further advancements in modeling fidelity for the LM application require experimental data from an applicable fluid system. Since no fluid system similar to those proposed and demonstrated in a lab meets the requirements for the LM, laboratory development is required before completing a 0.5 m demonstration.

4.1 Phases I-II Modeling & Simulation

4.1.1 Ferromagnetic modeling

2D Halbach arrays, conceptualized in Figure 4-1, are the discrete implementation of the continuous one-sided flux concept introduced by Mallinson in 1973, where a 2D magnetic layer with thickness b is magnetized following a sinusoidal magnetization pattern.[30] This ideal profile results in a **perfectly vertical magnetic force**

$$\boldsymbol{f_0} = \boldsymbol{\mu_0 M \nabla H} = \boldsymbol{-\mu_0 k \chi M_0^2 \left(1 - e^{-kb}\right)^2 e^{-2ky} j} \tag{1}$$

where $\mu_0, k = 2\pi/\Lambda, M = \chi H$, and H are the vacuum permeability, wave number, magnetization, and magnetic field modules, respectively, and the other parameters are defined in Figure 4-1. Cubic 3/8" N52 neodymium magnets with $M_0 \approx 1138\, kA/m$ patterned with $\Lambda \approx 3.8$ cm produce **forces on the order of 20$\mathbf{g_0}$** on a 1:10 vol EMG-700 ferrofluid solution with $\chi_0 \approx 0.19$ ref 22 at distances $h \approx 15$ mm. **If the ferrofluid is tilted 10º**, the lateral gravity force tilts the equipotential line ≈ 0.47º, but **the ferrofluid remains attached to the Halbach array** due to the small magnitude of the disturbance, experiencing maximum vertical displacements of 4 mm in this configuration (to be optimized). The rotation of 1 deg/s induces a centripetal acceleration of ~1.5×10^{-4} m/s^2 which is four orders of magnitude below that imposed by the tilting, making it negligible. These results have been verified using numerical simulations and, although largely unoptimized, prove the first-order feasibility of the concept. The magnetic force field is **homogeneous across the plane of the array** and can therefore be **easily scaled to any aperture size**, unlike previous coil-based implementations. **Edge effects** may influence the

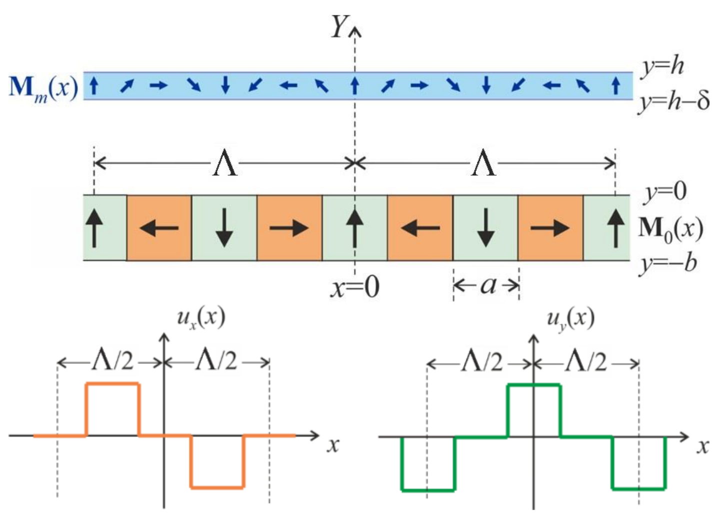

Figure 4-1. Halbach array and magnetization patterns.

point of contact of the ferrofluid with the lateral walls, but these are bounded to contours of ~0.5 mm radius (Bo = 1) which can be easily shielded.

Because Halbach arrays are discrete implementations of a continuous magnetization profile and the ferrofluid itself is magnetized (i.e. generates its own magnetic field), second-order disturbance terms act on the system. Our team has characterized this interaction by expressing the magnetization field in Figure 4-1 through the Fourier series

$$\mathbf{M}_0(x) = M_0\left[u_x(x)\mathbf{i} + u_y(x)\mathbf{j}\right] = \frac{2\sqrt{2}M_0}{\pi}\sum_{i=1}^{\infty}\frac{1}{(2i-1)}\mathbf{m}_{2i-1}(x)$$

with

$$\mathbf{m}_n(x) = \begin{cases} (-1)^{(n+3)/4}[\mathrm{sen}(k_n x)\mathbf{i} - \cos(k_n x)\mathbf{j}], & \text{si n} = 1,5,9,\ldots \\ (-1)^{(n+5)/4}[\mathrm{sen}(k_n x)\mathbf{i} + \cos(k_n x)\mathbf{j}], & \text{si n} = 3,7,11,\ldots \end{cases}$$

and where only the harmonics $n = 4i - 3$ with $k_n = 2n\pi/\Lambda$ contribute to the field at $y > 0$. The effect of higher-order magnetic force harmonics is bounded by

$$\frac{f_{\text{dist\_ho}}}{f_0} \sim \frac{6}{5}e^{-\frac{8\pi}{\Lambda}h} \sim 6 \times 10^{-4} \quad \text{if } h \approx 0.3\Lambda \tag{2}$$

which shows that higher-order disturbances are $\sim 10^{-4}$ times weaker than the underlying magnetic force in Eq. 1 when the ferrofluid layer is sufficiently detached from the magnets. These disturbances have $>4k$ spatial frequency. However, surface waves are also produced by the magnetization of the ferrofluid layer depicted in blue in Figure 4-1. Assuming a saturated ferrofluid with its corresponding demagnetization field, this second type of disturbance has $2k$ spatial frequency and is bounded by

$$\frac{f_{\text{dist\_demag}}}{f_0} \sim \frac{M_s}{H_0}\, \mathrm{e}^{\frac{2\pi h}{\Lambda}} \approx 2.5 \cdot 10^{-2} \quad \text{if } h \approx 0.3\Lambda \tag{3}$$

and where the saturated 1:10 vol solution of EMG-700, as an example, is assumed.[22] The dominant disturbance is that induced by the demagnetization field of the ferrofluid, which can be minimized by reducing the height of the fluid layer and the saturation magnetization M_s of the liquid. The proposers will gladly provide the (lengthy) derivations leading to these results if requested.

Even though this is a highly simplified analytical framework, it clearly discloses the key trade in the design: minimizing M_s/H_0 decreases the surface waves but also the magnetic force. This is true also in the presence of surface tension, which plays a favorable role to reduce surface waves. Open-source analytical,[31] quasi-analytical,[32] and numerical[21] capillary ferrohydrodynamic interface M&S tools like that depicted in Figure 4-2 will be employed in Phase I to evaluate the trade space. Shall this be insufficient to guarantee spatial waves with amplitudes below 50 nm, the 3D printing of ferromagnetic patterns on the mirror surface (see Sec. 4.3.3) and the use of electro-permanent magnets will be explored. The preliminary model guides the initial design for the ferrofluid and the Halbach array:

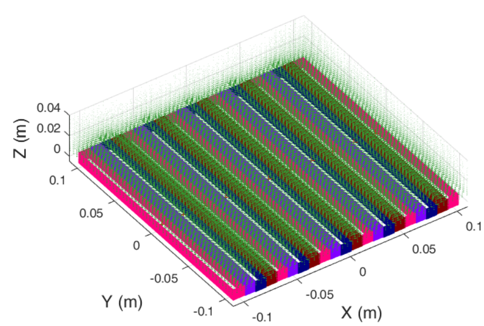

Figure 4-2. Analytical open-source Halbach simulator developed by the authors in preparation for the program.

- To minimize the disturbances imposed by the demagnetization of the ferrofluid layer, the ferrofluid described in Section 4.2 must have, as an upper limit, approximately 0.63% vol concentration of magnetic NPs leading to $\chi_0 \approx 0.19$ and $M_s \approx 4000$ A/m.

- The Halbach arrays will be built using cubic N52 neodymium magnets with $M_0 \approx 1138$ kA/m and a maximum length of 3/8 in. Different sizes and 1D/2D configurations will be explored to tune the Halbach scale Λ and minimize the cost of the magnetic substrate.

4.1.2 Optical modeling

The surface output of the interface-tracking CFD and quasi-analytical magnetohydrodynamic models will be prepared as WFE maps up to 3 m diameter for ingestion by optical modeling software such as ZEMAX and/or CODE V to assess the optical performance of a future LMT. A preliminary LMT reference design (Figure 4-3) aligned to the BAA metrics (Table 4-2) will be refined early in Phase I to guide the WFE requirements for 1) the demonstration 0.5 m diameter FILM and 2) the large Phase II FILM M&S demo. The LMT reference design will also address other aspects such inclusion of pupil re-imaging in the optical design / layout to mask edge effects. For ease of testing, the 0.5 FILM demo ideal shape will be set as spherical with a radius of curvature of 2.3m, giving a focal length of 1.15m and an F/# of 2.3. The surface height difference between a 3m F/2.3 spherical mirror and the reference design mirror is < ±60 µm.

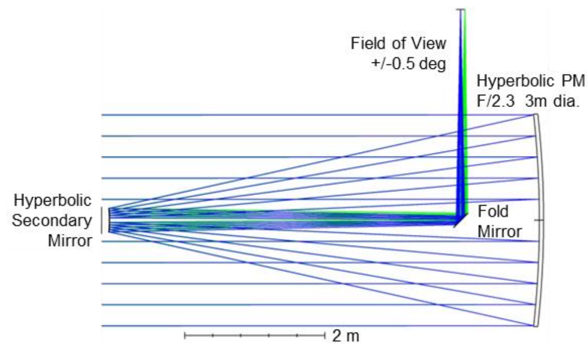

Figure 4-3. LMT reference design layout.

Defining the imaging performance of an optical system by RMS and peak-to-valley (P-V) WFE at different spatial scales is useful for system budgeting and is traceable to the encircled energy (EE) at the focal plane. The low spatial frequency WFE (<5 cycles across the aperture) determines the width of the core of the PSF, the mid-frequency WFE (5-30 cycles) determines the energy in the adjacent wings of the PSF,[33] and the high spatial frequency WFE (>30 cycles) impact is similar to large angle scattering, reducing the EE but not significantly impacting the image quality.

For the 0.5 m FILM demo, most of the WFE will likely be in the mid-frequency range and a preliminary example of the possible residual height differences from the ideal spherical surface shape using 3/8" magnets indicates that the impact of this mid-frequency wavefront error on the point spread function is significant, despite an RMS WFE of <λ/5. Figure 4-4 provides WFE

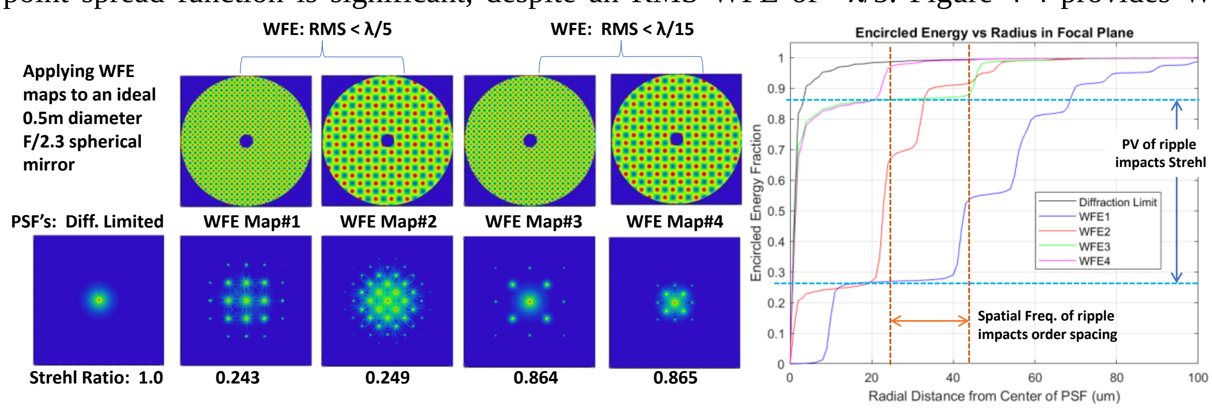

Figure 4-4. Example WFE maps with residual sinusoidal ripples (i.e.. as expected from a Halbach array) projected on to the 0.5m F/2.3 spherical mirror demonstrator and the resulting EE.

examples with two different ripple amplitudes (±100 nm, ±33 nm P-V surface height) and two different spatial frequencies (8 and 16 cycles) across the aperture. The lower spatial frequency, even at the same ripple amplitude, has significantly better imaging performance, while achieving a reasonable Strehl ratio (<0.8) requires smaller amplitude ripples. The target RMS WFE requirement at the mid-frequency scale will likely be in the 6 to 10 nm range, and a WFE requirement in terms of local slope of the WFE (in nm per mm) may need to be specified.

The M&S work will provide direction for scaling rules for the magnet size scaling from the 0.5 m to the 3 m M&S demo. The scaling rules will be explored and selected early in Phase I based on iterations between the ferro-fluid modeling and the resulting LMT reference optical performance.

The optical modeling work will include evaluation for non-uniformities in the top IL. Thickness variation in the <1 µm thick top IL is tolerable in the overall WFE budget up to 50 nm due to the relatively low index of refraction (~1.44) for the top IL. The reflectivity and optical scattering of the reflective particle layer & top IL combination will be characterized in the materials testing phase and used in the optical model to assess the impact on the system.

4.2 Phases I-II Fluid System Development

A significant development effort is proposed in Phase I to demonstrate the materials system, followed by refinement in Phase II. In each Phase, development of the four subsystem pairs of fluid components (the polar ferromagnetic IL, the two IL biphase system, the reflective surface, and the base IL contact with the support structure) is followed by combination of the approaches that are common to successful pair formulations into a single full fluid system. Beginning fluid systems development in Phase I is necessary to address the significant advance in the state of the art required for this technology, and to allow feedback from materials development to the modelling tasks. The self-assembly of the liquid mirror requires proper selection of both ILs, each type of NP's core composition and coating, the composition and potential coating including smoothness or structure at the micro- to nanoscale of the supporting surface, and ratios among components.

4.2.1 Development of pairs of fluid system components

The **polar ferrofluidic layer** includes magnetic NPs in the base IL and must have the target magnetic susceptibility and high suspension and material stability. Maghemite is the preliminary magnetic NP material based on demonstrated colloidal suspension and oxidative stability in ILs.[34] The cited work used the FILM team's preferred grafting technique to stabilize the colloid, instead of surfactants, which may have undesired interactions with the reflective and top liquid components. The size, polarity, and charge of the NP ligand provides opportunity to optimize for colloidal stability with IL options. Preliminary ferromagnetic modeling indicates the NPs should be at most ~0.63 vol% (~3.0 wt% maghemite) in the base IL to provide magnetic susceptibility to counteract gravity without inducing surface distortion (see Sec.4.1.1).

The IL pair includes **two immiscible fluids** that must have high layer purity, a rapid disengagement rate, and moderate viscosity and that will be evaluated for formation from homogenized mixtures. A preliminary IL pair for the FILM includes a base IL [EMIM][NTF_2] and top IL [$P_{6\,6\,6\,14}$][NTf_2] (Table 4-1) which have demonstrated phase separation across a range of temperatures and volume fractions and include a common anion to preclude possible formation of more than two phases.[35] Higher density of the base IL is required to keep it on the bottom, while higher surface tension

Table 4-1. Properties of an Example Pair of Ionic Liquids

	Example base liquid	Example top liquid
Property	[EMIM][NTf_2]	[$P_{6\,6\,6\,14}$][NTf_2]
Name	1-ethyl-3-methyl-imidazolium bis(trifluoromethylsulfonyl)-amide	trihexyltetradecylphosphonium bis(trifluoromethylsulfonyl)-amide
Molec. weight (g/mol)	391.3	764.0
Density (g/mL)	1.52	1.07
Surface tension (mN/m)	41.6	33.6
Viscosity @30°C (cP)	35.5	243
Refractive index	1.4298	1.4496

resulting from higher polarity provides a surface tension difference to favor phase separation. This IL pair will act as a baseline for evaluation of alternate ILs, and viscosity or surface tension enhancers could be considered, including components that evaporate following initial formation of the bilayer. Efficient phase separation will be achieved by tuning the viscosity of the continuous phase (base IL), droplet size of the discontinuous phase (top IL), and density difference and interfacial tension between the two phases.[36] Low density and high viscosity of the top fluid resists disturbance by vibrations, wind, tip, or tilt. The refractive indices of the fluids indicate that the variation in thickness in the upper fluid should target less than ±50 nm.

The **reflective MELLF layer** includes reflective NPs and the top IL and must have high specular reflectance (350 nm – 950 nm). The initial reflective system will use silver NPs <10 nm in diameter.[8] Gold NPs are alternatives if the silver NPs oxidize and/or their toxicity is deemed too high,[37] at the expense of reflectivity below 500 nm.[38] Use of an aliphatic top IL such as [$P_{6\,6\,6\,14}$][NTf_2] ensures effectively no absorption above 350 nm, though even the more absorbing cations such as [EMIM] have little ab sorption of visible light.[39] Diffraction limited performance also requires a low surface roughness reflective layer to avoid scattering too much light from the core of the PSF. Requiring <10 nm particle size and close particle spacing should produce <5% scattering at 550 nm wavelength, providing a manageable contribution to the image quality budget. Formation of the reflective NP layer at the interface will be facilitated by NP surface treatments that enhance electrostatic or steric repulsion, resisting agglomeration, and may have tailored features to adjust the colloidal properties. Proper ligand selection and repulsion from the fluid should reduce average distance between particles to much less than the particle diameter,[40] which requires a uniform layer to be quite thin, though the overall layer may be ~150 nm thick in practice.[8]

The solid surface of the underlying dish must be well-wetted by the lower IL, non-magnetic, smooth enough not to add imperfections to the liquid layers, and stable to the IL (e.g. glass). The walls of the dish should be non-wetting to prevent liquid spread outside of the dish (e.g. PTFE). Liquids similar to those in Table 4-1 demonstrate that a wide range of contact angles are accessible through proper IL and material selection (19° to 104° in Figure 4-5).

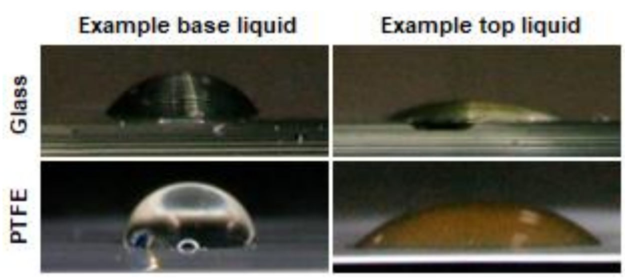

Figure 4-5. Contact angle measurements on example FILM ILs on glass and PTFE.

4.2.2 Combined fluid system

The Phase I combined fluid system effort includes at least one trial of initial top candidates with common ILs from each of the subsystems and development of a prioritized list of candidate materials for further optimization. The Phase II effort includes evolutionary optimization of the prioritized components to refine the initial self-assembly, maintenance of self-assembly, and longterm stability of the fluid system. Each layer will use a minimum depth of each liquid, approximately 2-3 mm for the base liquid layer, 1 micron for the upper liquid layer, and 150 nm for the reflective layer (Figure 3-3), resulting in a high surface area of each interface relative to liquid volume. High surface area will stabilize the reflective surface but will require ingenuity to obtain continuity of all phases.

Suspensions of ferromagnetic particles are generally darkly colored, so clean separation of the reflective particles from this suspension will be required to optimize reflectivity of the mirror. Targeted phase separation refinement to achieve phase purity and low coalescing time will focus on maximizing the polarity differences between the liquid components, increasing the surface charges of the magnetic particles, and developing a fluid dispensing process that may require shear mixing to achieve the required droplet size for the discontinuous liquid and ensure wetting of the NPs.

Introduction of the top liquid and reflective layer to the ferrofluidic layer in the presence of the magnetic field introduces potential challenges. If the magnetic field spreads the base liquid across the dish prior to coalescence, the upper liquid will also be carried across the dish, and coalescence can create the bilayer structure and mirror. The magnetic field will impact viscosity, coalescence time, and potentially the degree of liquid phase separation. These impacts will be addressed by minimizing the volume of the upper liquid and maximizing interfacial tension among components. An estimated coalescence time for the two ILs is <1 s based on relationships outlined by Jeelani *et al.*,[41] and the reflective NPs will be formulated to avoid suspension in either liquid, so overall fluid system initial coalescing time should be rapid even in the presence of a magnetic field but must be measured experimentally.

Following FILM self-assembly, the main system challenge for disruption of the assembly is dislocation of the upper IL and reflective layer if the upper IL does not adhere to the lower IL and/or is not sufficiently viscous. Tilt, slew, and aging experiments with the dish can measure the extent of this effect, and further materials development may be required to alleviate it. Use of a more viscous and thinner upper IL will minimize the effects of angle or motion on the upper surface stability. Since the major function of the upper IL is to generate a reflective surface through capillary smoothing, this layer can approach the thickness of the reflective layer, estimated above at 150 nm. The properties from Table 4-1 and a slew rate of 1°/sec (4.4e-3 m/s at the edge of a 0.5 m mirror) indicate the Reynolds number for flow of the upper liquid ($\rho vL/\eta$), where ρ, v, L, and η are density, velocity, film thickness, and viscosity, would be 9.6e-4, which corresponds to very slow creeping flow and would not result in mirror disruption. For the same example, the Ohnesorge[42] number is the ratio of viscous and inertial forces to surface tension ($\eta/\sqrt{\rho\sigma L}$), where σ is surface tension, is 5.7, which is much greater than 1 and indicates a high tendency for the film to resist droplet or micelle formation. Finally, the spreading coefficient indicates the ability of one liquid to spread over another without dewetting, with positive values indicative of spreading.[43] For the above example, the coefficient is negative, but adjusting the interfacial tension between the two liquids, such as by increasing the chain length on [EMIM] or adding surfactant to reduce surface tension of the lower IL, is a sound approach to adjusting it. If adjusting these parameters does not mitigate the problem, approaches to forming the reflective layer with only a single liquid may need to be explored.

4.3 Phases I-II Bench Level Testing

4.3.1 Material property and configuration testing

The development and verification of the ILs will be done in stages as described in Sec. 4.2. After the initial trials and downselect, the most promising IL pairs and reflective particles will undergo initial optical testing at Honeywell's optics lab in Ottawa, Ontario, including reflectivity and WFE measurements in an optically flat container in a cryostat, initially at ambient temperature. The test samples will be mechanically disturbed (tilted and rotated) to assess the stability of the mixture and provide feedback to the materials selection. These tests will provide an assessment of the optical impact of the top IL and the nominal ability of the IL pair to produce the reflective layer at the interface. Similarly, the ferro-fluidic properties of the base IL will be evaluated before merging the two streams for a more complete FILM test before PDR.

4.3.2 Ferromagnetic properties and configuration testing

Different ferrofluid solutions and Halbach arrays will be tested following the guidelines presented in Sec. 4.1.1 to optimize the performance of the liquid mirror. For each configuration, the team will (i) characterize the individual magnetization of every magnet to ensure homogeneity, (ii) measure the magnetic field above the arrays using a magnetic field mapper, and (iii) characterize the magnetic response of the ferrofluids using a vibrating sample magnetometer. Interferometric ferromagnetic fluid testing is additionally described in Sec. 4.3.3.

4.3.3 Hardware and mirror property testing

Multiple lab-scale Halbach arrays, fluid sub-systems, and fluid systems will be iteratively designed, built, and tested. Soter Technology will work with the rest of the Zenith team to develop a staged testing program to measure surface WFE ($\lambda/8$ RMS for $\lambda = 550$ nm), while varying the tip and tilt up to 10.0°, and will also measure reflectivity (with the goal of >0.65).

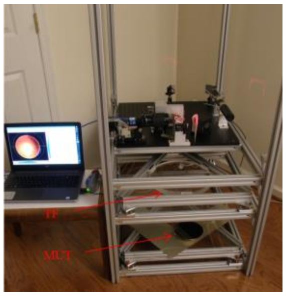

Figure 4-6. A custom spatial carrier phase shifting interferometer capable of measuring 300 mm diameter flat LMs to 10 nm accuracy.

Initial surface figure testing on small flat optics will use the interferometer shown in Figure 4-6, following upgrades for accuracy, stability, and capture range. The optical test wavelength is 632.8 nm, and results can be computed relative to 550 nm. Further Phase I test facility upgrades include capability to test tilted LMs and a custom controlled airflow clean room with humidity control, based on previous experience with similar measurements (Figure 4-7). Test results will be subsequently used to calibrate the ferrohydrodynamic fluid models to inform designs for the 0.5 m concave spherical mirror for Phase II.

Phase I bench-level testing of samples with various magnetic actuators, fluid systems, and spacings between magnet array and ferrofluid will characterize the sample normal to gravity (i.e. zenith looking) and while tilted for reflectivity and scatter/microroughness. Fluids without magnet arrays will be tested in a zenith looking orientation only for reflectivity, surface roughness/scattering, and any forming of features of the liquid interface.

Figure 4-7. Interferometric measurements on a concave liquid mirror surface. The fringes are not straight because the part was parabolic, but the test was set up with a spherical reference surface.

Phase I testing will characterize the optical print through from the magnets multiple iterations with different Halbach array configurations. If the liquid surface optical mid-spatial frequency errors cannot be reduced to acceptable levels by adjusting the magnets in the array directly, Soter Technology has engineered a technique for 3D printing magnetic correctors using material extrusion filament printing, with filaments that have been doped with a low concentration of ferromagnetic particles. These doped filaments can be manufactured using standard filament recycling equipment. The profile of this corrector plate will be designed by Georgia Institute of Technology (see Sec. 4.1.1) and printed by Soter Technology. It will consist of a relatively thin (few millimeters thick) ferromagnetic particle doped plastic sheet sitting between the magnets and engineered with varied magnetic permeability to move the magnetic field away from areas where the fluid surface is otherwise raised by the Halbach array.

During the Phase I effort, the Phase II test set for tilting and slewing concave liquid mirrors will be designed. The Phase II test set will be similar to that shown in Figure 4-6Figure 4-7, but designed to test a concave spherical 0.5 m mirror.

4.4 Phases I-II 0.5 m Laboratory Demo Hardware

4.4.1 0.5 m Laboratory demo hardware design

In Phase I, Soter will begin design of the test configuration needed for testing the 0.5m concave spherical optic in Phase II. The concave 0.5m optic is easier to scale to larger sizes because it can be tested with an optical test that diverges from the center of curvature. The Phase II test will leverage learning and improvements realized as part of Phase I test. The design will mature to a PDR level in Phase I, with final design activities to be completed as part of Phase II. The magnet placement in the 0.5m Halbach array will be designed by the modeling team, and Honeywell Aerospace will coordinate with a suitable internal or external supplier for manufacturing design.

4.4.2 0.5 m Laboratory demo hardware fabrication and demonstration

In Phase II, the team will prepare and test the down-selected magnetic configurations and liquid systems for a 0.5 m concave liquid mirror. The Phase II test will be for a spherical optic because of simplicity in magnetic array design, only 60 µm deviation from a hyperbolic mirror, and lack of need for a null test optic. Scaling to larger sizes will be done by upgrading metrology equipment from the machine shown in Figure 4-8. The Halbach array will be manufactured by the internal or external supplier who completed the design and delivered to Soter Technology for assembly into the test apparatus.

Figure 4-8. The 1m capable concave metrology machine.

4.5 Metrics, Challenges & Solutions, and Risks & Mitigation

4.5.1 Metrics

The program will target meeting technology metrics as described in Table 4-2. As described in Sec. 4.1.1, the magnetic force on the liquid mirror is at least an order of magnitude greater than that of gravity when evaluated for the Phase II laboratory demo metrics, which indicates that the fluid will remain within the dish. In addition, the fluid system properties described in Sec. 4.2 indicate that the fluid will maintain its shape within the dish. The fluid system development and bench level testing to be performed in Phase I is enabled by existing laboratory capabilities and will refine models, Halbach array design, and fluid system design to enable the team to meet the increased tip and tilt, slew, and aperture diameter requirements for Phases II and III.

The early laboratory testing will also allow for refinement of the top IL thickness and properties and refinement of the reflective layer particle size and properties in order to minimize the contribution of the top IL and reflective particle layer to wavefront error and to scattering. Segmentation follows naturally from increases in scale and can be achieved with the same fluid system applied to a refined Halbach array and dish shape based on experimental and modeling principles developed in Phases I and II for the flat and spherical circular mirrors. High reflectivity in Phase II will be enabled by iterative fluid system development beginning in Phase I.

Table 4-2. Target Metrics for the Program

Metric	Phase I (Base)		Phase II (Option)		Phase III (Notional)		
	Lab demo	PDR-level Design & M&S	Lab demo	Design & M&S	Non-segmented demo	Segmented demo	Telescope Design & M&S
Tip and tilt	Attempted	>10.0°	>10.0°	>25.0°	>25°	>25°	>25°
Slew, deg/sec rate	Attempted	1	1	3	3	3	3
Aperture diameter, m	Attempted	0.5	0.5	3	2	1	20 – 50
Correctable wavefront error at $\lambda = 550$ nm	Measured	$\lambda/4$	$\lambda/4$	$\lambda/8$	$\lambda/8$	$\lambda/8$	$\lambda/10$
Segmentation	No	No	No	No	No	≥6	TBD
Reflectivity	Measured	N/A	>0.65	>0.65	>0.65	>0.65	>0.65

4.5.2 Challenges and solutions

The proposed solutions to technical challenges inherent to the development and demonstration of the FILM telescope are described in Table 4-3 as planned in the SOW for Phases I and II.

Table 4-3. Challenges Matrix for the Program

Challenge (*metrics*)	Solution
Ferromagnetic Control	
Spatial frequency induces mid-spatial frequencies in the liquid surface (*peak to peak distance, spatial wave frequency*)	Tune magnet size/location. Modify magnetization through material choice and concentration. Increase surface tension.
Normal magnetic field triggers **Rosensweig instability** (*threshold magnetization*)	Lower the concentration of magnetic NPs. Reduce magnetic flux.
Magnetic field decay/inconsistency (*wavefront error*)	Lower the concentration of magnetic NPs. “Magnetic smoothing" option such as by addition of a variable thickness magnetically permeable surface. Downstream optical correction for any permanent aberrations.
Permanent magnets exhibit **large magnetization error** (*magnetization error, spatial inhomogeneity*)	Change provider. Characterize & select.
Fluid System	
Integrity of two liquid phases as discrete continuous layers (*mirror surface area, settling time*)	Minimize volume of upper liquid. Optimize interfacial tension via IL choice or surfactants.
Maldistribution of NPs (*reflectivity, light scattering*)	Optimize surface coatings and charge on NPs to minimize agglomeration. Maximize density & polarity difference between liquid layers.

Refraction from top liquid layer (*refractivity, thickness inhomogeneity*)	Minimize thickness of upper liquid (e.g. < 1 um thick)
Chemical stability and compatibility of mixture components (*shelf life through chemical analysis*)	Phase I material compatibility screening.
ILs will vary in **water concentration** when exposed to ambient conditions (*water analysis*)	Phases I and II control ambient conditions and quantify dependence on humidity
System and Program	
Edge effects (*spatial inhomogeneity*)	Fluid diameter is larger than aperture size by ~1 cm. Minimize interfacial tension between fluid and surface Correction by optics not preferred
Assembly and handling of ≥0.5 m magnetic arrays has special safety considerations (*magnetic field*)	Assembly will be completed by (a) trained supplier(s)
Supply chain challenges for neodymium and Halbach array vendors and IL vendors	Phase I establishment of vendors. Consider multiple manufacturers, assembly Halbach array from individual magnets

4.5.3 Risks and mitigations
Proposed mitigations to technical risks not within the SOW scope for Phases I and II include resolution of magnetic field inconsistencies and supply chain challenges that are not resolved by the steps described in Table 4-3. If reduced magnetic NP concentration, a variable thickness magnetically permeable surface, and downstream optical correction do not resolve magnetic field inconsistencies, additional scope of work could include superposition of an electromagnetic or displacement field. If shortages of raw magnetic materials available commercially drastically increase costs or lead times, the team would discuss with DARPA opportunities to source materials at increased cost or adjust program schedule.

4.6 Phase III (Notional)

4.6.1 Technical approach
Soter Technology will be pleased to propose a Phase III, including analysis and telescope and mirror demonstrations. The Soter team has experience designing and fabricating telescopes at sizes larger than 2 m. The Phase III effort will include: (1) laboratory testing of a 2 m diameter monolithic primary mirror, (2) integration of a 2 m diameter telescope and demonstrating diffraction limited imaging performance in an on-sky demonstration, (3) laboratory testing of a 1 m diameter spherical mirror, which consists of a central segment and six petals, and (4) modeling and simulation to evaluate the scaling of ground-based nonrotating liquid mirrors to 20 to 50 m diameter aperture sizes.

The monolithic 2 m diameter demonstration will begin with the design for the liquid PM. Soter Technology has in house fabrication and testing equipment that allows rapid production of the secondary and other mirrors. Georgia Institute of Technology will design the magnet array and Honeywell will provide fluid, fluid handling equipment, and optical modeling and design support.

The primary mirror will be fabricated first in the laboratory and will be optically tested with an interferometric test set that includes a hologram to correct aspheric departure. Early in Phase III, analysis and testing at both Honeywell and Soter Technology will evaluate the effects of on-site atmospheric conditions, including temperature and humidity effects, and will evaluate the required processes and equipment to maintain fluid in the field.

Soter Technology will build the 2 m telescope into a standard shipping container such that it can be integrated in a controlled laboratory environment and then shipped to a dark sky site for on sky testing. Preliminary analysis has indicated that a 2 m telescope will fit in a standard shipping container and will look notionally similar to the telescope shown in Figure 4-9, which is a Soter Technology design for a 1 m LEO satellite observing telescope. The larger telescope would tilt to deploy out of the shipping container and would use a hexapod actuator for ± 20° of tilt.

The segmented mirror containing (6) 1 m diameter apertures will be designed to have the same curvature as the 2 m mirror such that it can be tested in the same laboratory test equipment that was used to test the 2 m mirror. Honeywell will supply the fluids for the segmented mirror and Georgia Institute of Technology will be contracted to perform the magnet design. In addition to testing the overall surface figure of the 1 m mirror, additional test equipment will be designed to examine the phasing between the segments.

Figure 4-9. A Soter Technology 1 m LEO satellite observing telescope integrated into a standard shipping container.

Phase II outputs M&S code, reports, and plan for advancement of the M&S tools. This plan will be informed by the Phase II work to validate the model against the 0.5 m demo FILM results and to create the 3m FILM M&S demo. This plan will be used in Phase III to advance the M&S work, validate it against the new hardware test results and thus produce a 20-50m FILM M&S demo. Soter Technology will also work with a team of companies to examine scaling limitations and scaling cost for ground-based nonrotating liquid mirror telescopes at 20 and 50 m aperture.

4.6.2 Draft SOW

A draft SOW for Phase III is provided in Table 4-4.

Table 4-4. Draft SOW for Notional Phase III

WBS	Description	Scope/approach	Deliverables
3.0	**Phase III Program**	For proposal ROM purposes only	
3.1	**Program Management**	Project management, incl. procurement, reporting, & PI coordination.	Technical and cost customer reports
3.2	Upgrade assembly, integration, & test facility	Expand clean facility, testing equipment	Clean environment surrounding test facility to execute slewing optical test of unit under test.
3.3	**2m dia. LM and LMT design & build**		Design, build, test 2m telescope.
3.3.1	Optical design & analysis	Optical design/analysis of tele. including tolerancing for manufacturability	Toleranced optical design.
3.3.2	Telescope structure	Design and build telescope structure	2m telescope structures.
3.3.3	Telescope slewing mechanism	Design and build telescope slewing mechanism/structure	2m telescope slewing mechanism/structure.
3.3.4	Modified shipping containers	Modified shipping containers for tele. and STE to process/condition fluids	Shipping containers to house 2m telescope.
3.3.5	**2m primary LM**	2m monolithic primary mirror	
3.3.5.1	Design 2m PM	Design magnet array & optimized fluids	Design for 2m PM components.
3.3.5.2	Build 2m PM components	Halbach magnet array, structure to hold fluid, permeability structure, fluids	Procured 2m PM components

3.3.5.3	Integrate PM Assembly	Integrate 2m PM components.	Integrated 2m PM
3.3.5.4	2m dia. LM testing	Test asphere at zenith, tilted, & slewing	Test report
3.3.6	Secondary Mirror	Design, build, test SM through post-coat	Test report
3.3.7	Aft Optics (FM, TM)	Design, build, test FM and TM through post-coat	Test report
3.3.8	Focal plane	Focal plane to capture telescope imagery.	
3.3.9	Integrate tele. (structure, optics, focal plane)	Integrate 2m telescope.	Assembled 2m telescope
3.4	**2m dia. LMT testing in lab. and on-sky demo**	Test telescope at zenith, tilted, & slewing	Test report
3.5	**1m segmented PM**	1m segmented primary mirror	
3.5.1	Design 1m segmented PM	Design magnet array (GIT) and optimize fluids (Honeywell)	Design for 1m PM components
3.5.2	Build (6) 1m segmented PM components	Halbach magnet arrays, structures to hold fluid, permeability structures, fluids	Procured 1m PM components
3.5.3	Integrate PM Assembly		Integrated 1m segmented PM
3.5.4	Segmented PM testing	Test sphere at zenith, tilted, & slewing	Test report
3.6	**Scaling Challenge**	M&S to understand how ground-based LMTs scale to 20m-50m apertures based on Phases II and III wok. Develop fluid recycling equipment.	Scaling report describing scalability and cost profiles

4.6.3 ROM budget estimation

The Phase III cost is likely to evolve based upon Phases I and II development and has significant dependence on materials choices (ILs under consideration vary from $0.43/mL to $29/mL). The preliminary ROM for the Phase III scope described in Sec. 4.6.2 is $26M and includes risk mitigation factors. The Phase III ROM will be updated at the end of Phase I.

5.0 MANAGEMENT PLAN

The program will be contracted out of the Honeywell Aerospace Advanced & Applied Technology group, with key contributions from Honeywell Aerospace Missions and Payloads, Georgia Institute of Technology (sub-contractor), and Soter Technology (sub-contractor) (Table 5-1). In additional, Georgia Institute of Technology will sub-contract to the University of Seville, Spain. The qualifications, capabilities, and anticipated amount of effort of the team members are further described in Section 6.0. Organizational experience and capabilities are described in Section 7.0.

Table 5-1. Teaming Arrangement

Technical Area	Section Lead Investigator	Contributor
Overall Program Leads	PI: Dr. Rowlands (Honeywell) *WBS (1.2-1.6, 2.2-2.6)*	PM: Dr. Childers (Honeywell) *WBS 1.1-1.2, 2.1-2.2*
Magnetic Control System Modeling and Simulation includes the capillary ferrohydrodynamic LM interface and magnetic subsystem and optical performance modeling	Dr. Romero-Calvo (Georgia Institute of Technology) *WBS 1.3.1, 1.5.2, 1.6.1, 2.3.1, 2.5.2*	Mr. Zheng (Honeywell), optical performance modeling *WBS 1.3.2, 1.5.1, 2.3.2, 2.5.1*
Fluid System Development includes development of the liquid system with reflective & ferrofluidic properties	Dr. Kamire (Honeywell) *WBS 1.4, 2.4, 1.6.2, 2.6.1*	Dr. Yates (Honeywell), materials expert
Hardware includes lab-scale mirror testing and demo-scale design, build, & test, & model verification	Mr. Strafford (Soter Technology) *WBS 1.5.3, 1.6.3, 2.5.3, 2.6.2*	Mr. Cameron (Honeywell), design review and path to commercialized LMT design

Team member responsibility for high-level WBS items is indicated in italics

All team members will share relevant information produced during execution of the program with the other team members and with DARPA. This information includes design, build information, procedures, and raw and processed test data for the M&S, Halbach array, fluid system, demonstration hardware, and test equipment. Regularly held (bimonthly) virtual technical meetings with at least one team member from each leading organization will facilitate information sharing. The indicated responsible team member in Table 5-1 for each task will be responsible for collecting and disseminating information among the team and writing and delivering reports for that task. These conversations will facilitate identification of risks and challenges in addition to those described above (Sec. 4.5) as they arise and develop mitigation strategies.

6.0 PERSONNEL, QUALIFICATIONS, AND COMMITMENTS

6.1 Level of Commitment

The level of effort to be expended per person and other major sources of support and/or commitments are indicated for key personnel in Table 6-1. Further detail on the qualifications, prior accomplishments, and closely related work of the key personnel is provided in Section 6.2.

Table 6-1. Key Personnel Level of Effort and Other Major Commitments

Primary Organization Team Member	**Hours per contract year**			**Other major sources of support and/or commitments**
	2023	**2024**	**2025**	
Honeywell Aerospace				
Dr. Amanda Childers (PM) [a]	400	690	400	PM of NASA Methane Pyrolysis Program (80MSFC21CA010)
Dr. Neil Rowlands (PI) [b]	460	790	460	Program Scientist for the FGS/NIRISS instrument on the JWST mission – supporting operations on an as-needed basis.
Dr. Rebecca Kamire [a]	450	590	340	PI of NASA CDRILS Program (80MSFC18C0045 and anticipated continuation)
Dr. Stephen Yates [a]	225	380	220	PI of NASA Methane Pyrolysis Program (80MSFC21CA010) Contributor to NASA CDRILS Program (80MSFC18C0045 and anticipated continuation)
Mr. Emir Rahislic [a]	560	780	500	Contributor to NASA CDRILS Program (80MSFC18C0045 and anticipated continuation)
Mr. Sheng-Hai Zheng	540	350	175	Optical design of the Optical Quantum Ground Station for the Canadian Space Agency's QEYSSAT program
Mr. Peter G. Cameron	320	100	50	Mechanical design of the Optical Quantum Ground Station for the Canadian Space Agency's QEYSSAT program
Georgia Institute of Technology				
Dr. Álvaro Romero-Calvo [c,*]	512	640	640	Co-I of ESA SolarMag (#2022-00037) and collaborator of DLR LiMO (#50WM2150) projects.
Dr. Gabriel Cano-Gómez [d,*]	320	600	600	Co-I for national project (""*Técnicas avanzadas de reducción de emisiones electromagnéticas en convertidores DC-DC de alta densidad de potencia para electrificación de vehículos y aeronaves*",TED2021-131954B-I00)
Dr. Miguel Angel Herrada [d,*]	320	600	600	PI for state project ("*Física y Modelización de la Micro- y Meso-Escala en Flujos con Entrefases para el Avance de Tecnologías Vitales*", PID2019-108278RB-C31) and national project ("*Generación controlada de micro-fibras y micro-gotas en sectores de materiales, salud y energía*", P18-FR-3623)
Doctoral student (×2) [c]	412	1000	580	Graduate students at Georgia Tech are expected to commit half of their time to their education. Hours are indicated per student.
Post-doctoral student [c]	824	2000	1160	No conflicts
Soter Technology				
Mr. David Strafford *	112	192	112	
Mr. Dale Zajac	480	800	460	PM of other commercial projects.
Mr. Eli Heisey	950	860	200	Supporting other commercial projects.
Mr. Steven Scheidt	1100	1120	490	Supporting other commercial projects.
Mr. Robb Ball	560	70	440	Supporting other commercial projects.

Leading roles in the program and leading contributors to the proposal are indicated in bold.
[a] Honeywell Aerospace Advanced Materials; [b] Honeywell Aerospace Missions and Payloads; [c] Georgia Institute of Technology; [d] University of Seville
* Not all hours are billable. See cost proposal for billable hours.

6.2 Qualifications and Accomplishments

The qualifications and accomplishments for the key personnel are described below.

8.0 STATEMENT OF WORK (SOW)

The proposed Tasks for the program are described below. Referenced Milestone ID#'s are identified in Section 9.0. The Contractor shall furnish the necessary personnel, materials, facilities, and other services as may be required to manage and complete the contracted effort in accordance with this Statement of Work (SOW) and the schedule set forth. The work and services to be performed hereunder shall be subject to the requirements and standards contained in this Statement of Work. The Contractor shall keep the DARPA Program Manager, the Contracting Officer Representative (COR), and the Contracting Officer (CO) informed on contract progress through submission of the reports and other deliverables in accordance with the SOW, Reports and/or Other Deliverables summarized below, and through participation in the meetings identified below.

Open-Source M&S Code – The Contractor shall provide open-source modeling and simulation code, delivered to DARPA.

Quarterly Technical Progress Report – The Contractor shall provide quarterly detailed progress reports within ten days of the end of the given quarter. The report will present a summary of work completed and milestones met; discuss any problems encountered; update the program schedule; present the program financial status; and discuss remaining work regarding technical tasks. Quarterly reports shall also include copies of research reports and publications. Other reports, briefings, media, etc. that document the results of the Zenith modeling demonstrations and/or findings, as requested by the Government.

End-of-phase reports – Phase completion reports will be submitted within 30 days of the end of each phase, summarizing the research done.

PI Meetings - The Contractor shall participate in meetings with the DARPA Program Manager, other Principal Investigators of the Zenith Program, or U.S. Government stakeholders at the discretion of the DARPA Program Manager. In this meeting, the Contractor will present a summary report of all work completed and milestones accomplished, as well as the planned work for the next six-month period. These meetings will require travel.

Site Visits - The Contractor shall host site visits from the COR and the DARPA Program Manager. The purpose of these visits is to present a summary report of all work completed and milestones accomplished and to discuss ongoing or future technical tasks.

Patent Reports and Notifications – Patent reports and notifications will be submitted electronically through i-Edison.

Travel – In addition to the travel indicated as part of PI Meetings, the Contractor will attend the SPIE Astronomical Telescopes and Instrumentation conference in Yokohama, Japan, for the purpose of interfacing with the broader astronomical community.

CUI Protection Plan – Final CUI protection plans will be due within 60 days of contract award, to be updated annually.

Honeywell

DARPA Zenith - Phase I

1.1 - Program Management

Duration: 06/01/2023 - 01/31/2024
Primary Organization: Honeywell Advanced Materials
Approach: Day-to-day management of the program, including project management, quarterly technical reports, Principal Investigator coordination, planning and control analysis, procurement, and export classification and control.
Deliverables: Technical and cost customer reports

1.2 - Requirements and Reviews

Duration: 06/01/2023 - 01/31/2024
Primary Organization: Honeywell Advanced Materials
Approach: Rigorous and continued technical oversight of requirements and reports will be used to ensure full coordination between the ferromagnetic, material system, modeling, and testing teams, via bimonthly technical coordination meetings. This will support the development of the Ferrofluidic Ionic Liquid Mirror (FILM) proposed in this work.

1.2.1 - Requirements Development

Duration: 06/01/2023 - 01/31/2024
Approach: Requirements will be developed considering the technical metrics of tilt angle, slew rate, wavefront control, aperture size, reflectivity, etc. outlined in the Broad Agency Announcement (BAA). Requirements may include bounds for the material system surface and hardware design.
Deliverables: Requirements guide, including properties such as material smoothness, control, and reflectivity to inform fluid system development, ferromagnetic control, and hardware design

1.2.2 - Kick-off Meeting

Duration: 06/01/2023 - 06/30/2023
Approach: A kick-off meeting will be prepared and presented, including scope of work, program management and financial tracking plans, and technical approach.
Deliverables and Milestones: Kick-off Presentation Deck and delivered Milestone #1

1.2.3 - PI Meeting #1

Duration: 07/01/2023 - 08/31/2023
Approach: A presentation deck will be prepared to facilitate a PI meeting, covering end-to-end second-order physical models that include fluid inertia, edge effects, and electromagnetic field interactions
Deliverables and Milestones: PI Meeting #1 Deck and delivered Milestone #2

1.2.4 - PDR Review and Package

Duration: 10/01/2023 - 11/30/2023
Approach: Provide preliminary design, code, and results for review
Deliverables: Draft M&S report, version 0 code, and PDR Package

1.2.4.1 - Draft M&S report (1)

Duration: 10/01/2023 - 10/31/2023
Approach: An end-of-phase report will be prepared and delivered, including modeling & simulation results and all final data
Deliverables and Milestones: Draft M&S report and delivered Milestone #3

1.2.4.2 - Version 0 code

Duration: 10/15/2023 - 10/31/2023
Approach: Version 0 of the computer code will be delivered
Deliverables and Milestones: Version 0 code and delivered Milestone #4

1.2.4.3 - PDR review and package

Duration: 11/01/2023 - 11/30/2023
Approach: A presentation deck will be prepared to facilitate a Preliminary Design Review (PDR) and discussion with the customer, including information on modeling & simulation, projected wavefront performance and optical coherence, aberration control, correction mechanisms, and liquid surface cohesion. The hardware purchasing plan and timeline for Phase II will also be presented.
Deliverables and Milestones: PDR Package and delivered Milestone #5

1.2.5 - Phase I Report

Duration: 12/01/2023 - 01/31/2024
Approach: An end-of-phase report, the Version 1 code, and a hardware delivery plan will be prepared and delivered. Orders will be placed for hardware with long delivery timelines.
Deliverables: Phase I report, version 1 code, orders placed, hardware delivery plan

1.2.5.1 - Phase I Report

Duration: 12/01/2023 - 01/31/2024
Approach: An end-of-phase report will be prepared and delivered, including modeling & simulation results and all final data
Deliverables and Milestones: Phase I Report and delivered Milestone #7

1.2.5.2 - Version 1 code

Duration: 12/01/2023 - 01/31/2024
Approach: Version 1 of the computer code will be prepared and delivered
Deliverables and Milestones: Version 1 code and delivered Milestone #8

1.2.5.3 - Order placement

Duration: 12/29/2023 - 01/31/2024
Approach: Orders will be placed for hardware with long delivery timelines as identified during PDR and specified in the hardware delivery plan
Deliverables and Milestones: Orders placed and delivered Milestone #9

1.2.5.4 - Hardware delivery plan

Duration: 12/01/2023 - 01/31/2024
Approach: Prepare a deliver a hardware delivery plan that adheres to the 0.5 m laboratory demo timelines.
Deliverables and Milestones: Hardware delivery plan and delivered Milestone #10

1.3 - Modeling & Simulation

Duration: 06/01/2023 - 01/31/2024
Approach: The modeling & simulation (M&S) work will incorporate both ferromagnetic and optical modeling contributions to endeavor to predict and design the Liquid Mirror (LM) surface. An iterative approach will be used, including preliminary steps such as small scales and flat surfaces.
Proposed classification and reasoning: Fundamental Research. Specified in BAA S1.F.

1.3.1 - Ferromagnetic Modeling & Simulation

Duration: 06/01/2023 - 01/31/2024
Primary Organization: Georgia Institute of Technology
Approach: The ferromagnetic M&S is centered around the ferromagnetic modeling software developed by the Georgia Institute of Technology. Fluid properties from the materials development and characterization tasks will be incorporated into these models. The surface profile of the LMT will then be iterated with the magnet array design and assessed against a varying gravity vector (tilting). This work will start with small scale (<0.2m) diameter models which will then endeavor to be validated against test LM's of the same diameter constructed with the most promising materials selected from the initial M&S. The M&S will then be extended to the 0.5m diameter design to establish the most promising combination of magnet array design and fluid selections which will aim to meet the established WFE requirements. The ferro-fluid model, its inputs and outputs will be documented and delivered as part of the open-source M&S deliverable. Use of open-source analytical and numerical tools to design the ferrofluid LM interface will be based on the characterization provided by the rest of the team.
Deliverables: M&S results as specified below

1.3.1.1 - Quantification of inhomogeneities in the magnetic force potential induced by discrete Halbach array configuration as a function of magnet size and spacing

Duration: 06/01/2023 - 08/31/2023
Approach: Analysis of constant magnetic potential lines based on an analytical approach to the electromagnetic problem followed by fluid-magnetic interface-tracking simulations
Deliverables: Peak-to-peak spatial inhomogeneities as a function of the physical (saturation magnetization, magnetic susceptibility) and geometrical (magnet depth, spacing, rotation) of the system

1.3.1.2 - Determination of Rosensweig-instability-free magnetization space

Duration: 06/01/2023 - 06/30/2023
Approach: Analytical verification of normal instability conditions
Deliverables and Milestones: Maximum allowed magnetic field and magnetization to support Milestone #1

1.3.1.3 - Determination of hysteresis-free Halbach parametric space

Duration: 06/01/2023 - 07/31/2023
Approach: Numerical computation of B field in points of high magnetic flux density and comparison with hysteresis curve
Deliverables: Minimum allowed magnet separation

1.3.1.4 - Sensitivity analysis of the magnetic force potential as a function of magnetization error

Duration: 06/01/2023 - 08/31/2023
Approach: Quantification of equipotential surface disturbance as a function of experimentally characterized errors in the magnetization of each magnet
Deliverables: Sensitivity coefficient (displacement / magnetization error)

1.3.1.5 - Quantification of mass force potential disturbances as a function of tilting

Duration: 06/01/2023 - 08/31/2023
Approach: Analysis of the deformation of equipotential lines as a function of tilting angle
Deliverables: Sensitivity coefficient (displacement / tilting angle)

1.3.1.6 - Design of 3D printed ferromagnetic material for tuning magnetic potential lines

Duration: 06/01/2023 - 06/30/2023
Approach: Design of 3D printed ferromagnetic patterns to tune the magnetic potential lines
Deliverables: Design for the ferromagnetic material

1.3.1.7 - Determination of feasible physical configurations

Duration: 06/01/2023 - 08/31/2023
Approach: Determination of physical and geometrical trade space where the required nm-level resolution is achieved using the results from Tasks 1.3.1.1 - 1.3.1.6
Deliverables: Combination of geometrical and physical parameters

1.3.1.8 - Design of axisymmetric Halbach array configurations

Duration: 06/01/2023 - 08/31/2023
Approach: Development of the axisymmetric equivalent of 2D Halbach arrays using analytical transformations and feasibility analysis based on available market magnets
Deliverables and Milestones: Axisymmetric Halbach array geometry and magnetization to support Milestone #2

1.3.1.9 - Computation of axisymmetric ferrofluid surface profiles subject to Halbach forces in flat setups

Duration: 07/01/2023 - 10/31/2023
Approach: Application of interface tracking tools in Task 1.3.1.1 to the configuration developed in Task 1.3.1.8
Deliverables and Milestones: Peak-to-peak spatial inhomogeneities for optimum configuration to support Milestone #3 and #4

1.3.1.10 - Computation of axisymmetric ferrofluid surface profiles subject to Halbach forces and tilting

Duration: 07/01/2023 - 10/31/2023
Approach: Inclusion of tilted potential surfaces on Task 1.3.1.9
Deliverables and Milestones: Peak-to-peak spatial inhomogeneities for optimum configuration to support Milestone #3 and #4

1.3.1.11 - Modal analysis of ferrofluid LM interface

Duration: 11/01/2023 - 01/31/2024
Approach: Use of global stability analysis framew ork to quantify the oscillatory response of the liquid mirror
Deliverables and Milestones: Modal shapes and frequencies to support Milestone #7 and #8

1.3.1.12 - Conceptualization of suitable magnetic liquid control methods

Duration: 10/01/2023 - 01/31/2024
Approach: Analysis of the influence of the magnetic force induced by options such as (i) thin 3D printed ferromagnetic layer, (ii) ferromagnetic tuners, and (iii) electro-permanent magnets on the equipotential lines of the LM and assessment of their capability to compensate for tilting and spatial frequency disturbances
Deliverables and Milestones: Sensitivity coefficients for different methods, deformation of equipotential surfaces as a function of the implementation to support Milestone #7 and #8

1.3.2 - Optical Modeling & Simulation

Duration: 06/01/2023 - 01/31/2024
Primary Organization: Honeyw ell Missions and Payloads
Approach: In order to prepare for the modeling & simulation demonstration in Phase II, a nominal LM telescope reference design w ill be established to set detailed w avefront error (WFE) requirements for the LM's in both Phase II and Phase III. The WFE requirements for the 0.5 m FILM design to be tested in Phase II w ill be set based on traceability to the LMT reference design. Both prescriptions and WFE maps w ill be documented alongside the open source ferro-fluid softw are.
Deliverables: LMT reference design, WFE requirements, and assessment of ferromagnetic model outputs for the 0.5 m demo design

1.3.2.1 - Establish LMT Reference Design & WFE Requirements

Duration: 6/1/023 - 08/31/2023
Approach: Document proposed LM telescope reference design and traceability to 0.5m demo design. Establish WFE requirements at low , mid & high spatial frequencies for both designs via optical modeling using initial representative WFE maps (i.e. sinusoidal ripple maps w ith a variety of spatial scales). Propose image quality metrics for these reference designs and for discussion w ith customer at PI Meeting #1.
Deliverables and Milestones: ZEMAX Prescriptions LM telescope reference design to support Milestone ID #1. 0.5m demo design and WFE requirements for both designs & image quality metrics to support Milestone #2

1.3.2.2 - Assess ferro-magnetic model outputs against 0.5 m demo LM design and against LMT reference design

Duration: 09/01/2023 - 01/31/2024
Approach: Develop the methods/algorithms to convert the ferro-fluid model output to WFE maps suitable for evaluation by commercial optical design softw are (e.g. ZEMAX). These methods/algorithms w ill be implemented as scripts and/or functions in commercial mathematical softw are such as MATLAB or Python and provided as part of the open source softw are deliverables. First, the ferro-model output w ill be assessed w ith respect to the 0.5m demo optical model. Next, potential scaling functions w ill be assessed and agreed upon to support Phase II w ork.
Deliverables and Milestones: Scripts for ferro-fluid model output conversion to ZEMAX sag maps, and image quality assessment for 0.5 m demo to support Milestone ID #3 and #4. Image quality assessment for LM telescope reference design to support Milestone ID #5, #7, and #8 to support Milestone #7 and #8

Honeywell

1.4 - Fluid System Development

Duration: 06/01/2023 - 01/31/2024
Primary Organization: Honeywell Advanced Materials
Approach: Develop the fluid system through laboratory demonstration to de-risk the PDR design of the Phase II 0.5 m liquid mirror demonstration.
Proposed classification and reasoning: CUI. Extrapolation of information in BAA S1.F to Phase I.
Deliverables and Milestones: Delivery of chemical safety handling instructions and approximately 3 fluids containing ionic liquids, reflective properties, and/or magnetic properties to each of Honeywell Missions and Payloads, Georgia Institute of Technology, and Soter Technology for test in Task 1.5. Completed test report and plan for Task 2.4 to support Milestone #7

1.4.1 - Development of Fluid System Pairs

Duration: 06/01/2023 - 10/31/2023
Approach: Demonstrate four pairs (types of subsystems) of fluid components through laboratory demonstration
Deliverables and Milestones: Completed preliminary design of each of four pairs of fluid components for use in 1.4.2. to support Milestone #3

1.4.1.1 - Development of ferrofluidic layer

Duration: 06/01/2023 - 10/31/2023
Approach: Demonstrate up to four formulations for a ferromagnetic ionic liquid (IL) (base liquid with magnetic nanoparticles), including surface modification of the magnetic nanoparticles. Evaluate based on criteria such as suspension and material stability and magnetic susceptibility.
Deliverables: Completed preliminary design of ferrofluidic layer

1.4.1.2 - Development of ionic liquid pair

Duration: 06/01/2023 - 10/31/2023
Approach: Demonstrate up to four pairs of ionic liquids (base liquid with top liquid) the separation into discrete phases. Evaluate based on criteria such as disengagement rate and purity of resulting layers.
Deliverables: Completed preliminary design of ionic liquid pair

1.4.1.3 - Development of reflective surface

Duration: 06/01/2023 - 10/31/2023
Approach: Demonstrate up to four formulations for a reflective surface (ionic liquid(s) with reflective nanoparticles). Evaluate based on criteria such as specular and diffuse reflectance, scattering, and stability.
Deliverables: Completed preliminary design of reflective surface

1.4.1.4 - Development of wetted surface

Duration: 06/01/2023 - 10/31/2023
Approach: Demonstrate wetting and stability of up to two support structure materials with ionic liquids (support structure with base liquid). Evaluate based on criteria such as surface tension, contact angle, and stability.
Deliverables: Completed preliminary design of liquid/support interface

1.4.2 - Downselection and Prioritization of Materials

Duration: 11/01/2023 - 01/31/2024
Approach: Select based on the pairwise demonstrations the prioritized list of ionic liquid pairs for further optimization and outstanding technical challenges. Trial up to one set of materials to build a complete ferromagnetic ionic liquid mirror. Refine plans for Phase II fluid system development.
Deliverables and Milestones: Completed plan for Task 2.4 to support Milestone #5, #7, and #10

1.5 - Bench-level Testing

Duration: 06/01/2023 - 01/31/2024
Approach: The bench level testing will support the downselection of the ILs, providing materials property inputs to the M&S tasks. This testing will be performed with small scale (ex: 10-20 cm diameter) samples. An incremental approach is taken where the IL pairs and reflective particles are developed in parallel with ferro-fluid studies in Task 1.3.1. Samples of the complete FILM system may be tested at Soter Technologies.
Proposed classification and reasoning: CUI. Extrapolation of information in BAA S1.F to Phase I.

1.5.1 - Material Properties and Configuration Testing

Duration: 06/01/2023 - 1/31/2024
Primary Organization: Honeywell Missions and Payloads
Approach: After the initial trials and downselect the most promising IL pairs and reflective particles will undergo some initial optical testing at Honeywell's optics lab in Ottawa, Ontario. This testing will consist of reflectivity and WFE measurements of the ILs in an optically flat container.
Deliverables: Capability to execute reflectivity and materials property tests at Honeywell and test results

1.5.1.1 - Procurement of Test Hardware

Duration: 06/01/2023 - 08/31/2023
Approach: A system of rotating stages, light illumination and camera will be assembled and verified with reference flat mirrors, including procurement of some new parts to assemble with existing test equipment.
Deliverables and Milestones: Capability to execute reflectivity and materials property tests at Honeywell to support Milestone #2

1.5.1.2 - Initial Reflectivity Tests of IL Pairs

Duration: 09/01/2023 - 10/31/2023
Approach: Up to four initial candidate IL pairs from Honeywell Advanced Materials (with and without reflective particles) will be characterized for reflectance and scattered light in the test setup. The test samples will be mechanically disturbed (tilted & rotated) to assess the stability of the mixture and provide feedback to the materials selection.
Deliverables and Milestones: Test results delivered to the team to support Milestone #3

1.5.1.3 - Materials Properties Testing

Duration: 11/01/2023 - 01/31/2024
Approach: Up to four downselected IL pairs and reflective particles will be tested for optical and material properties in a thermal chamber in order to assess Variation of these macro properties with temperature and disturbance level will provide a basic confirmation of the materials property assumptions (such as viscosity, and Bond, Weber & Ohnesorge numbers) and the behavior of the interface between the two ILs.
Deliverables and Milestones: Test results delivered to the team to support Milestone #5 and #7

1.5.2 - Ferromagnetic Properties and Configuration Testing

Duration: 06/01/2023 - 10/31/2023
Primary Organization: Georgia Institute of Technology
Approach: Prepare the Phase I Halbach array and perform ferrofluids testing
Deliverables: Build an characterized Halbach array assemblies and characterized ferrofluids

1.5.2.1 - Manufacturing of 20 cm scale Halbach array setup using suitable magnetic configuration

Duration: 06/01/2023 - 10/31/2023
Approach: 3D printing of up to three versions of the preliminary Halbach array structure and insertion of neodymium magnets
Deliverables: Halbach array assemblies

1.5.2.2 - Quantification and compensation of magnet magnetization error

Duration: 06/01/2023 - 10/31/2023
Approach: Measurement of internal magnetization of every Halbach magnet component and selection of uniform sample. Measure the magnetic field above each array prepared.
Deliverables and Milestones: Selection of magnets with uniform magnetization to support Milestone #5

1.5.2.3 - Characterize the magnetic response of ferrofluids

Duration: 09/01/2023 - 10/31/2023
Approach: Characterize the magnetic response of up to three ferrofluids using a vibrating sample magnetometer.
Deliverables and Milestones: Test data delivered to team to support Milestone #5 and #7

1.5.3 - Hardware and Mirror Property Testing

Duration: 06/01/2023 - 01/31/2024
Primary Organization: Soter Technology
Approach: Design and build test equipment and perform tests
Deliverables: Test equipment readiness; test data delivered to the team

1.5.3.1 - Prepare test set including tilt mechanism

Duration: 06/01/2023 - 10/31/2023
Approach: Design and build a test set including tilt mechanism to test Phase I samples for small 0.2 m dia. samples and Phase II 0.5 m dia. size hardware. Note that the STE involves upgrades to existing equipment and facilities and is not program deliverable hardware.
Deliverables and Milestones: Capability to execute tilt of optical test set and unit under test inside clean environment to support Milestone #3

1.5.3.2 - Prepare clean test environment

Duration: 06/01/2023 - 10/31/2023
Approach: Design and build a clean test environment to test samples up to 0.5m dia. (for small 0.2m dia. samples and Phase II 0.5m dia. size hardware). Note that the STE involves upgrades to existing equipment and facilities and is not program deliverable hardware.
Deliverables and Milestones: Improved capability of clean environment surrounding test facility to support Milestone #3

1.5.3.3 - Test Phase I samples

Duration: 11/01/2023 - 01/31/2024
Approach: For each of at least 3 samples and up to 8 samples, set up samples in test set, and test at zenith and at tilt if applicable. Evaluate based on criteria such as reflectivity and scatter/microroughness of the liquid mirror surface.
Deliverables and Milestones: Test report for each test article to support Milestone #7

1.6 - 0.5 m Laboratory-demo Hardware Design

Duration: 06/01/2023 - 11/30/2023
Approach: Prepare a PDR-level design of the 0.5 m dia. Halbach array and test equipment
Proposed classification and reasoning: CUI. Extrapolation of information in BAA S1.F to Phase I.
Deliverables and Milestones: PDR-level design of the 0.5 m dia. Halbach array and test equipment to support Milestone #5

1.6.1 - 0.5 m Laboratory-demo Halbach Array Magnet-level Design

Duration: 06/01/2023 - 11/30/2023
Primary Organization: Georgia Institute of Technology
Approach: Prepare a PDR-level design of 0.5 m dia. Halbach array magnet configuration
Deliverables: PDR-level design of 0.5 m dia. Halbach array magnet configuration

1.6.2 - 0.5 m Laboratory-demo Halbach Array Manufacturing Design

Duration: 06/01/2023 - 11/30/2023
Primary Organization: Honeywell Advanced Materials
Approach: Identify a supplier internal or external to Honeywell to manufacture the 0.5 m laboratory-demo Halbach array. The supplier completes a PDR-level design of the Halbach array for manufacture.
Deliverables: PDR-level design of the Halbach array for manufacture.

1.6.3 - 0.5 m Laboratory-demo hardware design

Duration: 06/01/2023 - 11/30/2023
Primary Organization: Soter Technology
Approach: Prepare a PDR-level design of the 0.5m dia. test configuration including tilt mechanisms.
Deliverables: PDR-level design of 0.5m dia. test configuration

DARPA Zenith - Phase II

2.1 - Program management

Duration: 02/01/2024 - 07/31/2025
Primary Organization: Honeywell Advanced Materials
Approach: Day-to-day management of the program, including project management, quarterly technical reports, Principal Investigator coordination, planning and control analysis, procurement, and export classification and control.
Deliverables: Technical and cost customer reports

2.2 - Requirements and Reviews

Duration: 02/01/2024 - 07/31/2025
Primary Organization: Honeywell Advanced Materials
Approach: Rigorous and continued technical oversight of requirements and reports will be used to ensure full coordination between the ferromagnetic, material system, modeling, and testing teams, via bimonthly technical coordination meetings

2.2.1 - Requirements Refinement

Duration: 02/01/2024 - 07/31/2025
Approach: Requirements will be reviewed and refined as findings flow in from the component subteams. Requirements will define the material system surface and hardware design based on the technical metrics of tilt angle, slew rate, wavefront control, aperture size, reflectivity, etc. outlined in the BAA.

2.2.2 - Conference & PI Meeting #2

Duration: 02/01/2024 - 03/31/2024
Approach: A presentation deck will be prepared and presented at a peer-reviewed conference, in support of the overall Zenith program. The presentation will cover technical approach and progress to date, including M&S results and fluid system development. A presentation deck will also be prepared to facilitate a PI meeting, as needed
Deliverables and Milestones: Conference Presentation deck, PI Meeting #2 Deck and delivered Milestone #11 and #12

2.2.3 - CDR and PI Meeting #3

Duration: 04/01/2024 - 11/29/2024
Approach: A presentation deck will be prepared to facilitate a Critical Design Review (CDR) and discussion with the customer, including information on M&S results on the projected wavefront performance and optical coherence of the LM, aberration control or correction mechanisms (if any), and liquid surface cohesion during slew and pointing, while at out of plane tip and tilt angles (per program metrics). Additional information to facilitate PI meeting #3 will be provided.
Deliverables and Milestones: CDR Package, PI Meeting #3 Deck and delivered Milestone #15

2.2.4 - PI Meeting #4

Duration: 12/01/2024 - 04/30/2025
Approach: Provide to date design, code, results, and plans for review
Deliverables: Test plan, PI meeting #4 deck

2.2.4.2 - 0.5 m Laboratory-demo test plan

Duration: 12/01/2024 - 01/31/2025
Approach: Prepare and submit test plan for 0.5 m lab demo
Deliverables and Milestones: Test plan and delivered Milestone #18

2.2.4.3 - PI meeting #4

Duration: 2/30/2025 - 04/30/2025
Approach: A presentation deck will be prepared to facilitate a PI meeting and site visit, covering display bench-level setup for lab demo, hardware delivery progress, and installation progress.
Deliverables and Milestones: PI meeting #4 deck and delivered Milestone #20

2.2.5 - Phase 2 Report

Duration: 06/01/2025 - 07/31/2025
Approach: An end-of-phase report will be prepared and delivered, including M&S results and all final data. This report will also provide an assessment of the FILM technology for potential commercial applications.
Deliverables and Milestones: Phase 2 Report and delivered Milestone #23

2.3 - Modeling & Simulation

Duration: 02/01/2024 - 07/31/2025
Approach: The M&S will be updated with the fluid parameters measured / inferred from the Phase I results, including any required updates to the M&S code. The scaling lessons from the Phase I sample testing will then be applied to the M&S of the 0.5 m demo and the 3 m M&S demo . The resulting M&S predictions of the optical performance of the LMT reference design will be assessed. Any required optimizations will be based on the Phase I and/or Phase II results when available. The M&S code will be open-source and provided as a deliverable to DARPA.
Proposed classification and reasoning: Fundamental Research. Specified in BAA S1.F.
Deliverables: Completed preliminary design of ferrofluidic layer

2.3.1 - Ferromagnetic modeling

Duration: 02/01/2024 - 06/30/2025
Primary Organization: Georgia Institute of Technology
Approach: Extension of Phase-I simulations to 0.5 m LM
Deliverables and Milestones: M&S results as specified below to support Milestone #22

2.3.1.1 - Fully coupled simulation of ferrofluid LMT system for axisymmetric and flat Halbach array configurations

Duration: 02/01/2024 - 06/30/2025
Approach: Application of pre-developed interface-tracking models to 0.5m Halbach array
Deliverables: Geometrical & physical configuration and peak-to-peak error estimation

2.3.1.2 - Simulation of electromagnetic actuation strategy for LMT

Duration: 02/01/2024 - 06/30/2025
Approach: Simulation of pre-selected actuation strategy and its effects on the liquid mirror equipotential lines
Deliverables: Fluid surface deformation prediction

2.3.2 - Optical modeling

Duration: 02/01/2024 - 06/30/2025
Primary Organization: Honeywell Missions and Payloads
Approach: The optical model of the 0.5 m FILM demo will be updated and the impacts on the potential performance of the LMT reference design will be assessed, as the preliminary M&S 3 m demo. This M&S demo will be iterated in an endeavor to identify FILM parameters and their scaling that would achieve the performance requirements for the M&S demo established in Tasks 1.2.1 and 2.2.1.
Deliverables: M&S draft reports, codes, demo, and tool advancement plan as specified below

2.3.2.1 - Update of Optical Models for Version 1.5 of M&S code

Duration: 02/01/2024 - 10/31/2024
Approach: Using the output of the ferro-fluid models from Task 2.3 and available test data on fluid systems from Phase I, the optical performance of the 0.5 m demo will be re-assessed and any needed corrections to the 0.5 m demo design will be determined
Deliverables and Milestones: M&S Draft report (2.1) update and version 1.5 of M&S code and delivered Milestone #13 and #14

2.3.2.2 - Update of Optical Models for Version 2.0 of M&S code

Duration: 11/01/2024 - 01/31/2025
Approach: Using the output of the ferro-fluid models from Task 2.3 and available test data on fluid systems, the optical performance of the 3 m M&S demo will be re-assessed and any needed corrections to scaling assumptions will be determined.
Deliverables and Milestones: M&S Draft report (2.2) update and version 2.0 of M&S code and delivered Milestone #16 and #17

2.3.2.3 - Update of Optical Models for M&S 3m Demo

Duration: 02/01/2024 - 02/28/2025
Approach: Document the optical performance of a 3m FILM in the context of the LMT reference design. In addition to the ground-based 3m FILM, the M&S will also be evaluated for potential commercial applications, including for example a putative space-based version of a 3 m FILM, with evaluation of the impact on the magnet array and the fluid dynamics without the influence of gravity.

2.3.2.4 - Update of Optical Models for Version 3.0 of M&S code

Duration: 02/01/2025 - 06/30/2025
Approach: With the results of the 0.5m demo FILM incorporated into the ferro-fluid model, revisit the scaling and FILM parameters required for the 3 m LMT reference design to achieve its target performance. Prepare the M&S Advancement Plan for Phase III. Analyze the potential for FILM technology commercialization.
Deliverables and Milestones: Version 3.0 of M&S code and M&S Tool Advancement Plan and delivered Milestone #22 and #24

2.4 - Fluid System Development

Duration: 02/01/2024 - 07/31/2025
Primary Organization: Honeywell Advanced Materials
Approach: Refine the fluid system to be used for the 0.5 m liquid mirror through laboratory demonstration.
Proposed classification and reasoning: CUI. Specified in BAA S1.F.
Deliverables: Delivery of chemical safety handling instructions and approximately 2 fluids containing ionic liquids, reflective properties, and/or magnetic properties to each of Honeywell Missions and Payloads, Georgia Institute of Technology, and Soter Technology for test in 2.5. Fluid system including dish selected, prepared, and delivered with safety handling instructions to Soter Technology for test in 2.6. Completed test report

2.4.1 - Optimization of Fluid System Pairs

Duration: 02/01/2024 - 11/29/2024
Approach: Refine fluid system with focus on four pairs (types of subsystems) of fluid components through laboratory demonstration
Deliverables and Milestones: Completed refined design of each of four pairs of fluid components for use in 2.4.2. to support Milestone #15

2.4.1.1 - Refine the ferromagnetic ionic liquid

Duration: 02/01/2024 - 11/29/2024
Approach: Refine the ferromagnetic ionic liquid (base liquid with magnetic nanoparticles), including surface modification of the magnetic nanoparticles by demonstration of up to three formulations. Evaluate based on metrics such as suspension stability and magnetic susceptibility.
Deliverables: Completed refined design of ferrofluidic layer

2.4.1.2 - Refine the ionic liquid pair

Duration: 02/01/2024 - 11/29/2024
Approach: Refine the ionic liquid pair (base liquid with top liquid) separation into discrete phases by demonstration of up to three formulations. Evaluate based on metrics such as disengagement rate, purity of resulting layers, and surface tension.
Deliverables: Completed refined design of ionic liquid pair

2.4.1.3 - Refine formation of the reflective surface

Duration: 02/01/2024 - 11/29/2024
Approach: Refine formation of the reflective surface (ionic liquid(s) with reflective nanoparticles) by demonstration of up to three formulations. Evaluate based on metrics such as specular and diffuse reflectance, and scattering.
Deliverables: Completed refined design of reflective surface

2.4.1.4 - Refine wetting and stability of a support structure with the ionic liquid

Duration: 02/01/2024 - 11/29/2024
Approach: Refine wetting and stability of a support structure with the ionic liquid (support structure with base liquid) by demonstration of up to two ionic liquids and one support. Evaluate based on metrics such as surface tension, contact angle, and stability.
Deliverables: Completed refined design of liquid/support interface

2.4.2 - Optimization of Fluid System Self-assembly

Duration: 11/30/2024 - 01/31/2025
Approach: Refine self-assembly of the overall system including endeavoring to isolate the magnetic and reflective nanoparticles into the target phases. Evaluate based on metrics such as suspension stability, magnetic susceptibility, disengagement rate, purity of resulting layers, specular and diffuse reflectance, scattering, surface tension, and contact angle.
Deliverables and Milestones: Completed refined design of overall fluid system to support Milestone #16 and #18

2.4.3 - Full Fluid System Characterization

Duration: 02/01/2025 - 07/31/2025
Approach: Final demonstration of fluid system and identification of outstanding technical challenges, if any. Refine any plans for Phase III fluid system development, if necessary.
Deliverables and Milestones: Preparation and delivery of fluid system including liquid and support for 2.6 and completed plan for fluid system development in Phase III, if necessary to support Milestone #23

2.5 - Additional Bench-level Testing

Duration: 02/01/2024 - 04/30/2025
Approach: The bench level testing will support the further development of the fluid system in Task 2.4. This testing will be done with small scale (ex: 10-20 cm diameter) samples.
Proposed classification and reasoning: CUI. Specified in BAA S1.F.
Deliverables: Test data as specified below

2.5.1 - Material property and configuration testing

Duration: 02/01/2024 - 12/31/2024
Primary Organization: Honeywell Missions and Payloads
Approach: Characterize the fluid systems and/or subsystems developed in Task 2.4.
Deliverables and Milestones: Test data delivered to team to support Milestone #16 and #18

2.5.1.1 - Reflectivity Tests of Updated IL mixtures

Duration: 02/01/2024 - 11/29/2024
Approach: Up to three candidate IL pairs from Honeywell Advanced Materials (with and without reflective particles) will be characterized for reflectance and scattered light in the test setup. The test samples will be mechanically disturbed (tilted & rotated) to assess the stability of the mixture and provide feedback to the materials selection
Deliverables: Test data delivered to team

2.5.1.2 - Materials Tests of Updated IL mixtures

Duration: 02/01/2024 - 12/31/2024
Approach: Up to three IL pairs and reflective particles will be tested for optical and material properties in a thermal chamber in order to assess. Variation of these macro properties with temperature and disturbance level will provide a basic confirmation of the materials property assumptions (such as viscosity, and Bond, Weber & Ohnesorge numbers) and the behavior of the interface between the two ILs.
Deliverables: Test data delivered to team

2.5.2 - Ferromagnetic properties and configuration testing

Duration: 02/01/2024 - 12/31/2024
Primary Organization: Georgia Institute of Technology
Approach: Characterize the magnetic response of up to two ferrofluids using a vibrating sample magnetometer.
Deliverables and Milestones: Test data delivered to team to support Milestone #16 and #18

2.5.3 - Hardware and mirror property testing

Duration: 02/01/2024 - 04/30/2025
Primary Organization: Soter Technology
Approach: For each of at least 2 samples and up to 6 samples, set up samples in test set, and test at zenith and at tilt if applicable. Evaluate based on criteria such as reflectivity and scatter/microroughness of the liquid mirror surface.
Deliverables and Milestones: Test report for each test article to support Milestone #20

2.6 - 0.5 m Laboratory-Demo Hardware Fabrication and Demonstration

Duration: 02/01/2024 - 06/30/2025
Approach: Complete the fabrication and demonstration of the 0.5 m dia. Halbach array and test equipment
Proposed classification and reasoning: CUI. Specified in BAA S1.F.
Deliverables: Test report for the 0.5 m dia. Halbach array and test equipment

2.6.1 - 0.5 m Laboratory-demo Halbach array build

Duration: 02/01/2024 - 01/31/2025
Primary Organization: Honeyw ell Advanced Materials
Approach: Manufacture the 0.5 m laboratory-demo Halbach array at Honeyw ell or an external supplier
Deliverables and Milestones: 0.5 m laboratory-demo Halbach array delivered to Soter Technology. to support Milestone #21

2.6.2 - 0.5 m Laboratory-demo Testing

Duration: 02/01/2024 - 06/30/2025
Primary Organization: Soter Technology
Approach: Design and build test equipment modifications, install the 0.5m mirror, and perform tests
Deliverables: Test equipment readiness; test data delivered to the team

2.6.2.1 - Test set for 0.5m dia. spherical liquid mirror

Duration: 02/01/2024 - 04/30/2025
Approach: Finalize design and build the test set modifications.
Deliverables and Milestones: Capability to execute tilt of optical test set and unit under test inside clean environment. Note that the deliverable involves upgrades to existing equipment and facilities and is not program deliverable hardw are to support Milestone #21

2.6.2.2 - Installation of 0.5m dia. spherical mirror

Duration: 04/15/2025 - 05/15/2025
Approach: Receive and install the 0.5m dia. spherical mirror dish w ith Halbach array in the test set.

2.6.2.3 - Testing of 0.5m dia. spherical mirror

Duration: 05/15/2025 - 06/30/2025
Approach: Test the 0.5m Laboratory-demo w ith one fluid formulation at zenith and tilt. Evaluate based on metrics such as reflectivity and scatter/microroughness of the liquid mirror surface.
Deliverables and Milestones: Test report for each test article and delivered Milestone #21

9.0 SCHEDULE AND MILESTONES

The detailed schedules for Phases I and II are in Figure 9-1 and Figure 9-1. Arrows indicate dependencies, and timings may vary from those shown. The final portions of tasks at the end of both Phases are preparation of information for delivery not new testing or modeling.

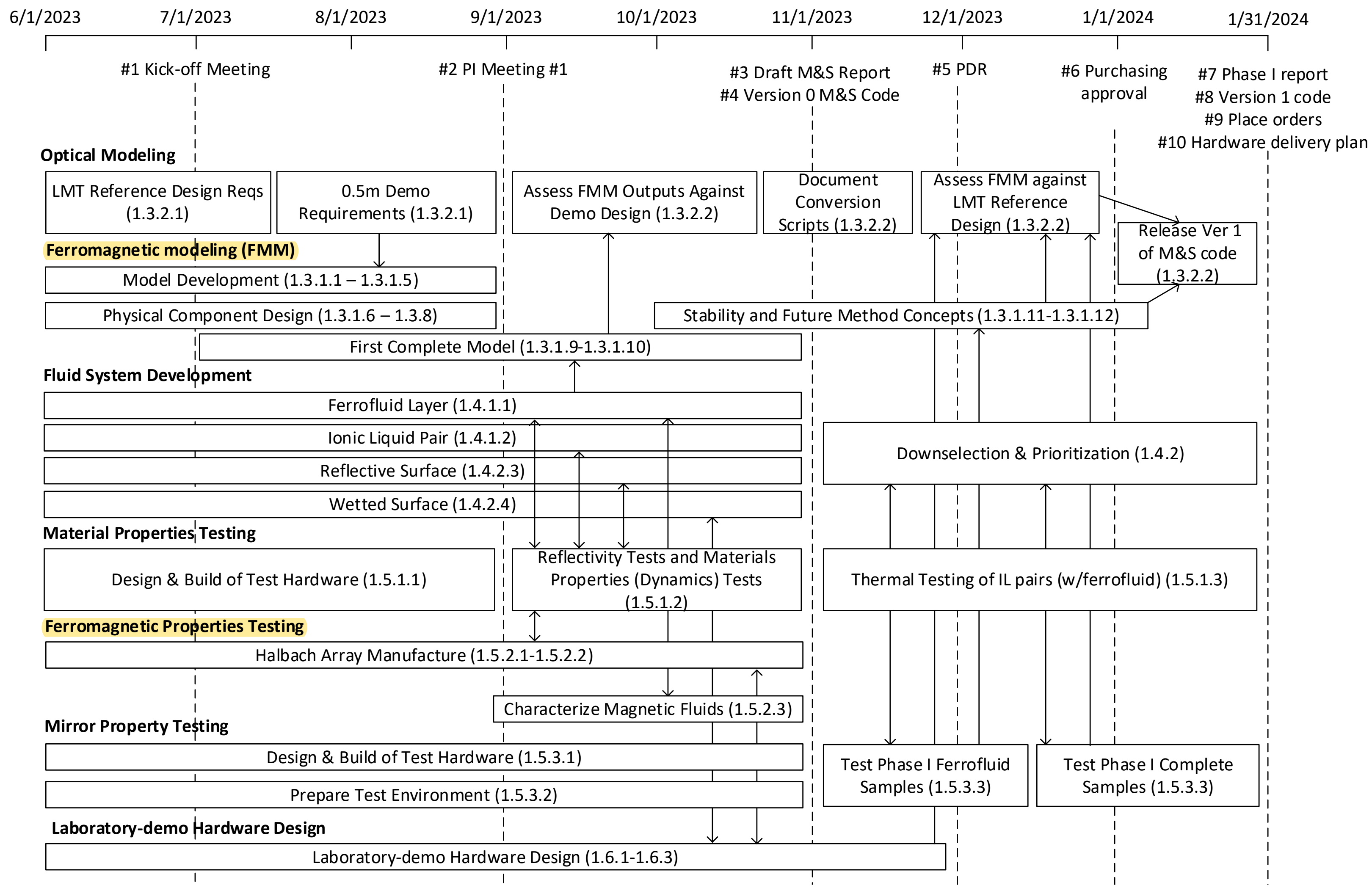

Figure 9-1. Detailed schedule for Phase I.

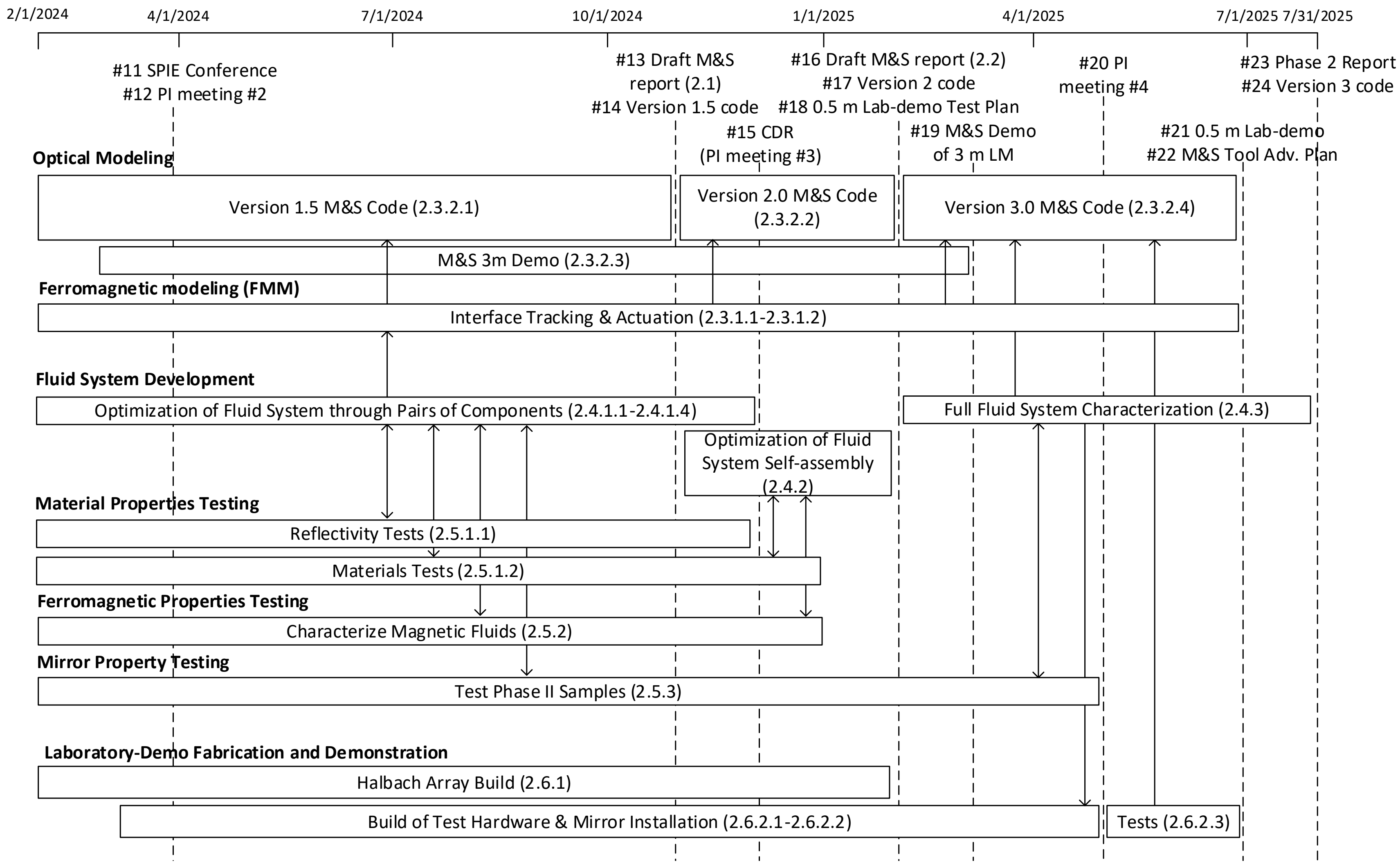

Figure 9-1. Detailed schedule for Phase II.

10.0 NOVELTY OF PROPOSED WORK

Has the proposed work been submitted to any other Government solicitation? No

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