August 25

Magnetic Control of Liquid Mirrors in Microgravity

Álvaro Romero-Calvo, Ph.D.

DARPA Zenith Lecture 1

Georgia Tech Space Systems Design Laboratory

LGST Lab

Liquid Mirror Telescopes (LMT)

A historical overview

PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *JS.* NEWTON, *Trin. Coll. Cantab. Soc.* Mathefeos Profeffore *Lucafiano*, & Societatis Regalis Sodali.

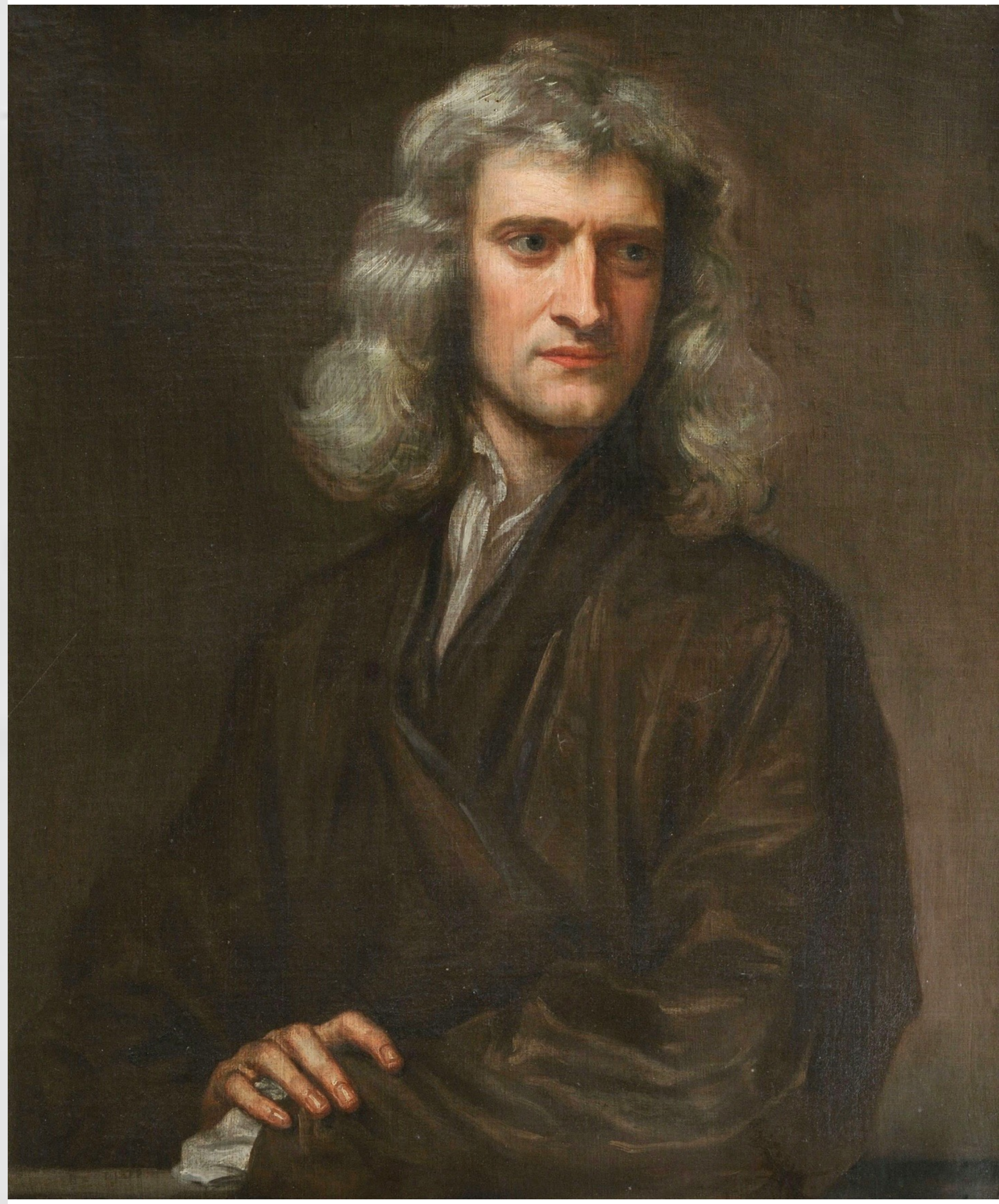
IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Juffu *Societatis Regiæ* ac Typis *Jofephi Streater*. Proftat apud plures Bibliopolas. *Anno* MDCLXXXVII.

motion. If a vessel, hung by a long cord, is so often turned about that the cord is strongly twisted, then filled with water, and held at rest together with the water; after, by the sudden action of another force, it is whirled about the contrary way, and while the cord is untwisting itself, the vessel continues for some time in this motion; the surface of the water will at first be plain, as before the vessel began to move; but the vessel, by gradually communicating its motion to the water, will make it begin sensibly to revolve, and recede by little and little from the middle, and ascend to the sides of the vessel, forming itself into a concave figure (as I have experienced), and the swifter the motion becomes, the higher will the water rise, till at last, performing its revolutions in the same times with the vessel, it becomes relatively at rest in it. This ascent of the water shows its endeavour to recede from the axis of its motion; and the true and absolute circular motion of the water, which is here directly contrary to the relative, discovers itself, and may be measured by this endeavour. At first, when the relative motion of the water in the vessel was greatest, it produced no endeavour to recede from the axis; the water showed no tendency to the circumference, nor any ascent towards the sides of the vessel, but remained of a plain surface, and therefore its true circular motion had not yet begun. But afterwards, when the relative motion of the water had decreased, the ascent thereof towards the sides of the vessel proved its endeavour to recede from the axis; and this endeavour showed the real circular motion of the water perpetually increasing, till it had acquired its greatest quantity, when the water rested relatively in the vessel. And therefore this endeavour does not depend upon any translation of the water in respect of the ambient bodies, nor can true circular motion be defined by such translation. There is only one real circular motion of any one revolving body, corresponding to only one power of endeavouring to recede from its axis of motion, as its proper and adequate effect; but relative motions, in one and the same body, are innumerable, according to the various relations it bears to external bodies, and like other relations, are altogether destitute of any real effect, any otherwise than they may perhaps partake of that one only true motion. And therefore in their system who suppose that our heavens, revolving below the sphere of the fixed stars, carry the planets along with them; the several parts of those heavens, and the planets, which are indeed relatively at rest in their heavens, do yet really move. For they change their position one to another (which never happens to bodies truly at rest), and being carried together with their heavens, partake of their motions, and as parts of revolving wholes, endeavour to recede from the axis of their motions.

Wherefore relative quantities are not the quantities themselves, whose names they bear, but those sensible measures of them (either accurate or inaccurate), which are commonly used instead of the measured quantities themselves. And if the meaning of words is to be determined by their

Newton's Philosophiae, Book 1: Definitions – Scholium, 1687



First attempt, 1909

R.W. Wood, “The Mercury Paraboloid as a Reflecting Telescope”, Astrophysical Journal, Vol. 29, p. 164, 1909

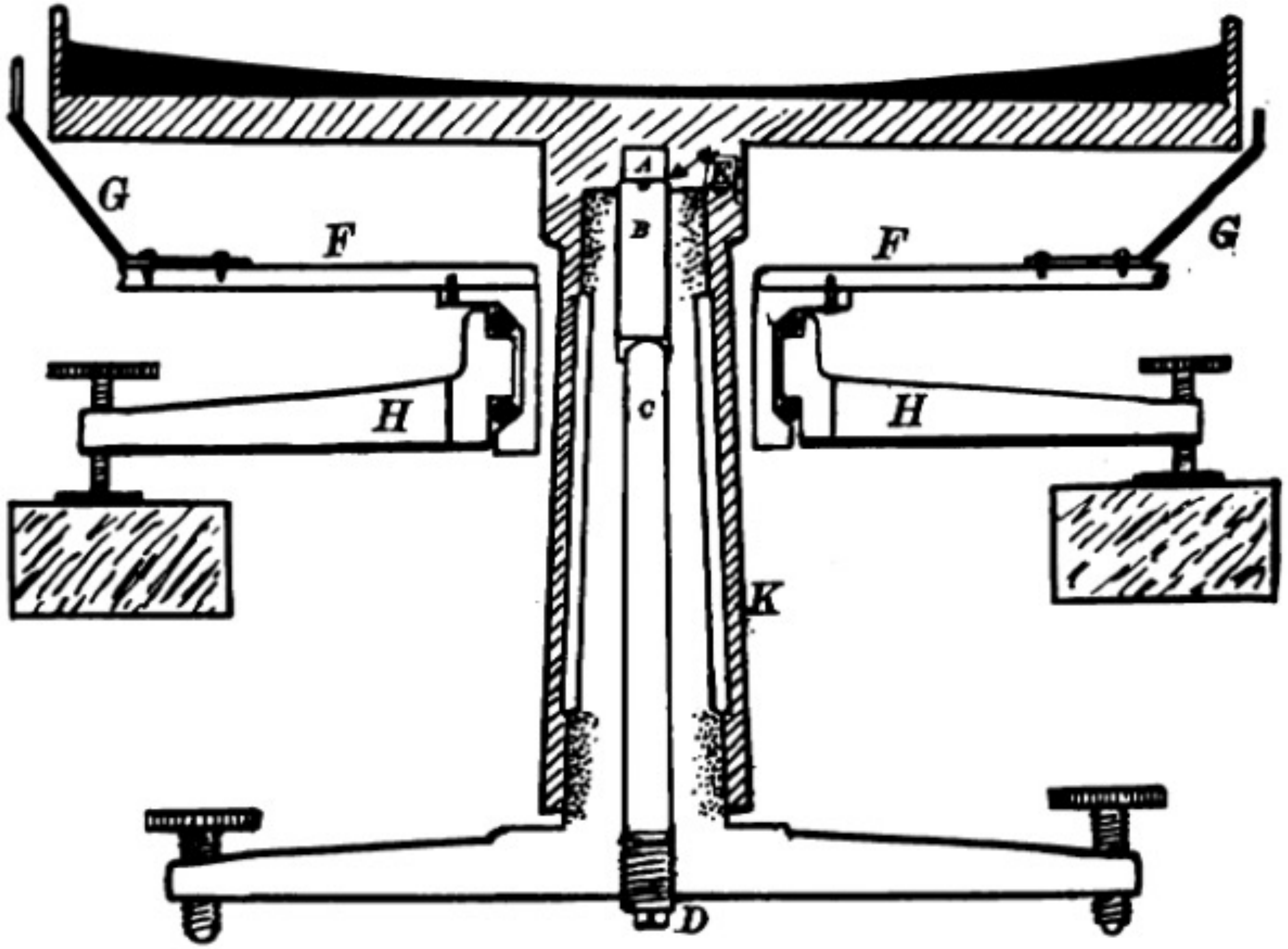


FIG. 1

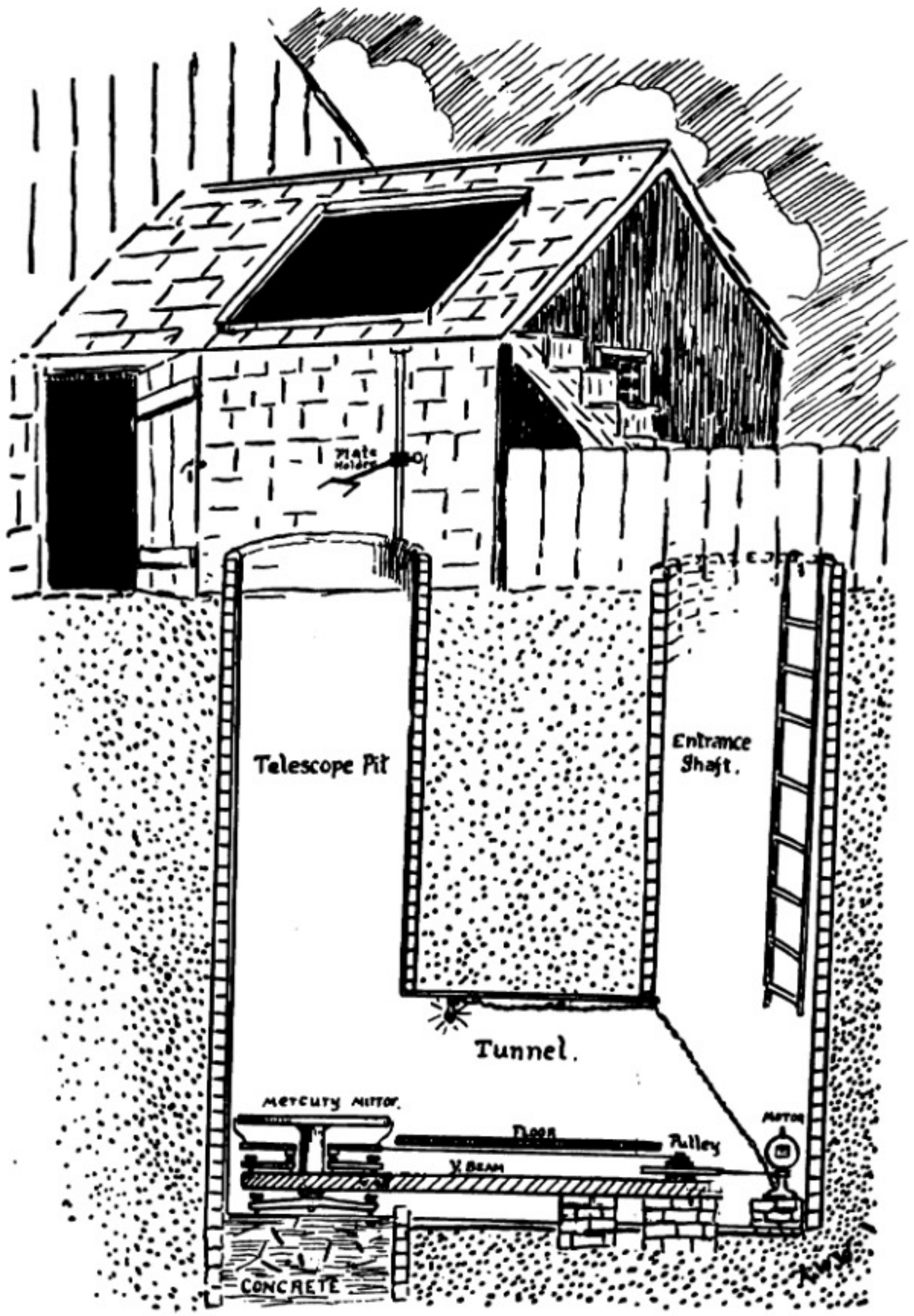


FIG. 5

Modern LMTs, 1982-1989

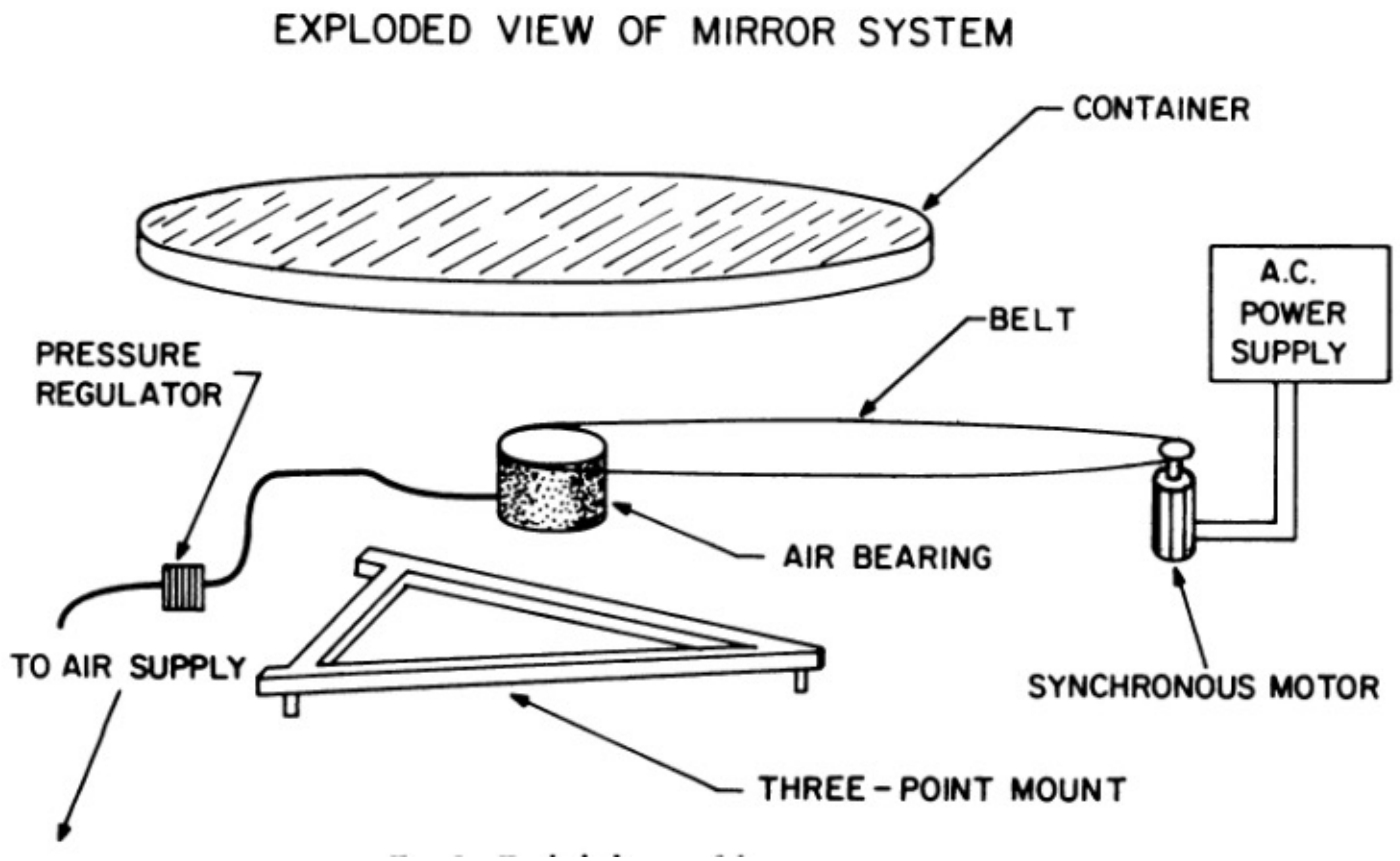
THE LIQUID-MIRROR TELESCOPE AS A VIABLE ASTRONOMICAL TOOL

BY ERMANNO F. BORRA
Département de physique, Observatoire du Mont Mégantic, Université Laval and Steward Observatory, University of Arizona

(*Received March 11, 1982, revised April 29, 1982*)

ABSTRACT

The surface of a rotating liquid takes the shape of a paraboloid. This fact can be used to build very large transit telescopes having as primary mirror a reflecting film of mercury. The practical aspects of this type of telescope are discussed. It is shown that a great deal of research can be done with the instrument, notwithstanding the fact that it is strictly a transit telescope and can only observe the zenith.



Ermann F. Borra, The Liquid Mirror Telescope as a Viable Astronomical Tool, J. Roy, Astron. Soc. Can, Vol. 76, No. 4, 1982

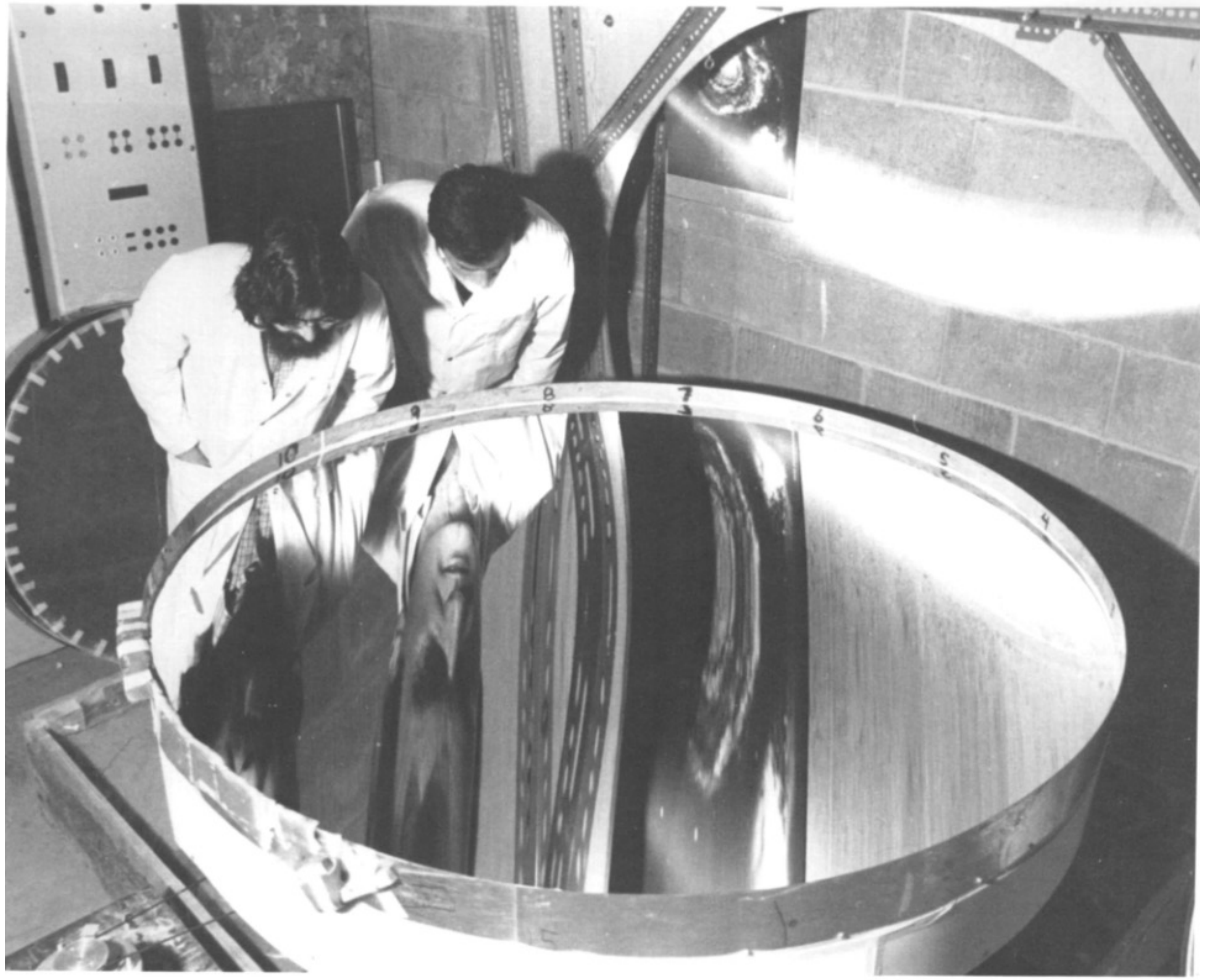


FIG. 1—Liquid mirror having a diameter of 1.65 meters and focal length of 1.5 meters.

First astronomical use of an LMT, 1989

THE ASTRONOMICAL JOURNAL VOLUME 97, NUMBER 3 MARCH 1989

A SEARCH FOR OPTICAL FLARES AND FLASHES WITH A LIQUID-MIRROR TELESCOPE

R. Content, E. F. Borra, M. J. Drinkwater, S. Poirier, E. Poisson, M. Beauchemin, E. Boily,
A. Gauthier, and L. M. Tremblay
Département de Physique, Université Laval, Québec, Québec G1K 7P4, Canada
Received 18 October 1988

ABSTRACT

We have used two liquid-mirror telescopes of 1.2 and 1 m diameters to search for optical phenomena that occur in the sky with short timescales (less than 2 min). We obtained a total of 130 hr of usable data. We did not find any event. This search shows that optical flashes and flares are rare events. Our data are useful for setting limits to the frequency of such events. The most noteworthy part of this work comes from the fact that this is the first time that a liquid mirror has been employed in a scientific project.

The Large Zenith Telescope

Publications of the Astronomical Society of the Pacific, **119**: 444–455, 2007 April

The Large Zenith Telescope: A 6 m Liquid-Mirror Telescope

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Mark K. Mulrooney
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Department of Astronomy, University of Arizona, Tucson, AZ
and
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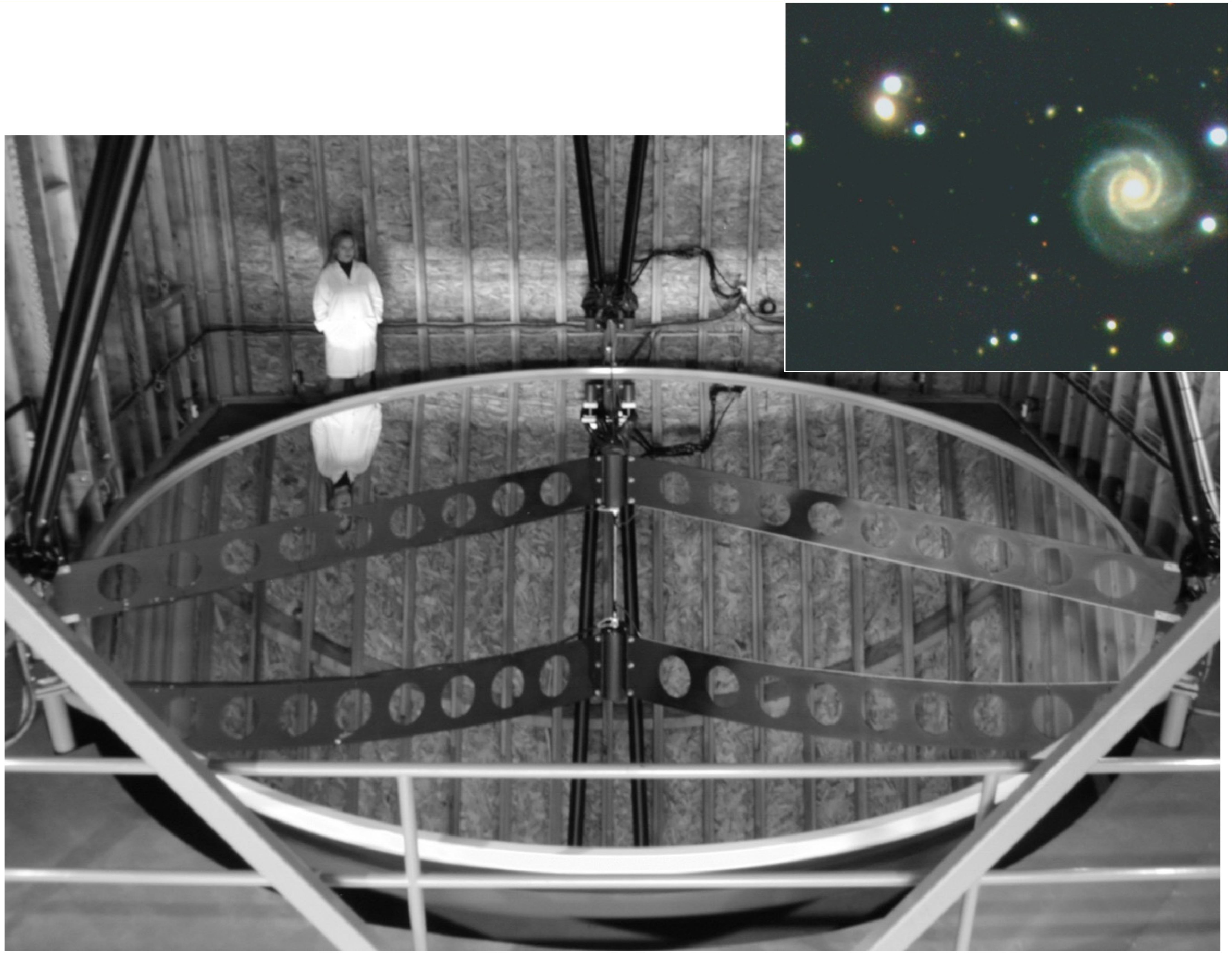
Diffraction Limited Design, LLC, Southington, CT

Received 2006 November 26; accepted 2007 March 6; published 2007 March 30

ABSTRACT. The Large Zenith Telescope is a 6 m optical telescope employing a rotating primary mirror coated with a film of liquid mercury. Located at an altitude of 400 m in the Coast Mountains of southwestern British Columbia, this telescope began regular operation in 2005 October. Equipped with a four-element Richardson prime-focus corrector and thinned 2048 × 2048 pixel drift-scanning CCD imaging camera, it is used for astronomical survey observations and also serves as an engineering test facility for further development of liquid-mirror technology. Built at a cost of less than $1 million dollars, it achieves an image quality and sensitivity comparable to that of a conventional telescope of equal aperture and is limited primarily by the astronomical quality of the site.



The 4m International LMT

Bulletin de la Société Royale des Sciences de Liège, Vol. 87, Actes de colloques, 2018, p. 68 - 79

The 4-m International Liquid Mirror Telescope

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"First Belgo-Indian Network for Astronomy & Astrophysics (BINA) workshop", held in Nainital (India), 15-18 November 2016

Analytical approach to low-gravity liquid interfaces

“The only rules that really matter are these:

What a man can do and what a man can't do”

Jack Sparrow

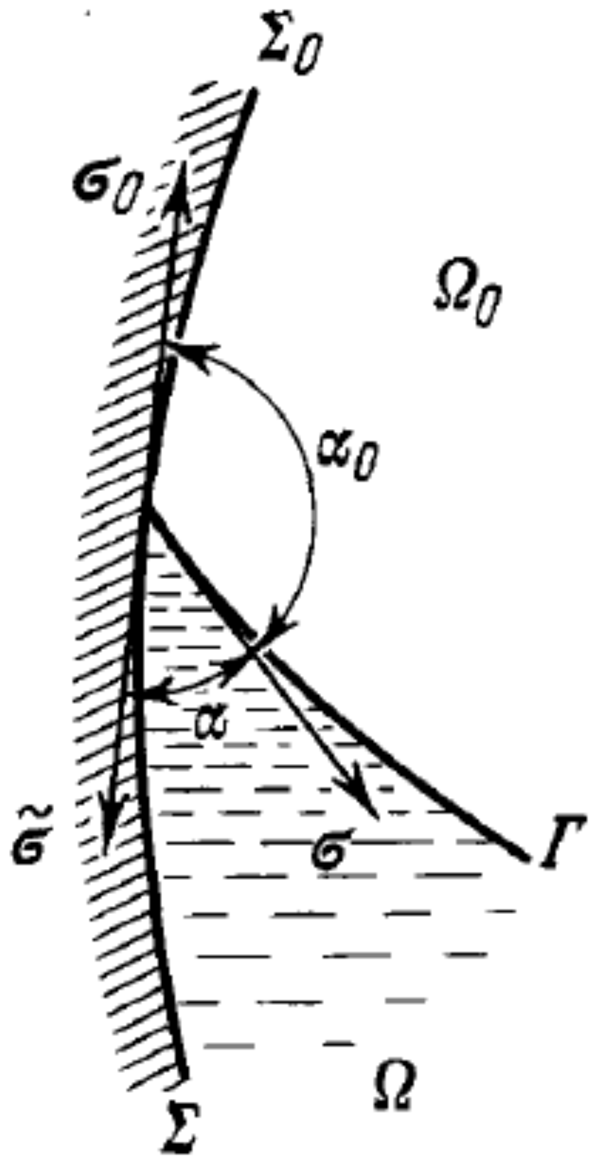
State of the art for microgravity mirrors

- There is one question that may have been overlooked:

Is it feasible to produce the surface profile we need in microgravity?

- Previously proposed solutions: high-viscosity liquid cycling, thermal fields, Lorentz forces, spherical mirrors, active correction, **ferrofluids**…
- Unfortunately, previous works on **ferrofluid-based liquid mirrors**…
  - Introduce **non-scalable** magnetic configurations in terms of geometry, power, or propellant management (e.g. continuous thrust)
  - Employ **questionable fluid and electromagnetic models**: no fluid-magnetic coupling, completely ignore surface tension, do not consider important disturbance factors, do not set a clear target/application, etc.
- Large-radius **ground telescopes** are limited by self-induced winds

The axisymmetric meniscus



Equilibrium liquid-gas interface (meniscus)

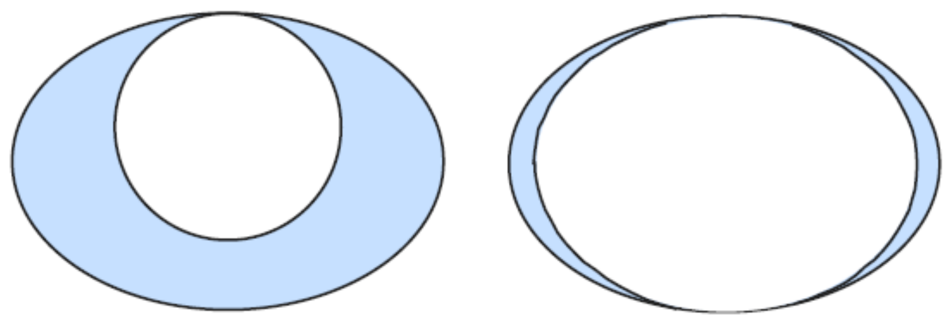
$$(rz')' = rr'\left(\frac{\rho}{\sigma}\Pi - \frac{p_n}{\sigma} + c\right)$$

$$r'r'' + z'z'' = 0$$

Mass-force potential

$$\Pi = \cancel{g}z - \frac{\omega^2 r^2}{2}$$

Microgravity



oblate spheroidal tanks

Solution:

- No rotation ($\omega = 0$): Constant curvature (sphere) → **Valid for spherical mirrors**

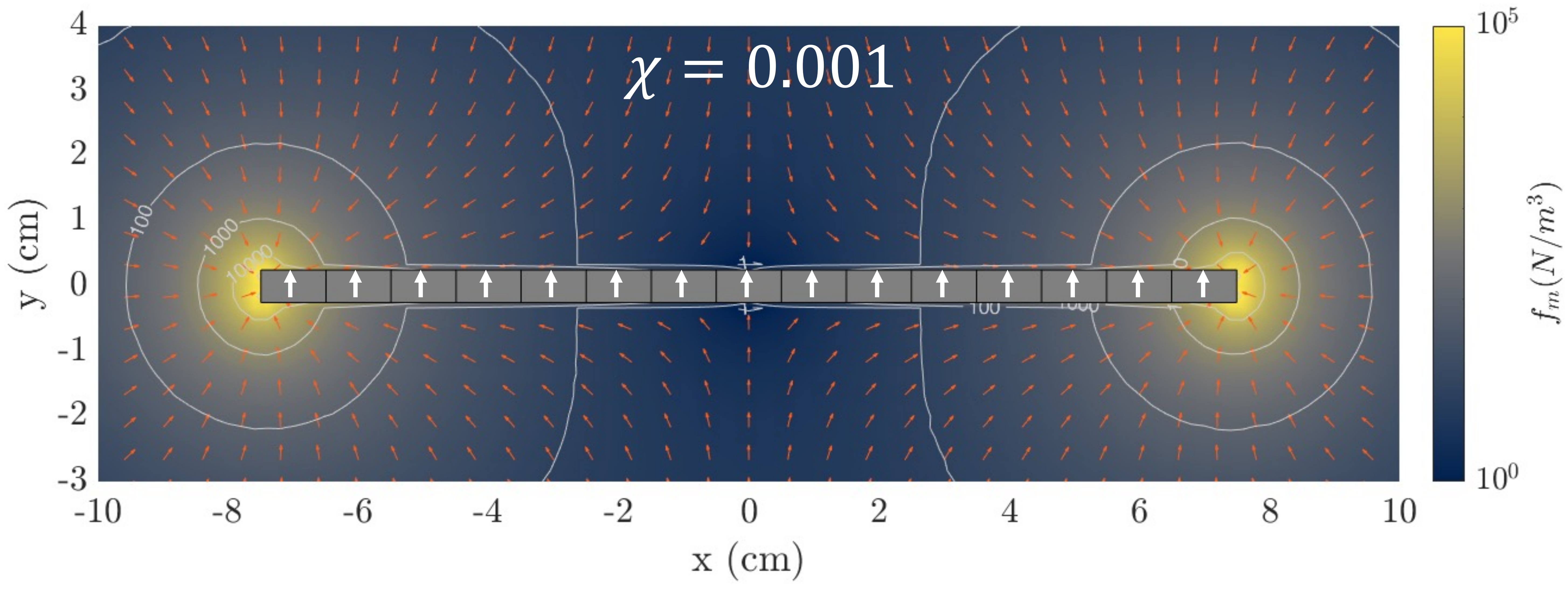
- Rotation ($\omega \neq 0$): $$\zeta = \rho_1\sqrt{h}\{E(\psi,l) - E(\psi_0,l) + [2/(\rho_1^3 h) - \tfrac{1}{2}]\cdot[F(\psi,l) - F(\psi_0,l)] - \sqrt{1-l^2\sin^2\psi}\tan(\psi/2) + \sqrt{1-l^2\sin^2\psi_0}\tan(\psi_0/2)\}.$$

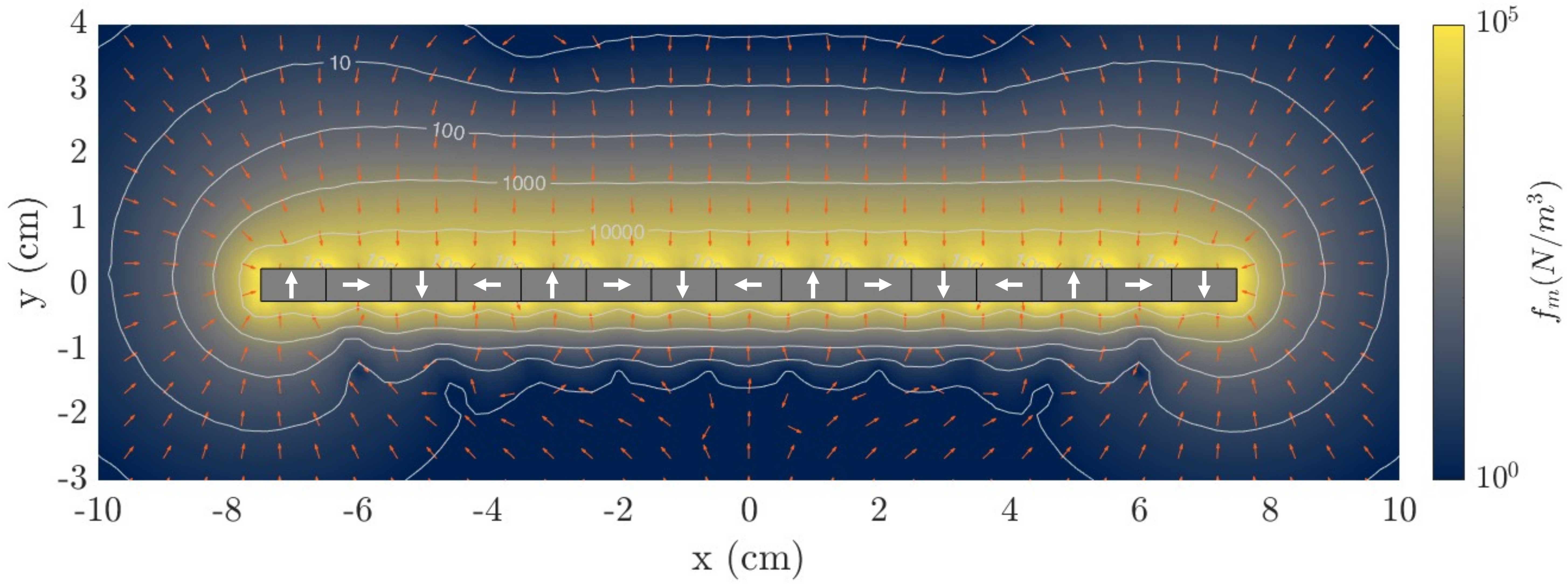
- Axisymmetric liquid interfaces **naturally** adopt spherical profiles in microgravity
- We need **additional body forces** to generate paraboloid surfaces

Using ferrofluids

An alternative that may solve the problem **in 3 steps**

Step 1: Generating a suitable force field





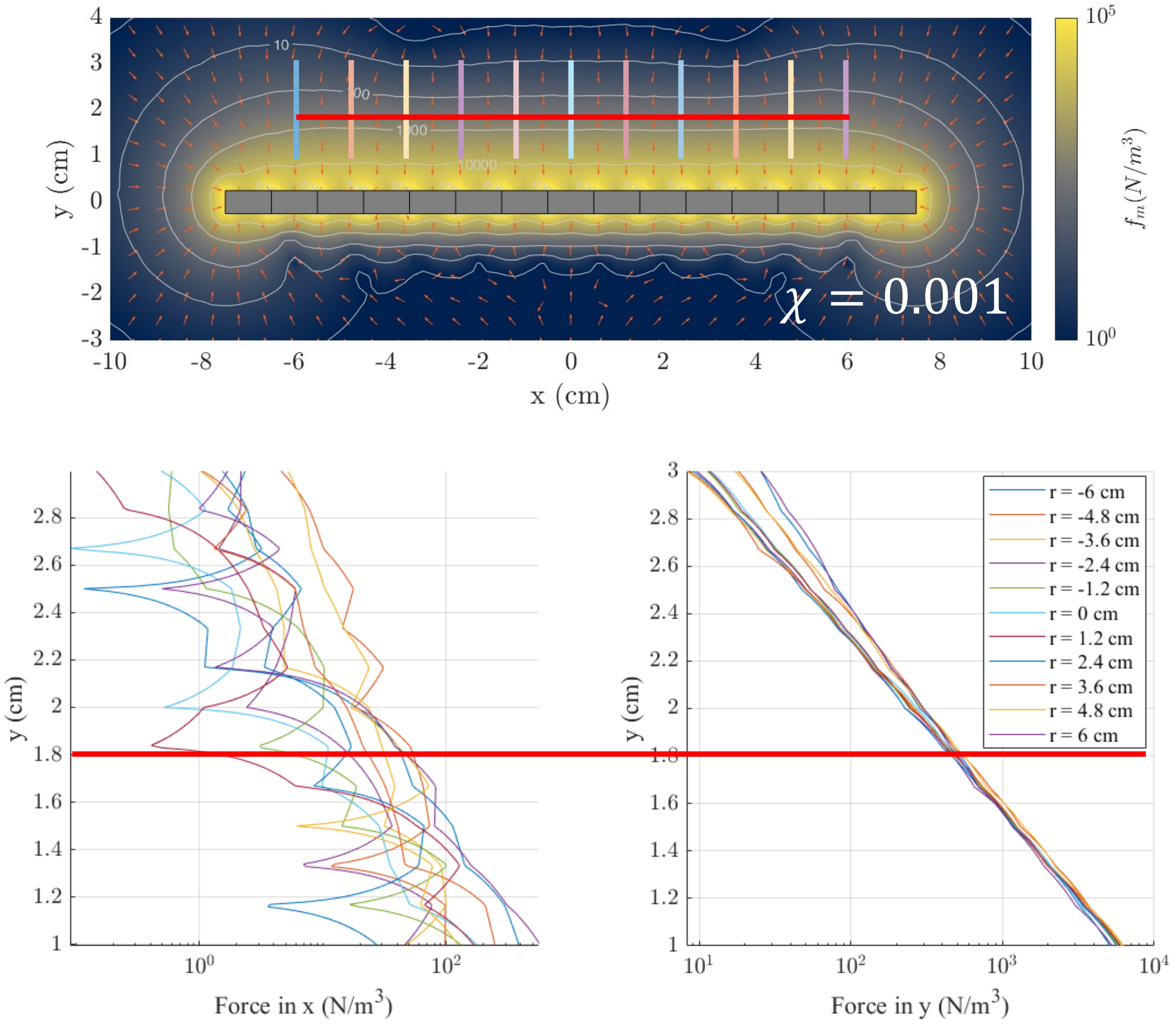
“Standard” magnet

- Uniform magnetization
- Analogous to what has already been proposed
- Inhomogeneous field
- Force “concentrated” in extremes

Halbach Array

- Oriented magnetization vectors
- Quasi-uniform force on one axis
- Can be simplified to alternate polarity (simpler config., lower performance)
- Scalable
- Readily available (N52 magnets)
- Tunable, with some work

Step 1: Generating a suitable force field



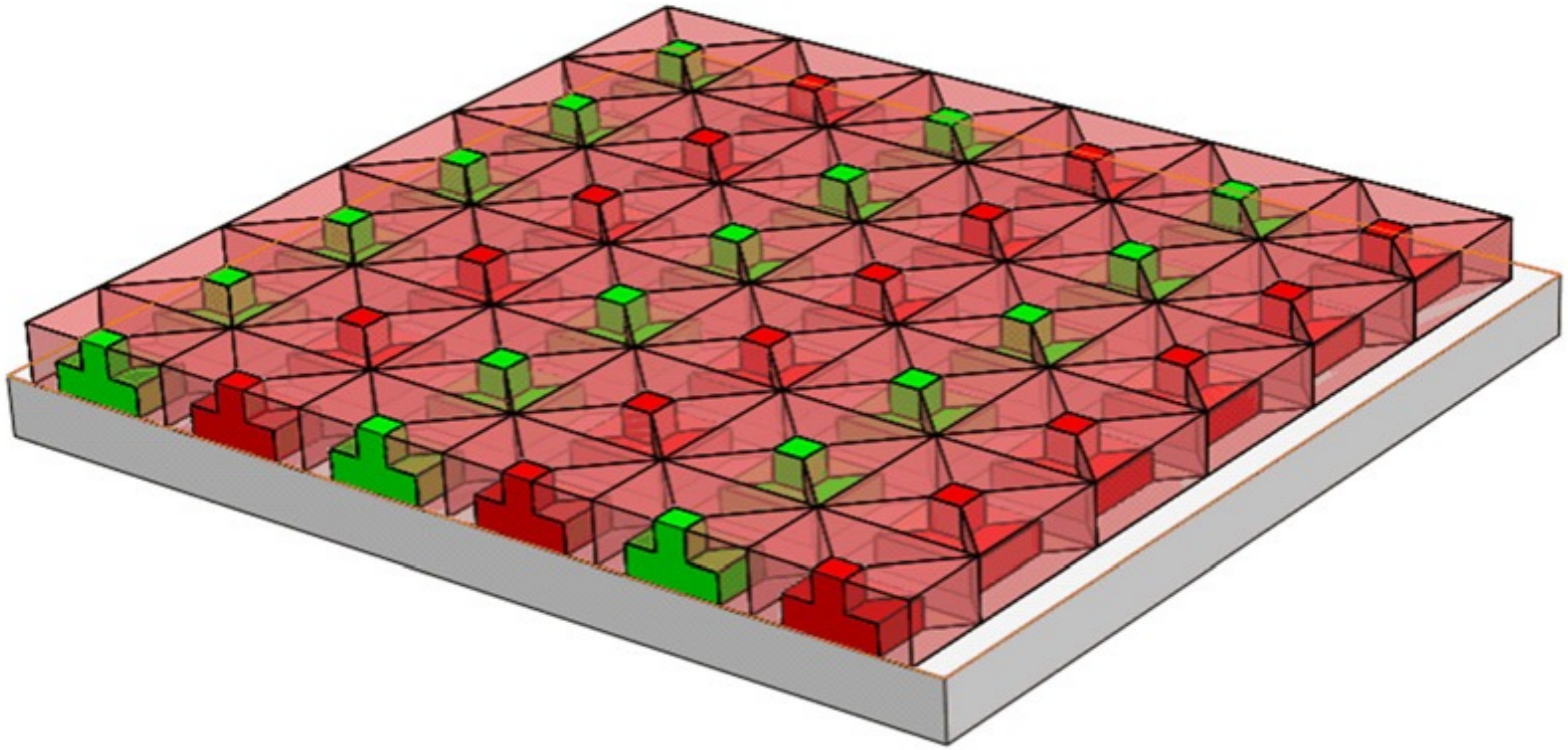
Magnetic forces in Halbach array

- Very significant $(10^{-2} - 1 g_0)$
- Homogeneous decay in y…
- …of the form $F_y = k_1{}' e^{-k_2' y}$
- Disturbances in x:
  - Almost negligible
  - 1 order of magnitude smaller that F_y
  - Can be reduced by design (e.g. using smaller magnets)

Halbach arrays provide a means to homogenize the magnetic force potential distribution on ferrofluids

Step 1: Generating a suitable force field

… and all of this applies to 2D problems as well

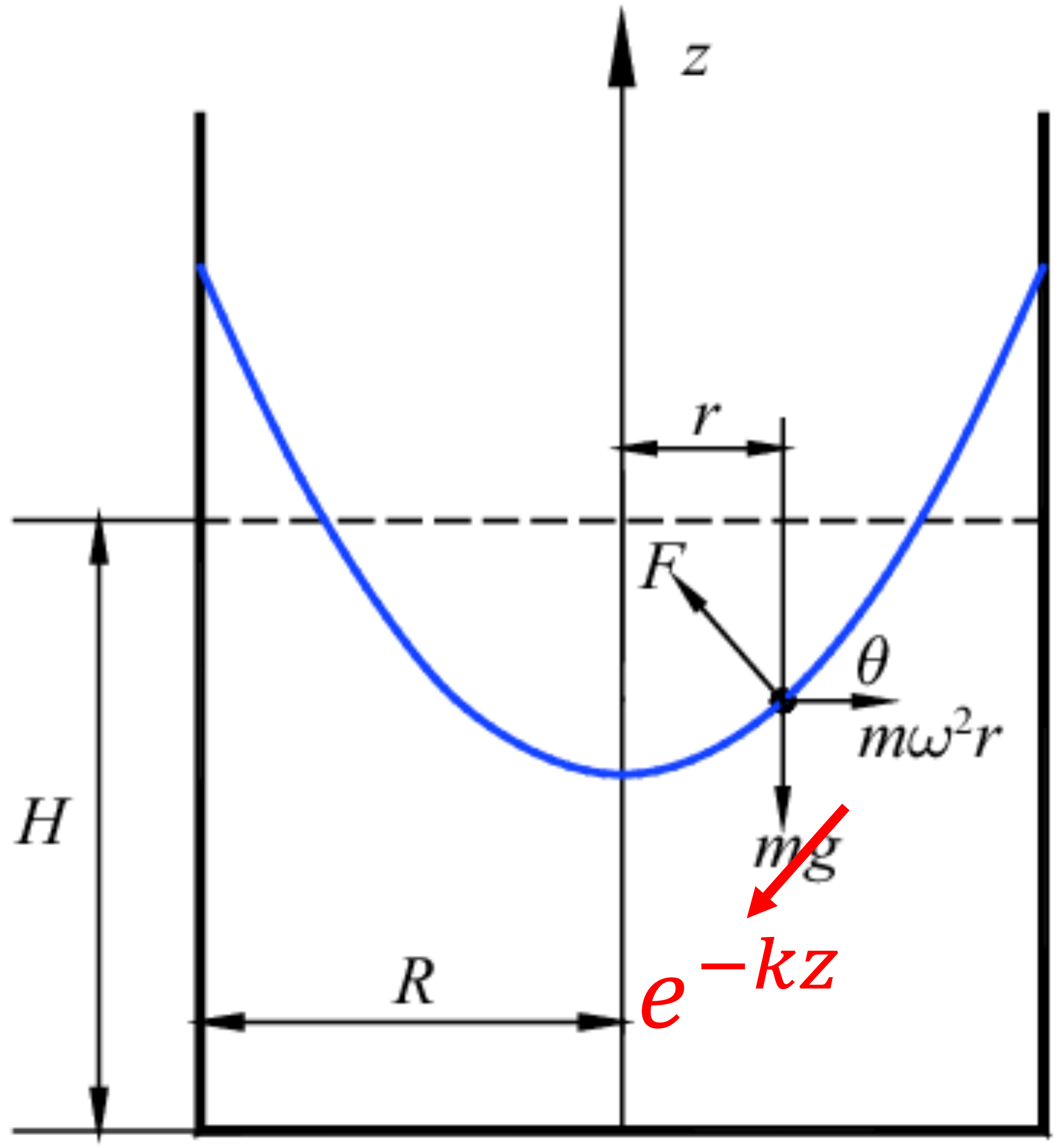


Zhang et al., "Analysis and comparison of two **two-dimensional Halbach permanent magnet arrays** for magnetically levitated planar motor", Journal of Applied Physics 115, 17E704, 2014

Step 2: Exploiting the force field

Strategy 1: Artificially-induced gravity using Halbach arrays + rotation

Non-capillary



$$z(k_1 e^{-k_2 z}) = \frac{\rho \omega^2 r^2}{2}$$

Capillary

Equilibrium liquid-gas interface (meniscus)

$$\left.\begin{aligned} (rz')' &= rr'\left(\frac{\rho}{\sigma}\Pi - \frac{p_n}{\sigma} + c\right) \\ r'r'' + z'z'' &= 0 \end{aligned}\right]$$

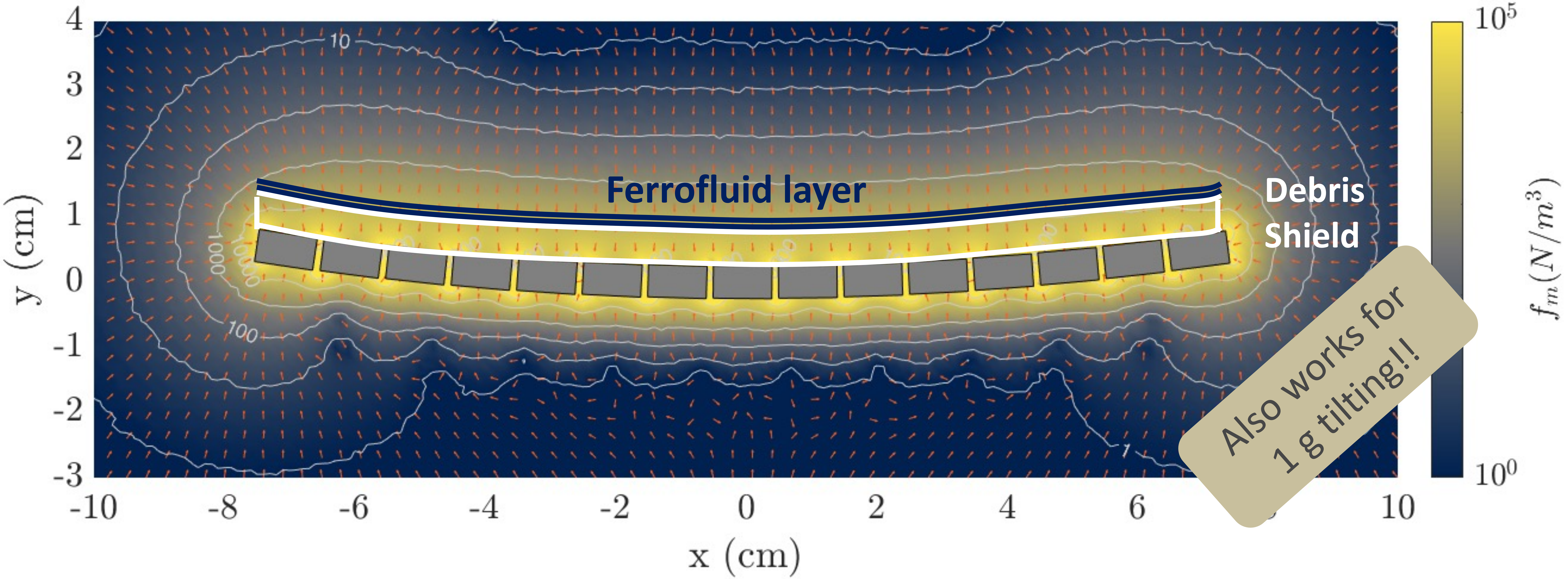
Mass-force potential (including magnetic terms)

$$\Pi = gz - \frac{\omega^2 r^2}{2} + \mu_0 \int_0^H M dH$$

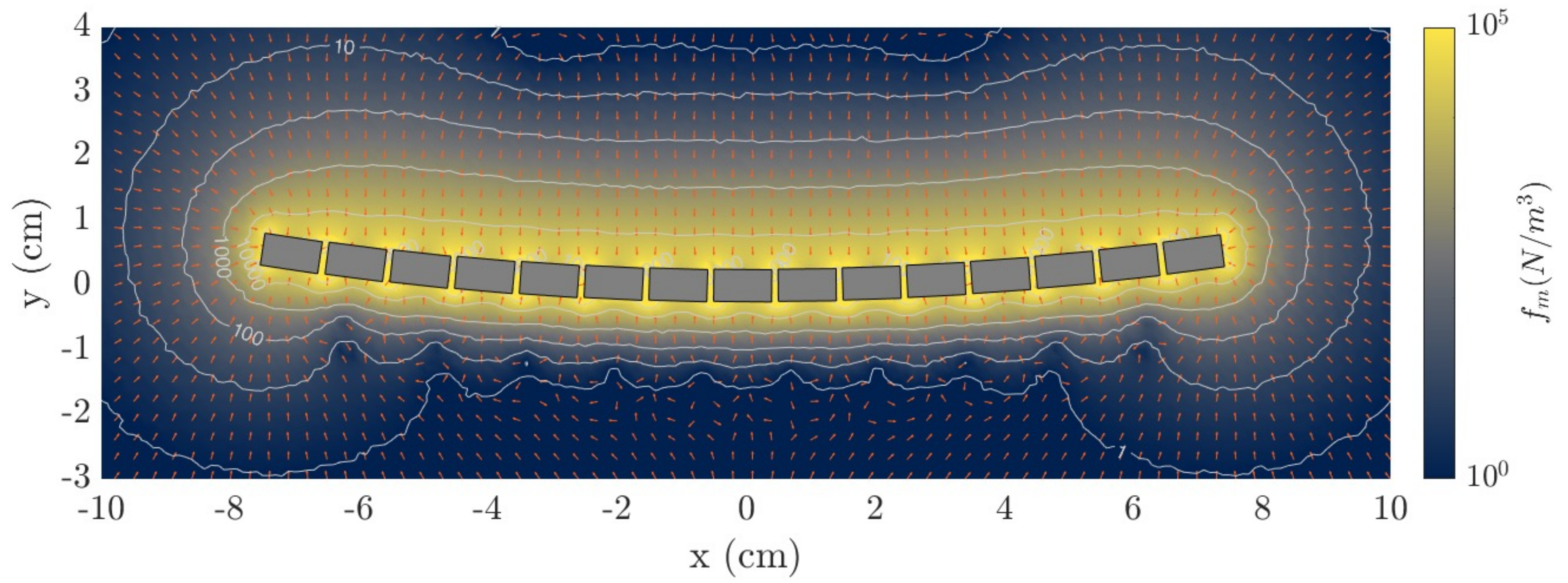
Only feasible for **small** deformations
(i.e. large focal lengths!)

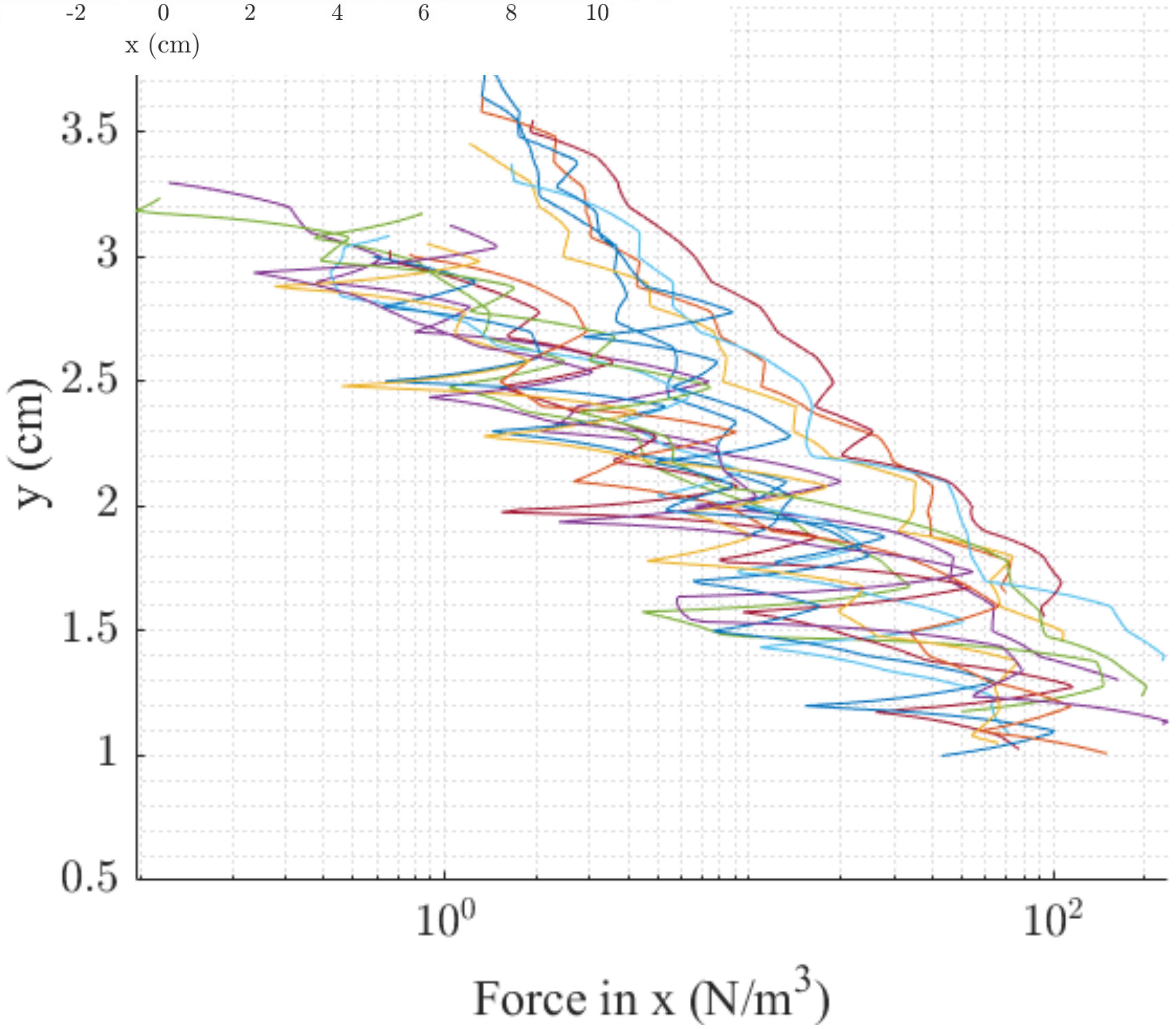
Step 2: Exploiting the force field

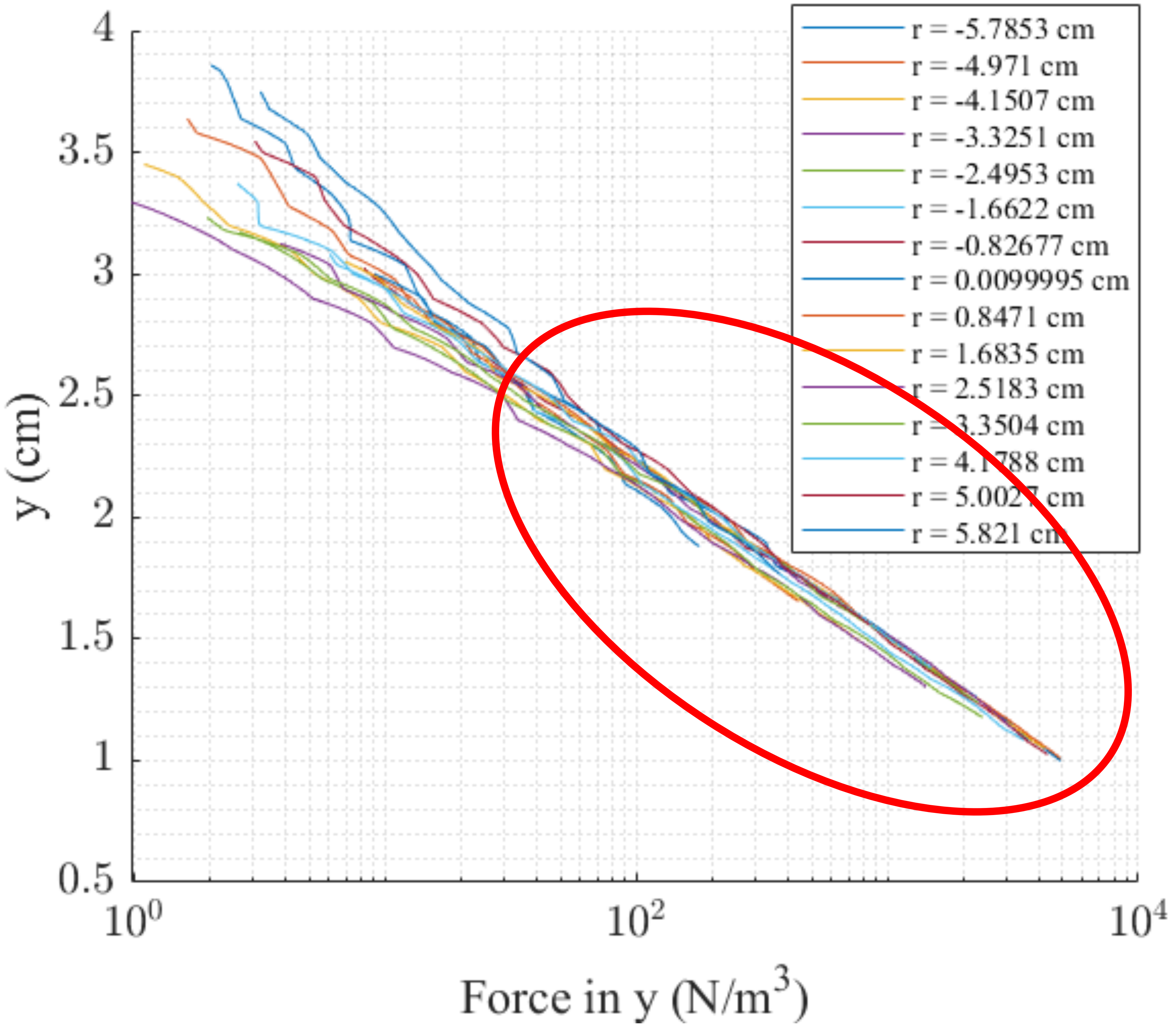
Strategy 2: Equipotential tuned surface using Halbach arrays. **No rotation**



Force field of tilted Halbach magnet array







Step 3: Finding a suitable ferrofluid

FerroTec
Ferrotec Holdings Corporation

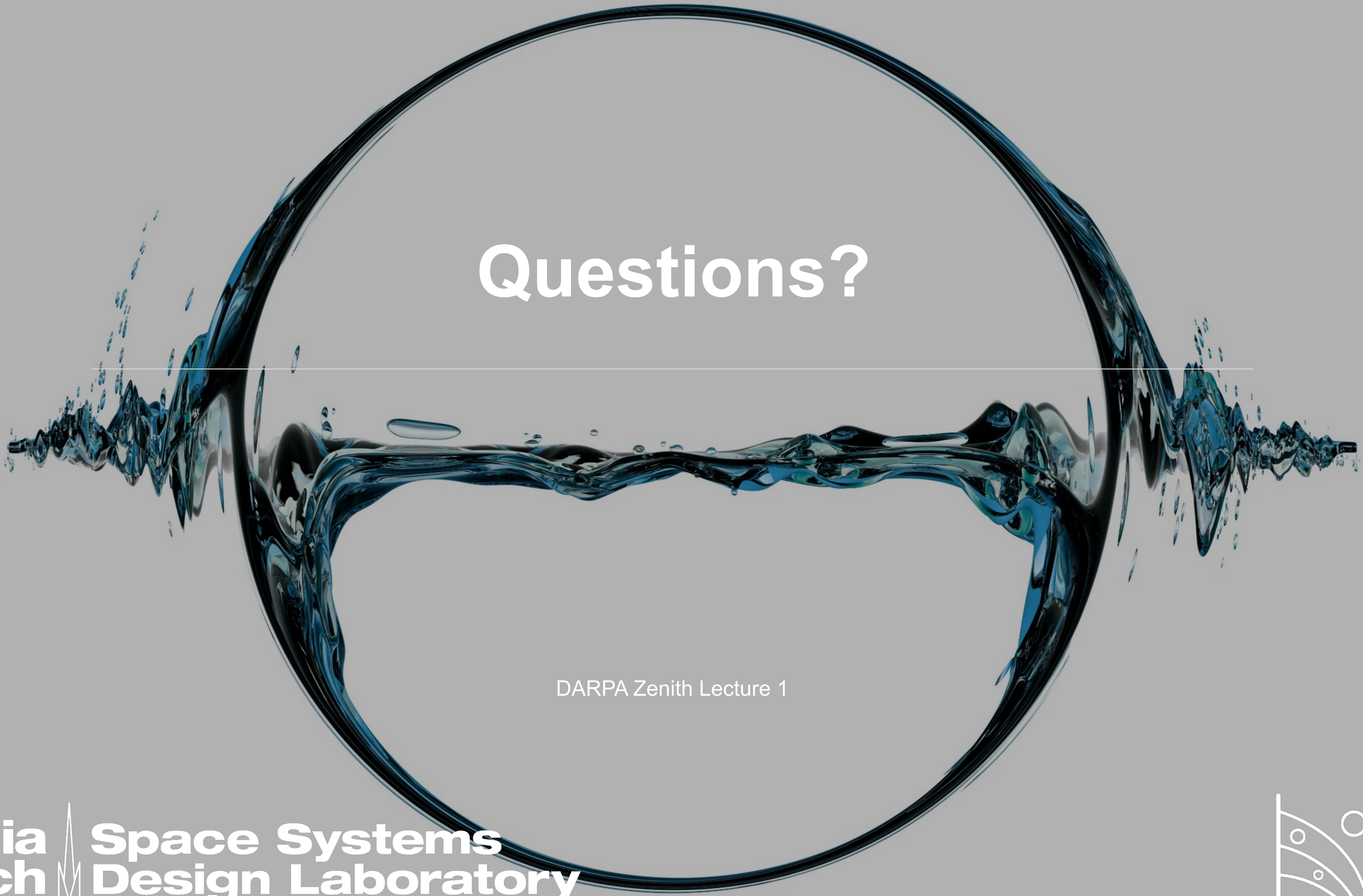
Task 1:

- Characterize optical properties of existing Vacuum Seal Grade (VSG) ferrofluids
- Test outgassing in application context
- Define operational T range (usually < 70º-100º C)

Task 2:

- Explore optically enhanced ferrofluids (e.g. metal-based, metal liquid-like films, etc.)
- Characterize optical properties

Questions?



DARPA Zenith Lecture 1