Smart Materials Nanocomposite Optical Mirrors

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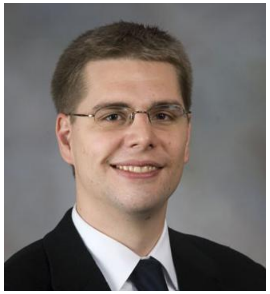
Lightweight Telescopes, Inc.

NASA SBIR NNX15CM63P



Co-Investigators

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JHU

Christopher
Williams VT

Joel Penelon
Innolab LLC

Summary

We report development of lightweight telescope mirrors using nanocomposites consisting of epoxy polymers, carbon nanotubes, and other ingredients

<u>What we have accomplished</u>

- Demonstrate the principle of ‘smart’ active optics with integrated actuation
- Build a working telescope with nanocomposite mirror
- Use advanced numerical modeling and 3D printing to fabricate lightweight mirrors

Active Optics – An Introduction

Historically as telescopes became bigger, the mirrors became thicker and more massive. Until a point was reached where this approach was no longer effective

Traditional telescopes were massive, like sumo wrestlers
Source:http://japanese.lingualift.com/blog/what-sumo-eat-wrestlers-diet/

The BTA-6 telescope* (circa 1976) has the biggest rigid mirror ever made.
Mass 42 tons D=6m, t=65cm, D/t ratio = 9
* Special Astrophysical Obs., Russian Academy of Sciences

Transition to Active Optics

Beginning in the 1980s, all large telescopes use thin mirrors. External sensors and actuators are used to flex the mirrors to maintain optical figure ('active optics')

Modern telescopes are built more like ballerinas. The emphasis is on flexibility and agility.

Source: https://encrypted-tbn3.gstatic.com/images?q=tbn:ANd9GcSJxcclv-Gt60ZYMARCtIiDhCxfu-VonGna1Jble02rZsI9qnmXgg

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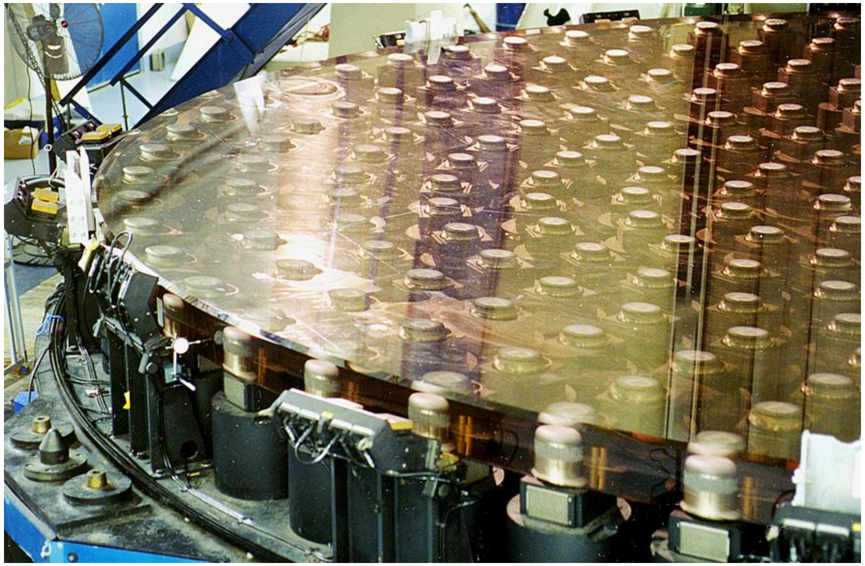
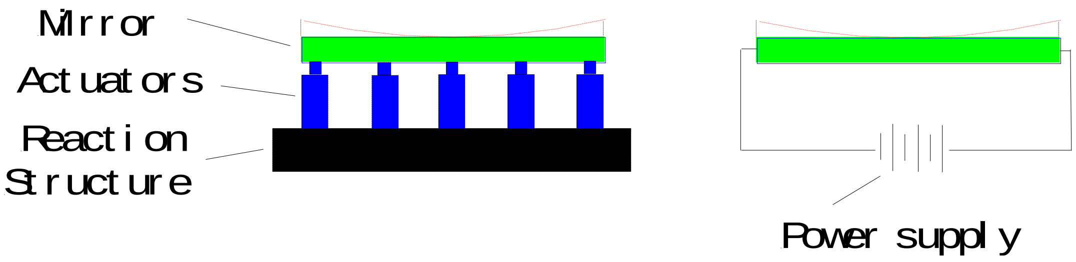


Thin, flexible (=active) mirror of the Subaru telescope*. Note the thin (20cm) mirror.
<u>Also note, however, the array of actuators and the support structure</u>.
Mass 22.8 tons Diameter 8.3m D/t ratio = 42

*Observatory of the NAOJ on Mauna Kea, Hawaii.

Our Idea - Use nano particles to make 'smart' telescope mirrors

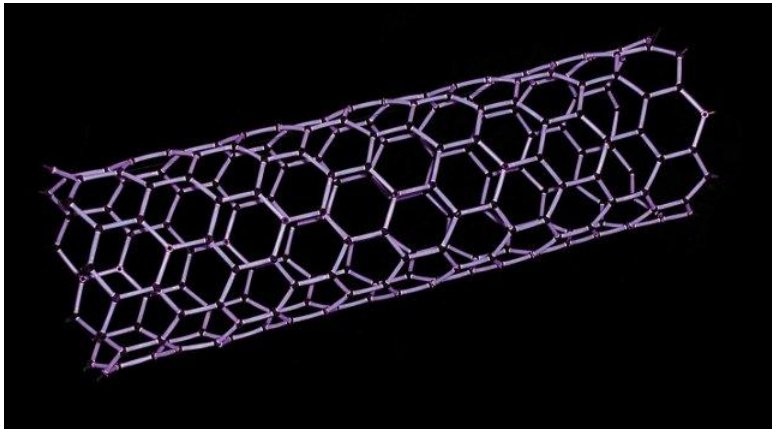


From this → To this

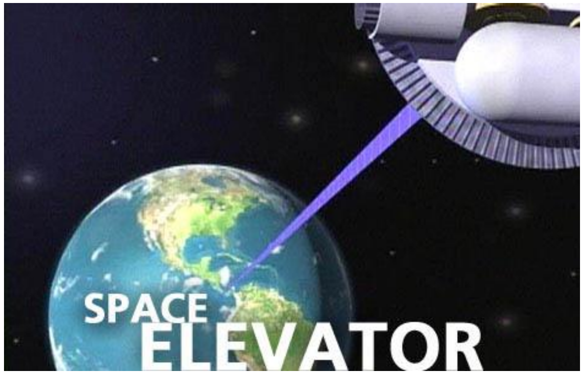
We can go one step further in active optics
Source:http://fc07.deviantart.net/fs71/f/2011/041/0/d/tinkerbell_by_noepinklove-d398enh.jpg

****Smart materials** are designed materials that have one or more properties (such as shape, stiffness, viscosity, etc.) that can be significantly changed in a controlled fashion by external stimuli, such as stress, temperature, moisture, electric or magnetic fields.*

Carbon Nanotubes – A Really Amazing Material



http://www.azonano.com/images/Article_Images/ImageForArticle_3158(1).jpg

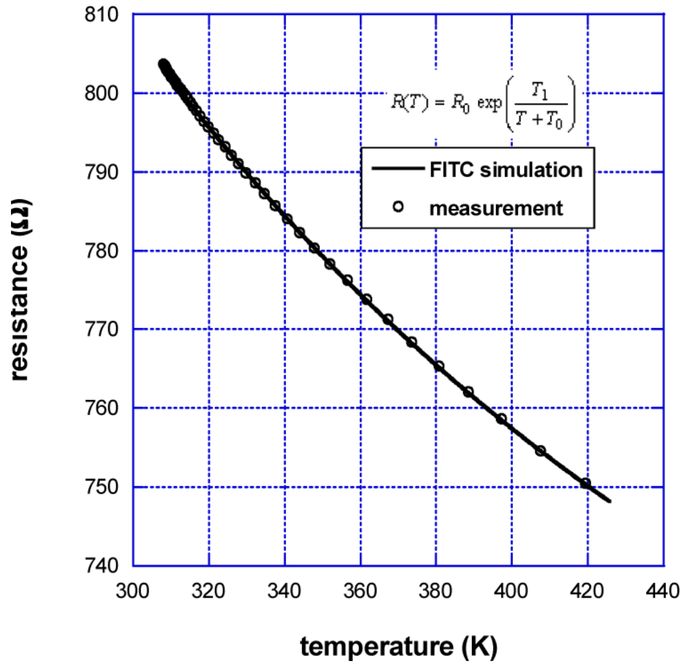


http://www.freewebs.com/lunarjacobsladder/space_elevator01.jpg

Discovered by Russian (Radushkevich 1952) and Japanese (Iijima 1991) scientists
Strongest and stiffest materials known: Specific strength 48000 vs Carbon steel 154 ($kN\text{-}m\text{-}kg^{-1}$)
Extremely high electrical conductivity ~1000X copper
High thermal conductivity ~10X copper
Huge number of applications – ships, wind turbines, baseball bats, surfboards, hockey sticks, skis, supercapacitors, etc.

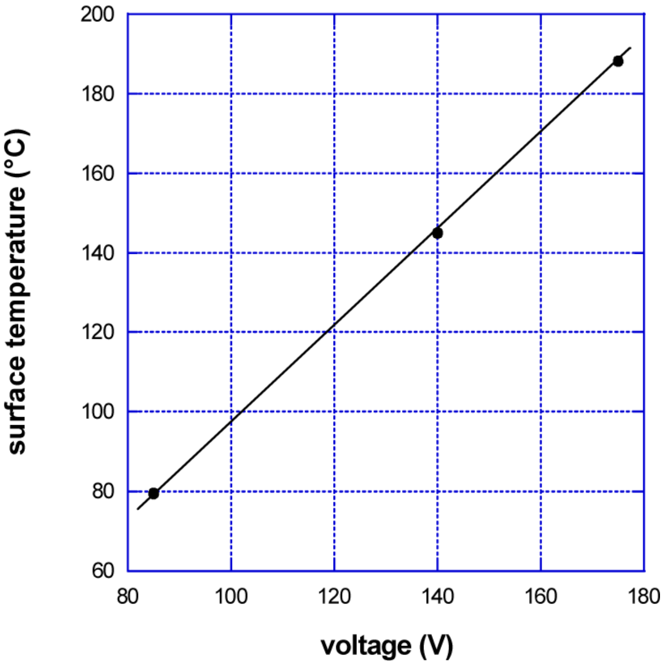
Carbon Nanotube/Epoxy as a Smart Material

For sensing



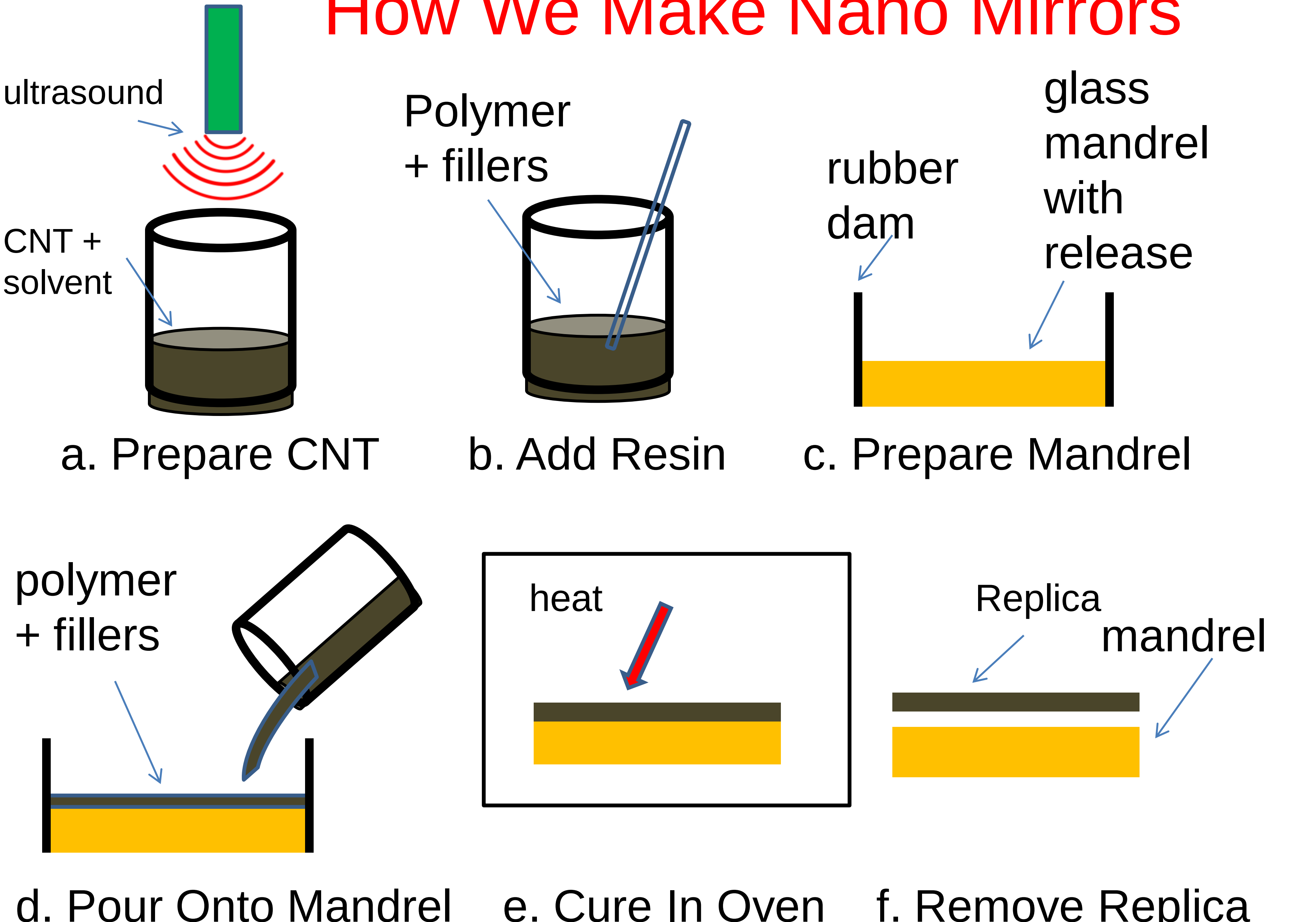
The temperature of CNT/E can be sensed by measuring its resistance. Source : Neitzert et al. IEEE Trans. Nanotech 10, No.4, 2011

For actuation

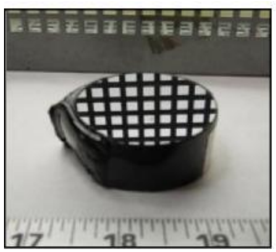
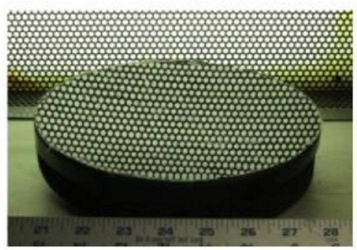
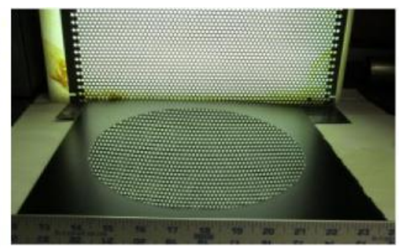


Applying power to CNT/E causes heating, thermal expansion, and change in optical figure.
Source: Neitzert et al. 2011

How We Make Nano Mirrors

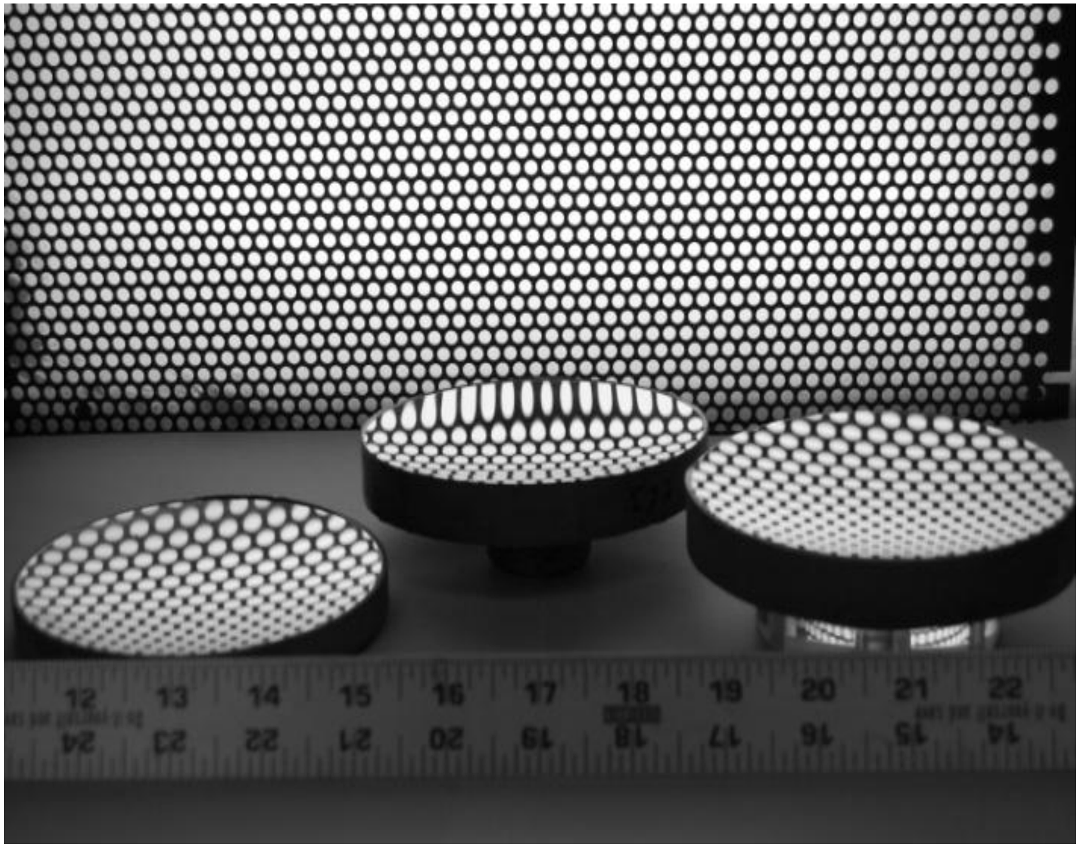


We have made nanocomposite mirrors in many forms

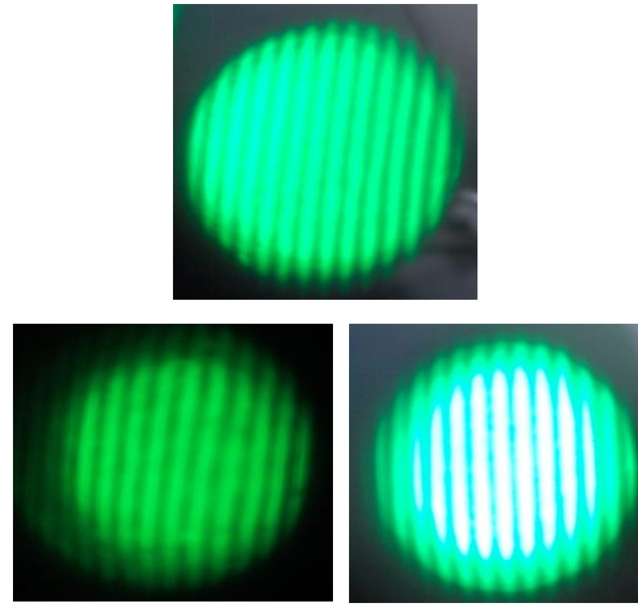





Diameter	5-cm	20-cm	25 cm	30 cm
Thickness	1 cm	3 mm + 5 cm	2 mm	4 cm
Type	homogeneous	carbon foam	adaptive mirror	spincast

Replication is a powerful technique for making multiple identical mirrors



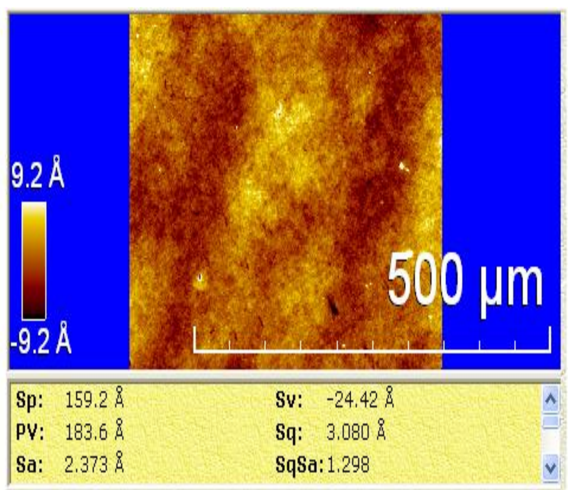
A set of three 11.4 cm diameter mirrors made from the same mandrel

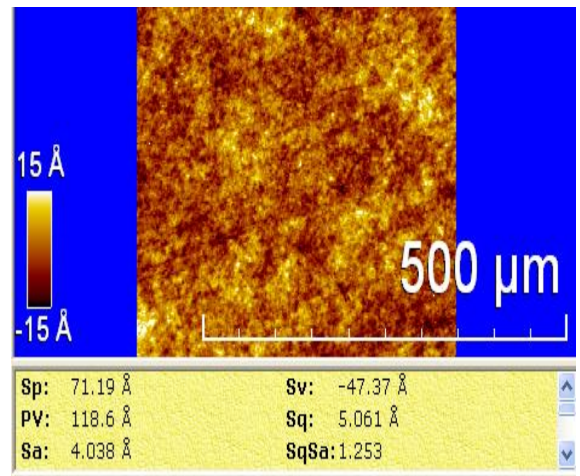


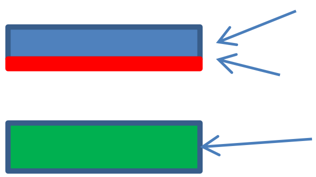
Ronchigrams showing excellent optical figures

We Can Make Supersmooth Mirrors

We have developed a process to fabricate mirrors with extremely smooth surfaces at very low cost







CNT/E
neat resin
mandrel

Surface smoothness of float glass mandrel ~3Å

Surface smoothness of 2 layer CNT/E replica is ~5Å

This technique can potentially make supersmooth mirrors of up to ~3 meter aperture

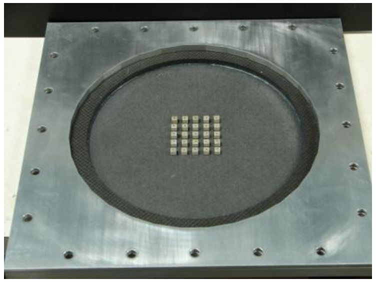
We Have Made Thin Deformable (Adaptive) CNT/E Mirrors

DM using PMN (lead manganese niobate) actuators for their low voltage, large force, and low hysteresis.

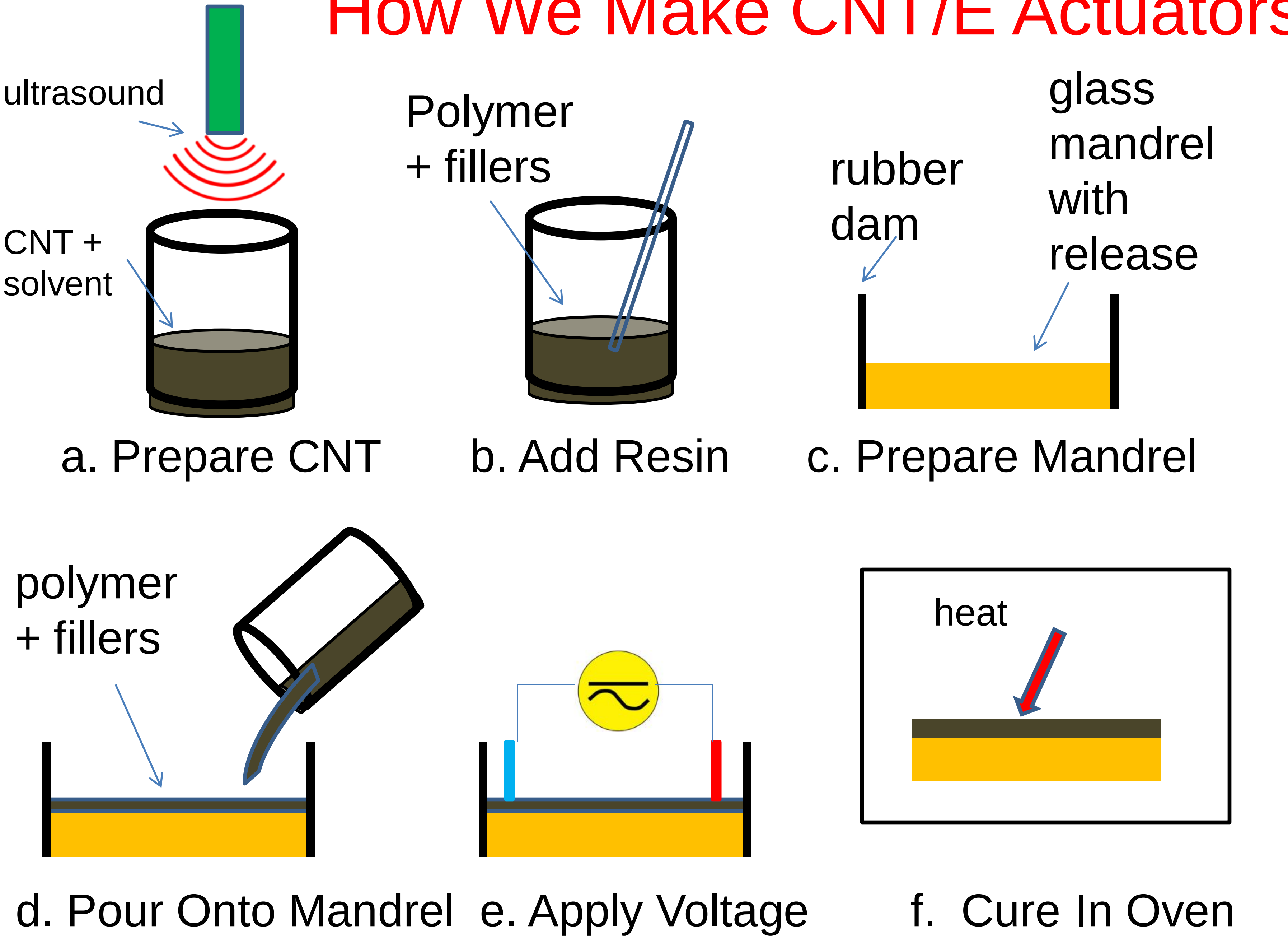
The actuator specs are:

- Mfr -TRS Ceramics, State College, PA
- Type - electrostrictive multilayer, PMN-38
- Size - 5 x 5 x 5 mm
- Composition - PMN-38
- Voltage - 0 to 200V
- Displacement - 5 um (20 um possible)
- Capacitance -1.4 uF
- Bandwidth- >100 Khz
- Temp range -10 to 50 C
- Cost - <$30 each

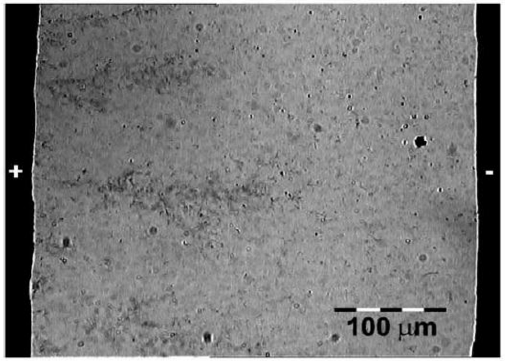
Above: Front side of a CNT/E deformable mirror
Right: Backside of mirror showing actuators



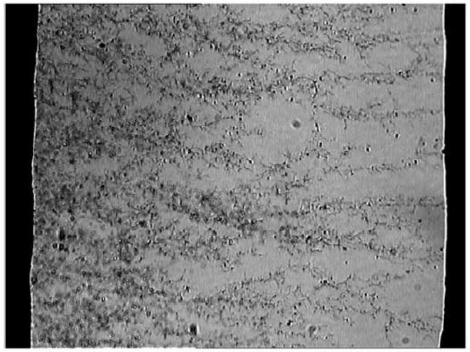
How We Make CNT/E Actuators



CNT Networks Enable Actuating Structures

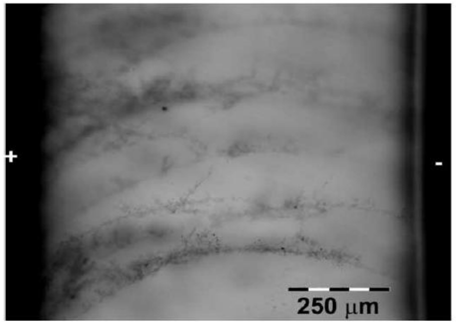


5 min

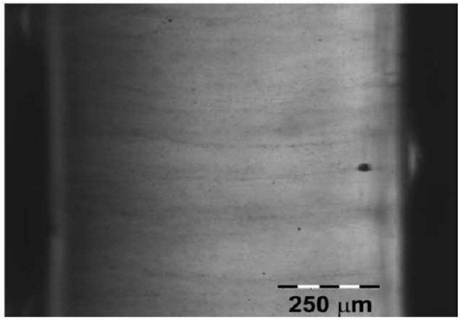


240 min

CNT networks are formed when an electric field is applied to carbon nanotubes in an uncured solution



Network formed by DC field in cured epoxy

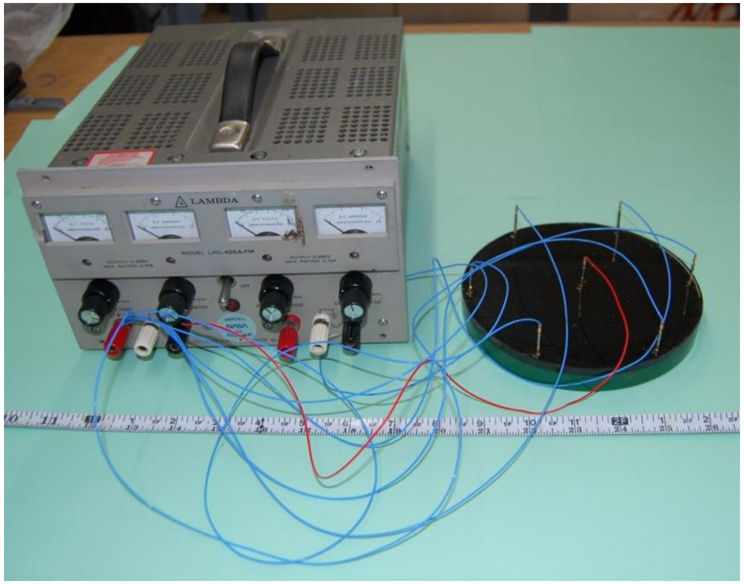


Network formed by AC field in cured epoxy

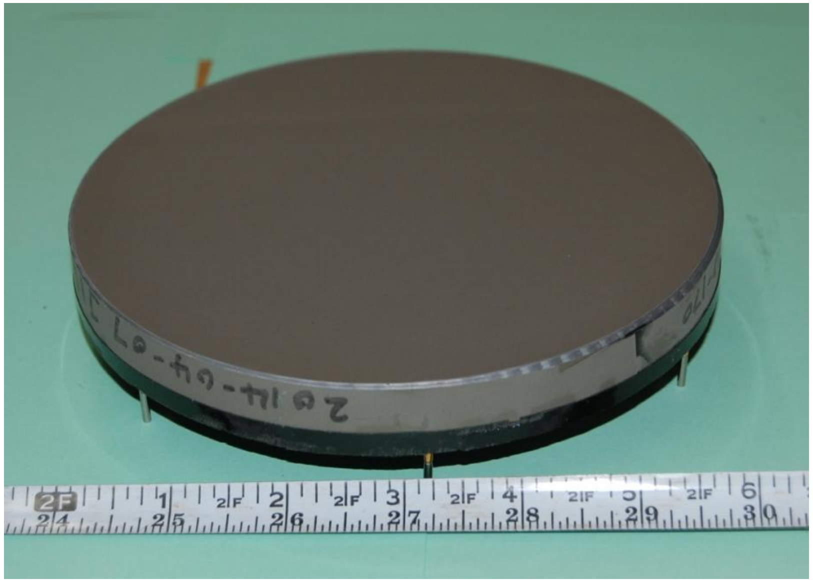
The formation of these 'reticulated' networks also make the CNT/E stiffer

Ref: Martin et. al. (2005) Polymer 46, 877-886.

A mirror with CNT/E actuating layer



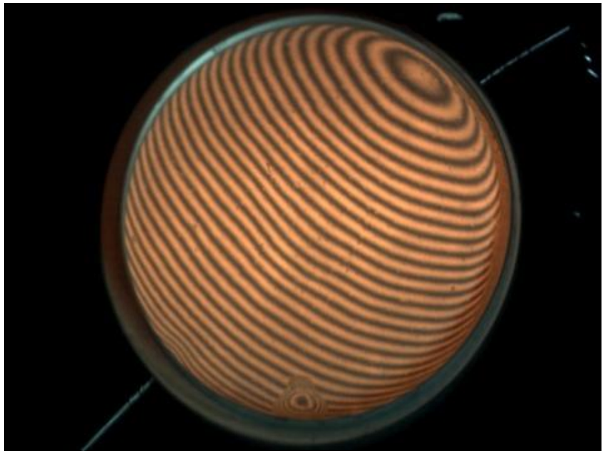
Backside View of Mirror



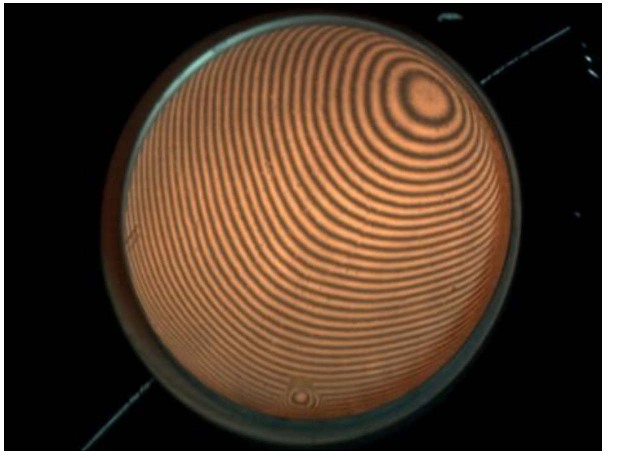
Front Side View

This is one of our recent samples. Note the two colors indicating a two layer structure

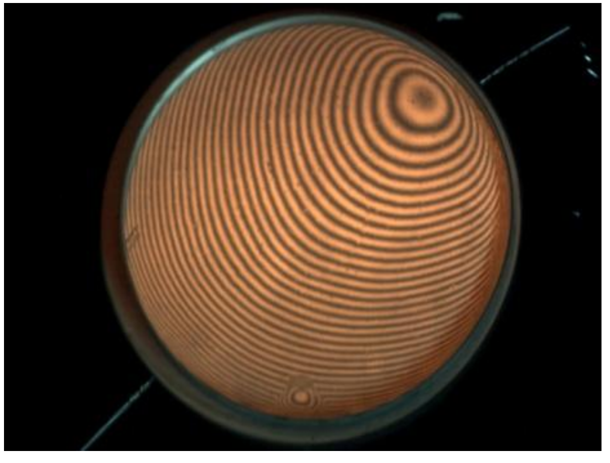
Applying a voltage to change mirror figure



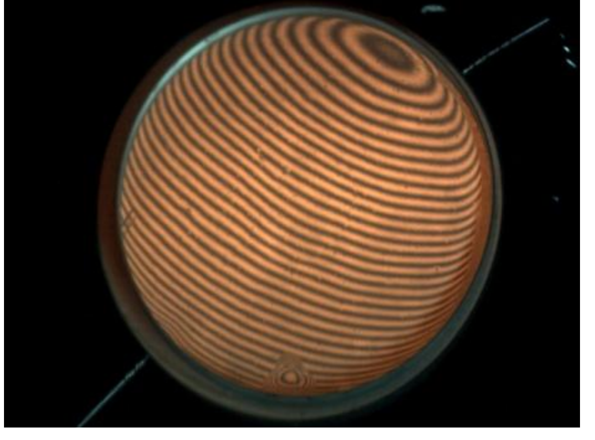
1 Power off t=0



2 power on t=14 min



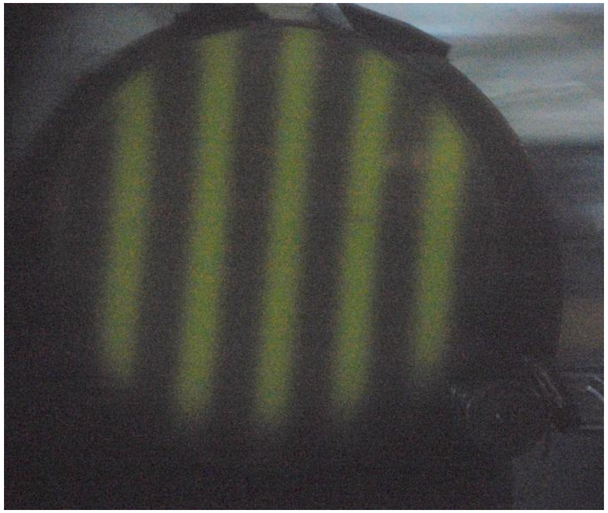
3 Power on t=18m

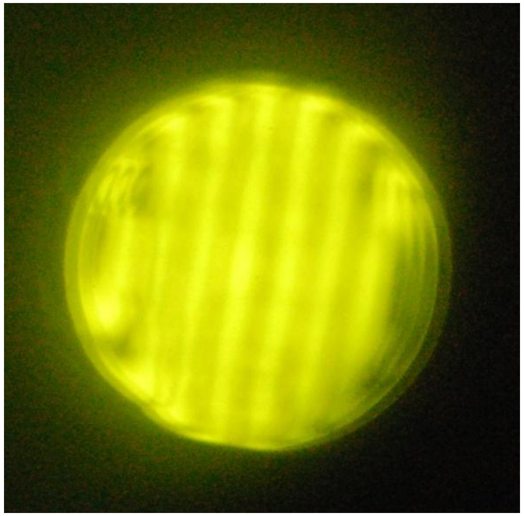


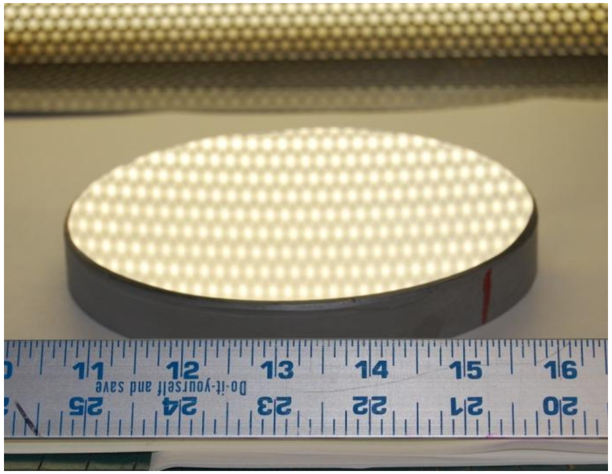
4 Power off t=36 min

Early results from a 5 cm mirror

Telescope Quality NanoComposite Mirrors
(A task objective of SBIR Phase I)



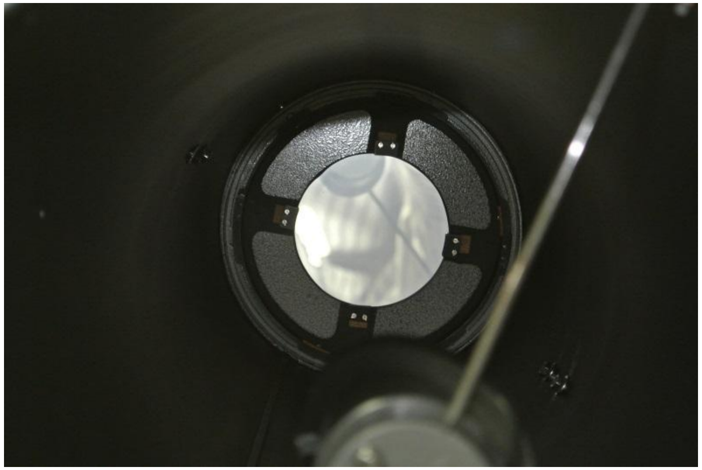




Top: Ronchigrams of 15 cm f/8 telescope mirror
Bottom: Coated mirror

Field Testing A Telescope Mirror

Our Test Telescope



6” f/8 nanocomposite mirror mounted inside the test scope

First Light Nanocomposite Mirror Scope

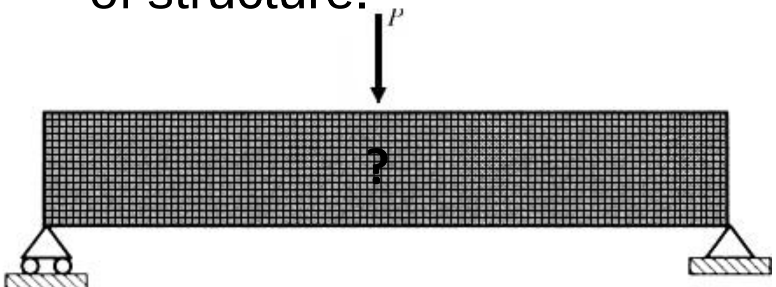
Picture taken by hand holding camera against eyepiece.
The visual image is much sharper and has more details.
Stars are sharp pinpoints.
No problems with thermal distortion or dewing.

Application

Nanocomposites combined with 3D printing make possible novel forms of mirrors and structures with higher rigidity at lower mass

We use topology optimization to design new forms of lightweight rigid support structures

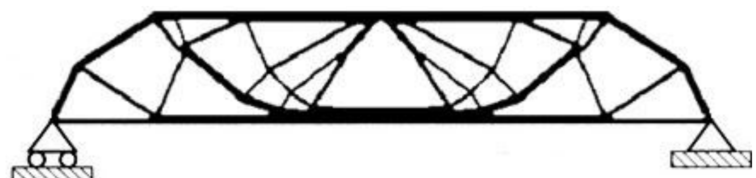
Topology Optimization is a **free-form, systematic** approach to design of structure.



Design problem: reduce beam weight

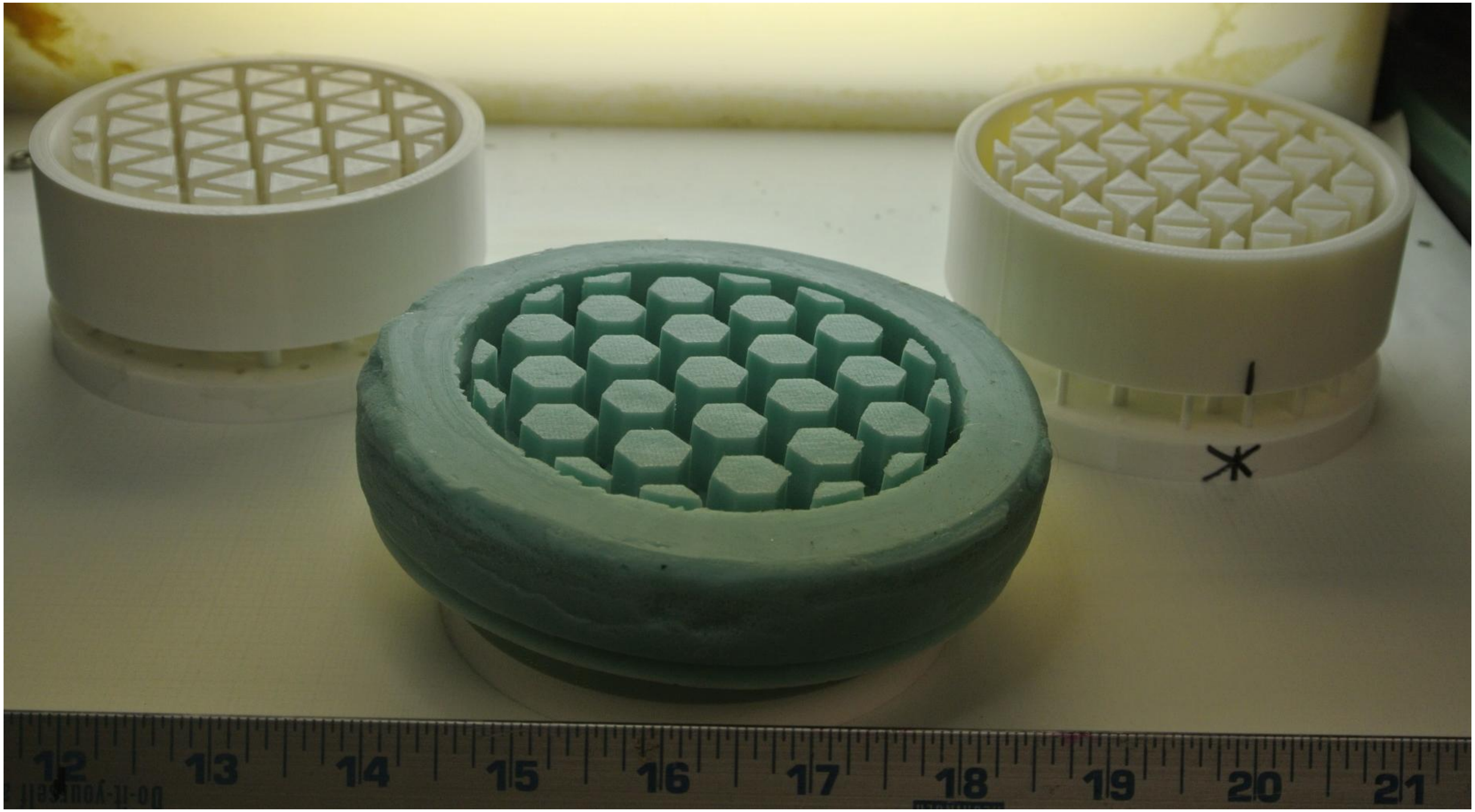
Conventional low-weight design

Topology optimized design:
~ 42% stiffer for same weight



Topology optimized design:
~ 48% lighter for same (elastic) stiffness

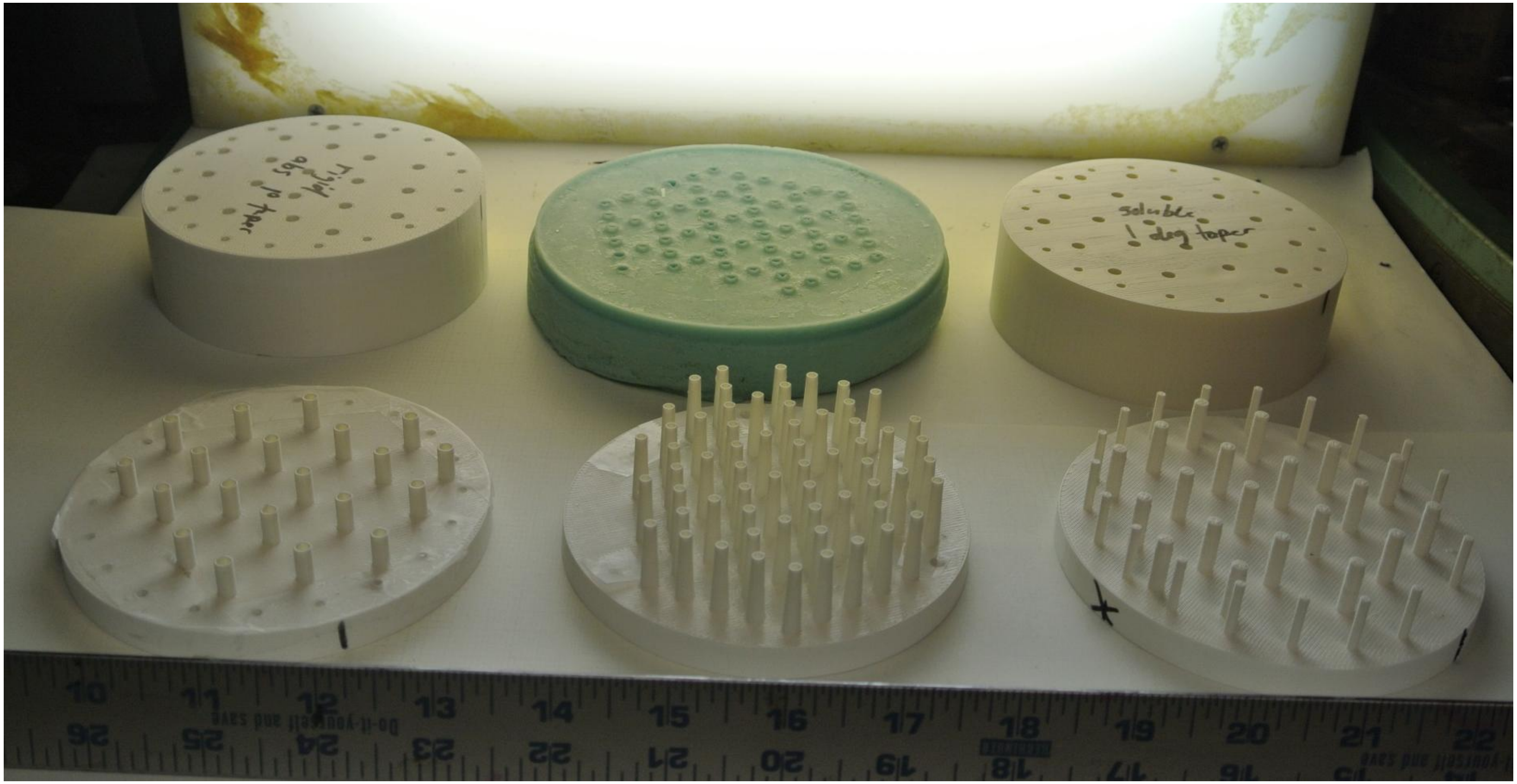
Molds for Making Structures For Lightweight Mirrors



For our first effort, we start with three classical lightweight open back structures*

•Vukobratovich, D. (1999) “Lightweight mirror design”, Optomechanical Engineering
•Handbook, Ed. Annes Ahmad Boca Raton: CRC Press LLC, p35.

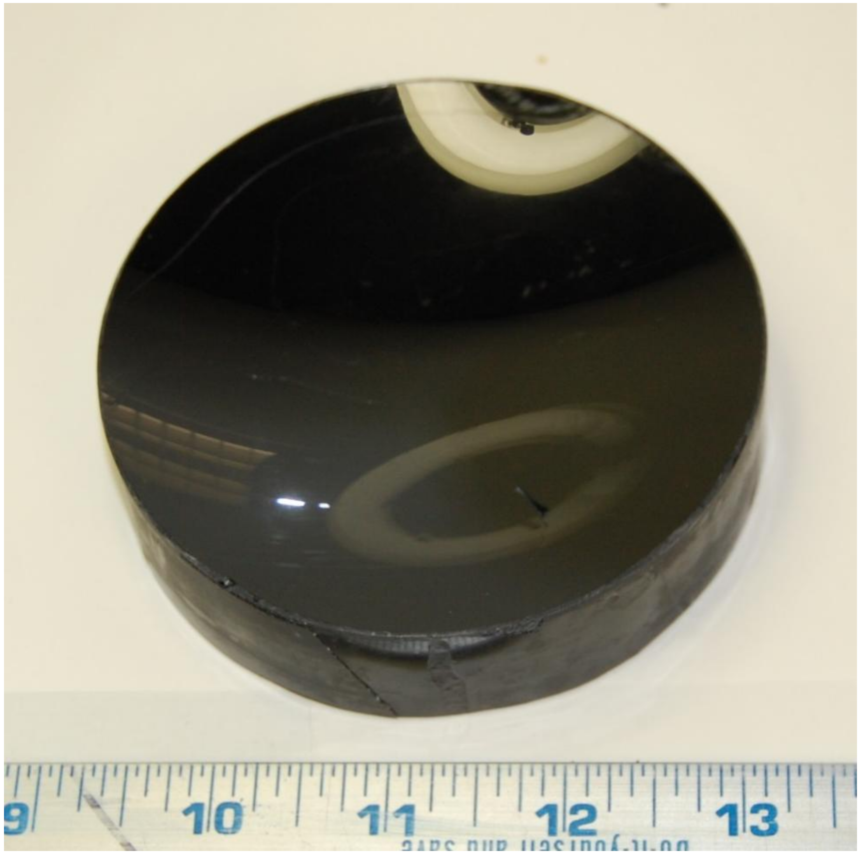
3D Printed Molds That Work in 3 Different Ways



Left - Rigid reusable mold. Center – Flexible reusable mold
Right: Rigid one-use mold. (Molds fab by Virginia Tech)

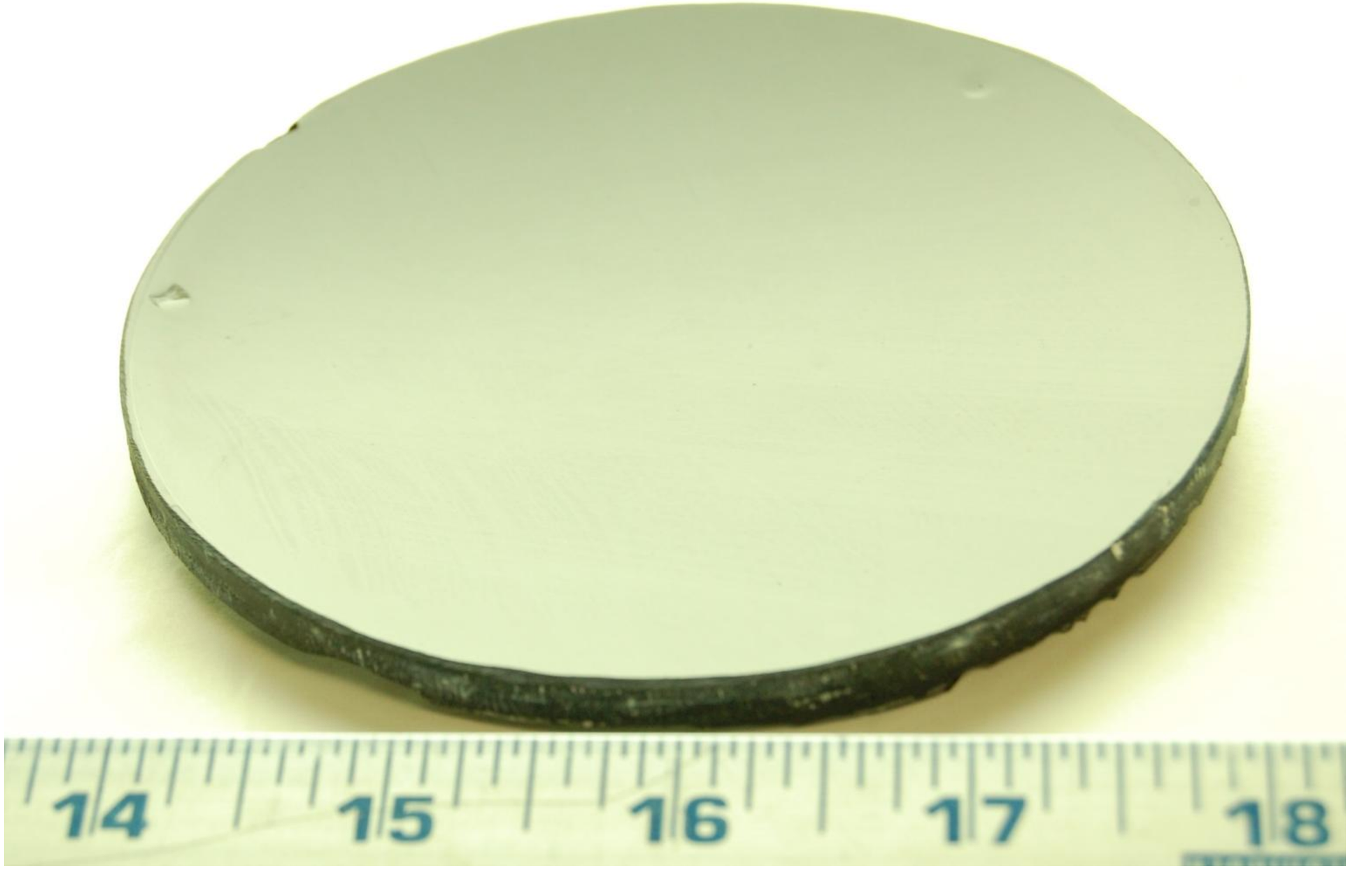
First Lightweight CNT/E Mirror Made using 3D Printing Technology

Molded back structure using molds from the Virginia Tech DREAM Lab

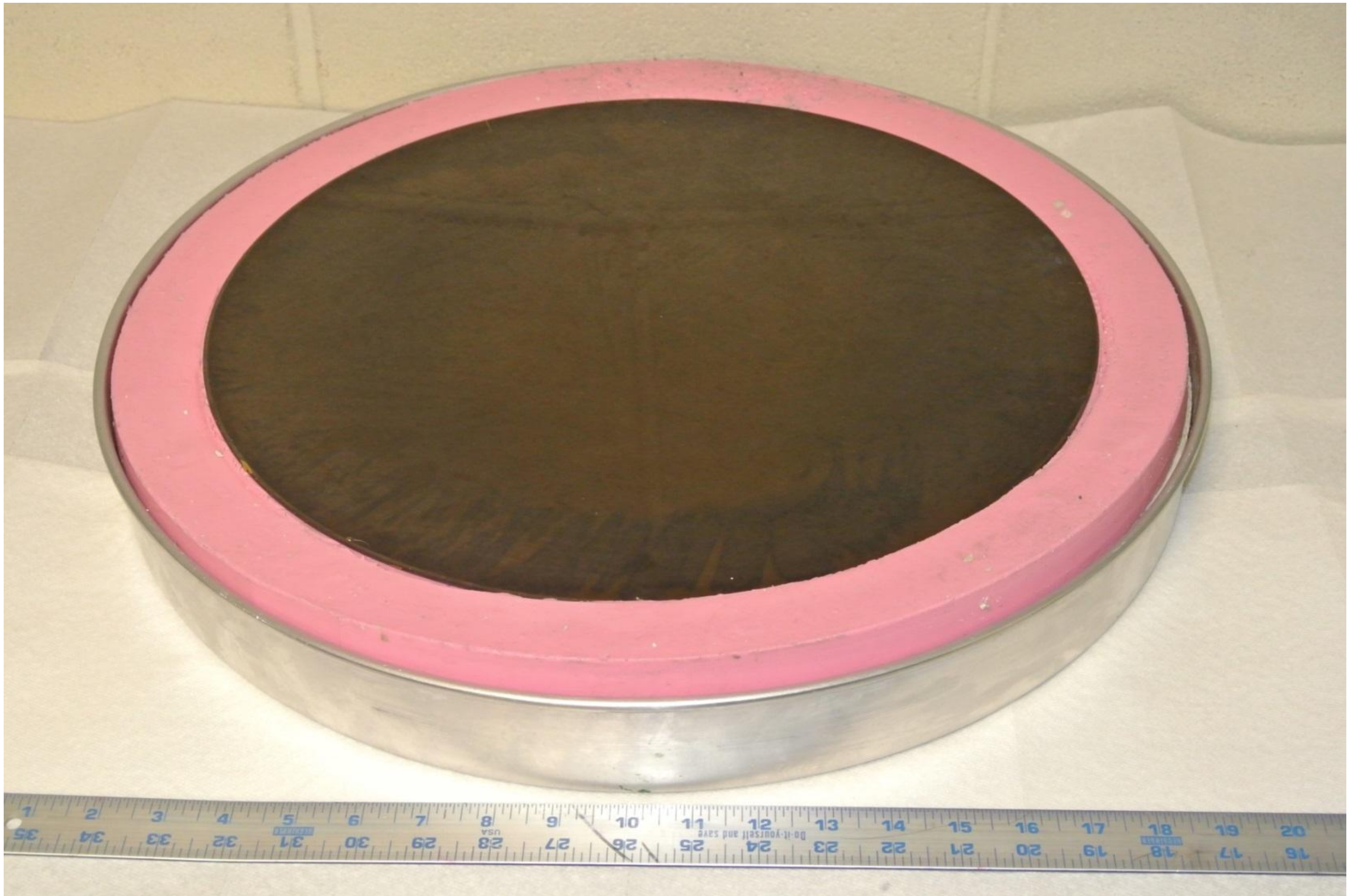


Front of 10 cm CNT/E mirror

A Potential Path to Advance the TRL
Prototype Lightweight CNT/E Mirror For CubeSat Applications



Mass 5.1g. Diameter 11.4 cm. f/1.4, uncoated.



Work in progress - 0.4 m lightweight active mirror

Current Status

1. We are working to produce and test lightweight, diffraction limited telescope mirrors (0.25 m)
2. We are designing and fabricating mirrors with novel 3D printer generated structures
3. Possible path to advance TRL - We are exploring making OAP and free form optics for CubeSat applications
4. We are making 0.4 – 0.6 m class active optics demonstration mirrors

Acknowledgements

We thank **D. Rabin** and **P. Mirel** (NASA GSFC) for helpful discussions and suggestions.

We thank **G. Canter, P. Cursey, T Plummer** (NASA GSFC), **R. Dutilly** (NASA ret.), and **E. Chen** (ACC) for technical assistance.

This work is supported under NASA SBIR program #NNX15CM63P

Epoxy Creep?

Creep = time dependent deformation at constant applied stress*

Causes*

Stress relaxation in graphite fiber epoxy systems usually cured under pressure and high temperature

Change in molecular structure under continuous loading stress

Completion of secondary and tertiary polymerization reactions

* Handbook of Composites, 2nd ed. Ed. S.T. Peters, Chapman Hall

For Nanocomposite Optics

- Cured free of stress – otherwise optics no good!
- Cured over very long periods (weeks)
- Cured at temperatures sufficient to complete secondary and tertiary reactions (amine systems)
- Long annealing cycles
- Can add moisture barriers if necessary
- Mirrors **ARE NOT** load bearing structures

Creep is not expected. However we are doing field testing to be sure.

An Illustrious Forerunner & Trail Blazer

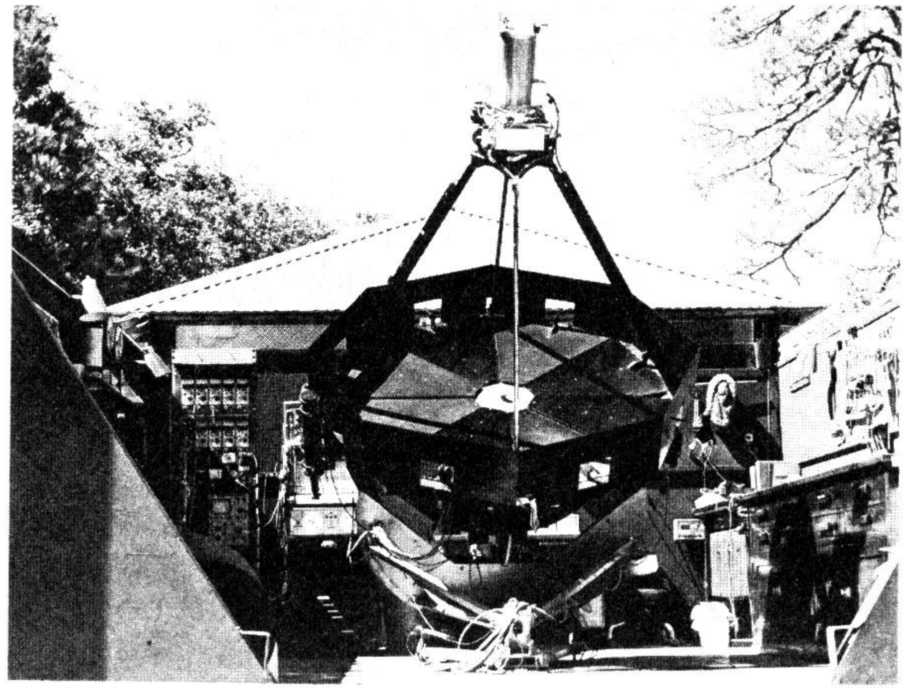


Figure 1. California Institute of Technology 62-inch telescope.

1.6 m epoxy mirror telescope made by Leighton and Neugebauer in 1965 to carry out the first IR sky survey. We are not aware of any creep problem associated with this mirror.