The Path to Life Finder

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Introduction: Rationale for Life Finder I

- A **large area high angular resolution telescope** is expected to be needed for detailed study of the spectra of extrasolar terrestrial planets (ESTPs) - when or if they are discovered.
- ESTPs will be as faint as Hubble Deep Field galaxies, and their observation will also be difficult because of the bright star which will typically be 0.05-0.1 arcseconds away from the planet

Introduction: Rationale for Life Finder II

- Life Finder is expected to be needed as a follow-up device for Terrestrial Planet Finder (TPF).
- TPF will in addition to discovering ESTPs, take low resolution low signal-to-noise spectra of the planets.
- The information from these spectra will be inadequate to determine within reasonable certainty that some of these planets are inhabited - at least by microbes. More detailed spectra will be needed.

Introduction: Nature of Life Finder

- Life Finder will need to have a substantially greater light collecting area than TPF's ~ 50 square meters. Useful ranges to consider are 500-5000 square meters.
- At the start of this study it was considered that the greatest difficulty for Life Finder would be in producing the light collecting area at reasonable cost, and at low enough mass that the USA could afford Life Finder.

Introduction: Beyond Life Finder

- An additional reason for studying the issues in producing Life Finder is that NASA wished to consider a device for imaging the surfaces of ESTPs.
- Such a device, Planet Imager would require ~ 50-100 Life Finder telescopes used together in an interferometric array
- The scientific benefit from this monstrously difficult task does not seem commensurate with the difficulty.

Goals and Guidelines

- The goal is to understand the best route for the Life Finder Mission, and to develop a roadmap for the necessary technology.
- Every essential invention must be described.
- If multiple inventions go beyond the capability of description at the present time, that version of Life Finder is too far in the future to be considered appropriate for the mission.

Tasks

These are to be complete at the end of this work

- Optics
- Optics Control
- Mechanical Structure
- Thermal control
- Testing
- Packaging Orbit and Rocketry
- Tasks and Roadmap

Origins Theme and its development

- Circa 1995 Dan Goldin noticed that the public could not understand NASA science because there was not a unifying theme that resonated within the public.
- The public does not understand science methods, but it does appreciate pictures, especially “Earth in Space”
- Therefore he wanted to take a major step forward by taking pictures of extrasolar earth-like planets, and using this as a springboard as a theme of searching for our Origins.

Ex-NPS Study (1995) Results

- Taking pictures of the surface of planets is, at best, a far distant future goal requiring huge technology development, probably requiring major space manufacturing and testing facilities that are not yet even in planning.
- Taking pictures of the nearest **planetary systems** is a reasonable goal on a 10 year time scale.
- The **Terrestrial Planet Finder** that makes these pictures would also automatically generate low quality spectra of objects in the planetary system producing **evidence whether Earth-type life is likely present.**

Earth In Space: a triumph and a disaster

A triumph because we learned our relationship to Earth and each other

A disaster if we are hooked on duplicating this tour-de-force

Ex-NPS extension (1997)

Dan Goldin asked for a detailed study of the requirements for a Planet Imager. The response was that :

Planet Imager required an extraordinary interferometer built with a large number of telescopes each ~ 100m across.

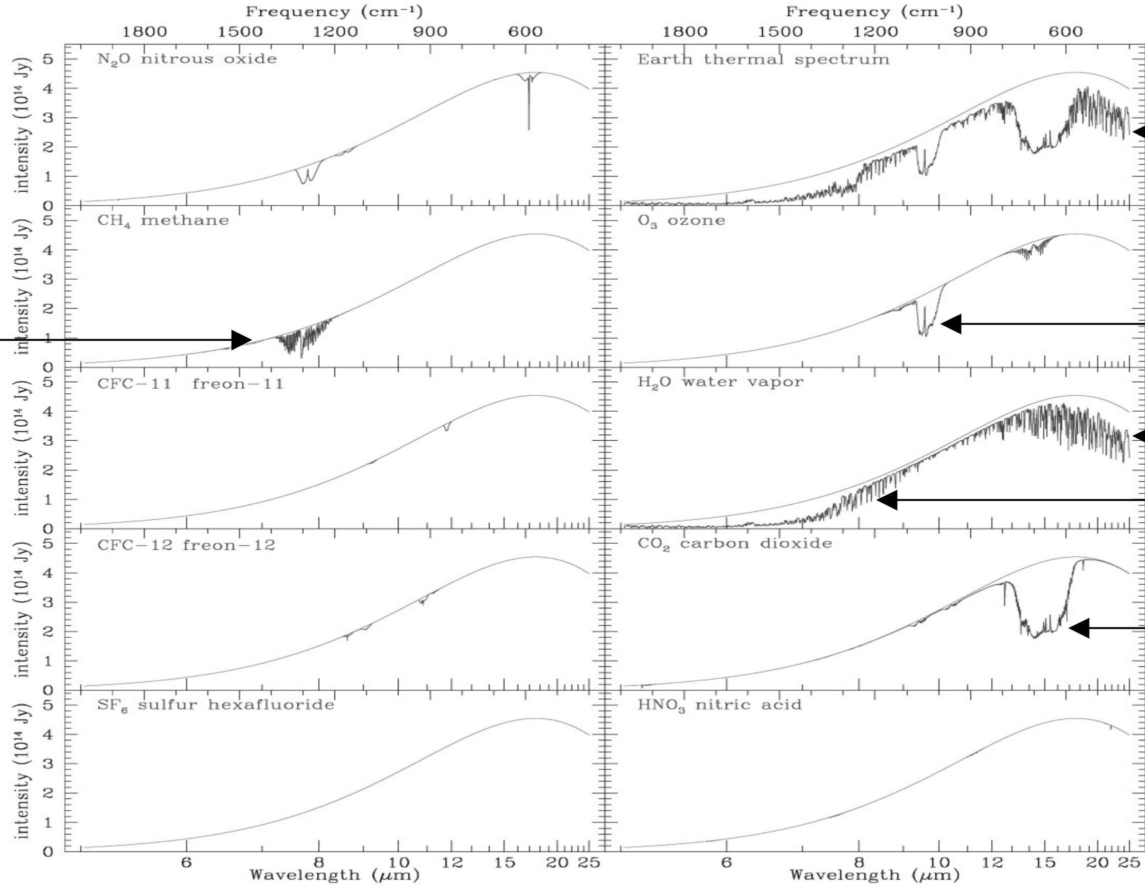
A huge program in lightweighting of optics is needed to keep giant telescope costs down (**if they can be kept down**).

An intermediate very valuable product would be a giant advanced spectroscopic telescope to study the "Earths" - **Life Finder**. This would produce **confirmatory evidence of the presence of life.**

Life Finder Science

- **Life** is a process where the **physical order** of an environment is converted to a **departure from chemical equilibrium.**
- **Evolution** makes life processes more efficient.
- So the **external indication of life** is from the **extreme departure from chemical equilibrium**.
- **Earth's atmosphere shows that extreme departure** in 1) The abundance of oxygen (20%) and 2) The abundance of methane (0.00016%)

Earth atmosphere:Mid-IR spectra Signature of gases



Earth Spectrum

Methane

Ozone

Water

CO2 band depth shows effect of ozone heating

Courtesy Wes Traub

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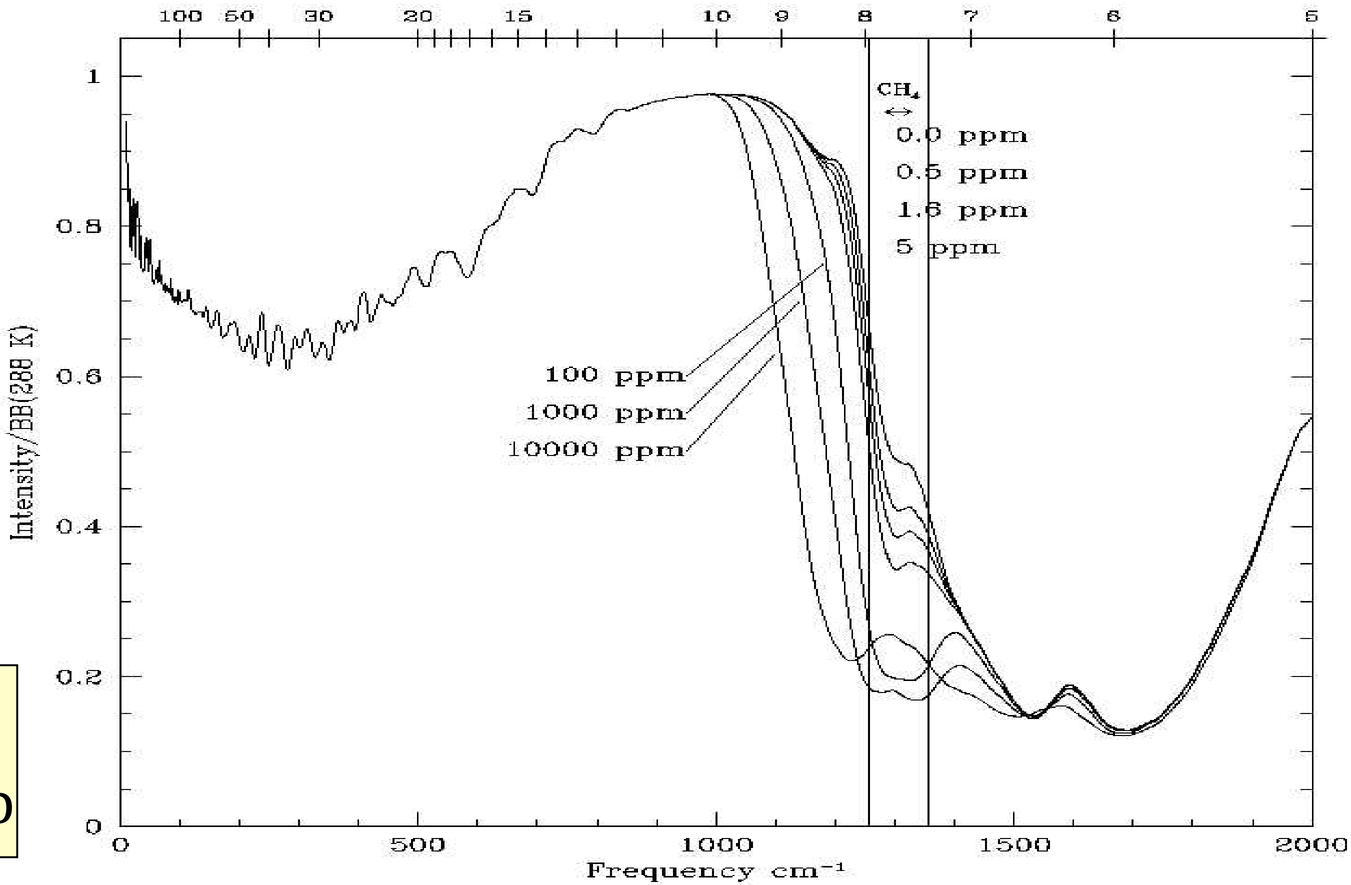
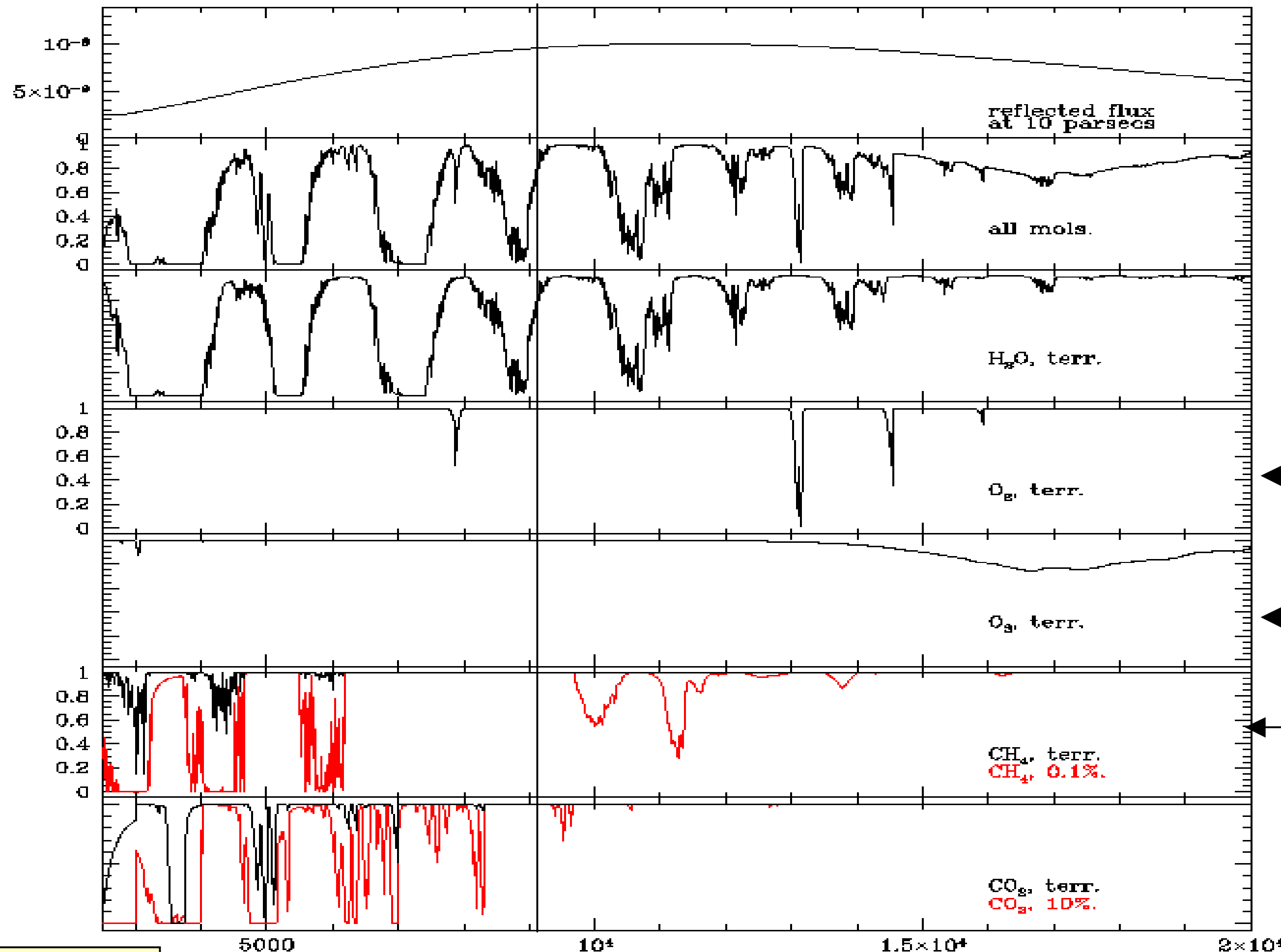
IR methane band vs amount (CO$_2$ and O$_3$ omitted)



Courtesy Wes Traub

Visible spectral signature of gases



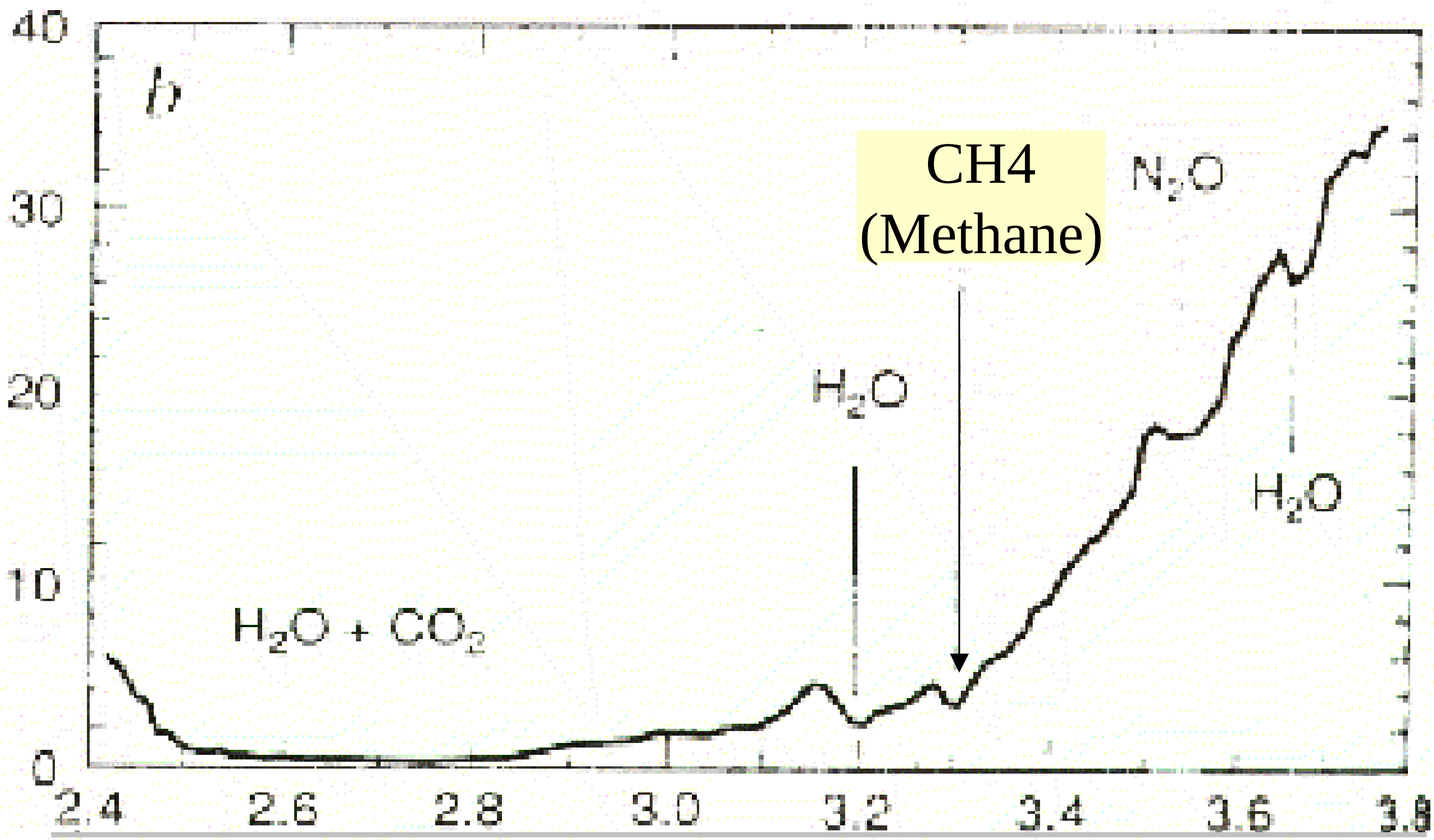
Oxygen

Ozone

Methane

Courtesy
Wes Traub

Near IR Earth Reflection Spectrum from Sagan et al(1993)



Microns Wavelength

Where to look for small amounts of Methane

- For Earth-like planets, TPF could find oxygen, but not methane.
- Methane options are at 7.6 microns, with a danger of being covered up by water vapor if the planet temperature is higher than Earth. The likely contrast ratio is $\mathbf{10^{8}}$.
- Or at 3.3 microns, where the planet emission is low, and the star is bright. The likely contrast ratio is $\mathbf{10^{10}}$.

The technical challenges

- An Earth at 30 light years is like a dust grain seen from across the continent! (100 μm at 4000 Km.)
- Extra-solar terrestrial planets not only have not yet been observed in their glow, they have not yet been detected indirectly, and current ground techniques are incapable of detecting them.
- We do not even know where the nearest one is and how bright it is!

Where is the nearest Earth-like planet?

1) At Ex-NPS (**1995**), the accepted "knowledge" was that 20 stars had been looked at for evidence of planets, and none had been seen.

2) All planetary systems were likely to be similar to the Solar System.

Currently

5% of stars show Jupiters but closer in than in the Solar System.

95% of stars show no planets, but *all* **or** *few* of these could be hiding a solar system.

Current TPF Strategy

- Develop technology for TPF, learn about space use with SIRTF (02), Starlight (05?) SIM (09), NGST (‘10).
- Fly a TPF capable of surveying the 200 nearest stars. Fly it after 2012. (Actual date would depend on accumulated delays in the other missions).
- Only consider Life Finder after TPF results are back.
- And from experience, we understand how the dates are likely to change with time.

How the roadmap works poorly for NGST/TPF

Needs passive cooling: SIRTF does passive cooling. BUT NGST needs to do it with a sunshield. So there is a totally new sunshield development!

NGST needs low mass optics: SIRTF uses low mass optics. BUT NGST needs segmented optics so there will be development needing a special flight!

NGST can live with SIRTF mirror quality and mass density, so it will probably use beryllium like SIRTF. But TPF needs lower surface density and better wavefront. TPF will need to develop its own mirrors!

Is there a better roadmap strategy?

- Accept that the chronic crisis in NASA science mission funding arises from too many projects chasing too few funds. Microtoming of funds merely causes frustration. It is better to kill projects or not start too many.
- Do not pretend that a mission requires a technology development from a **science** precursor. It is not their priority to provide the appropriate technical information. They are a roadblock on the project they are supposedly helping.

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A better strategy

TPF

Life Finder

Mini TPF

Are there Earth-like planets nearby?

Where are the nearest systems like our own(Jupiters/Saturns)?

If yes

If no

Mini-Life Finder

Make Life Finder appropriate to nearby planets.

Full-Size TPF

Appropriate for nearest systems like our own.(if found)

OR Search for nearest systems like our own to larger distance

When ready

Full-Size Life Finder

Make Life Finder appropriate to the distance Earth-like planets are found.

Life Finder starting point

- Early Earth probably had much methane, little or no oxygen.
- Now it has much oxygen, little methane.
- Planet Finder will find earth-size planets in the “Goldilocks zone”.
- Planet Finder may see oxygen, but methane is harder except perhaps in young Earths.
- Life Finder is needed to find methane when oxygen is present.

Coronagraph or Nuller?

- Nulling requirements get harder and harder as the telescopes get larger. In particular, once the planet is resolved, nulling becomes an aspect of coronagraphy, and requires complete control of mirror shape.

- Coronagraph requirements for seeing extrasolar planets have traditionally assumed uncorrelated errors across the wavefront. This requirement needs explicit expression.

- Coronagraph seems preferred for Life Finder

Acceptable light leakage

- The amount of spectral resolution available on the planet (at fixed Signal-to-Noise ratio) is linearly proportional to the available observing time.
- If the amount of starlight that leaks into the planet image core is **X** times the planet light, the observing time increases by a factor **(1+X)**, and so directly limits the spectral resolution or attained Signal-to-Noise ratio. ($\mathbf{10^{10}}$ or $\mathbf{10^{8}}$)
- **It does not help to make the telescope larger if X increases too**. Optical quality is essential for Life Finder

Meeting to re-examine coronagraph requirements

April 2001

M. Shao (JPL)

J. Trauger (JPL)

R.Angel (Az)

N. Woolf (Az)

D.Tenerelli (Lockheed-Martin)

C. Lindensmith (JPL)

And the discussion continues!

Coronagraph Wavefront Requirement

Required max surface error σ over a scale L

$L = \theta/\lambda$ (wavelength/angle in radians).

For 5th magnitude stars at ~10pc (sun-like),

$\theta \sim 0.1\text{-}0.05$ arc seconds or $1/2\ 10^{6}$ -$1/4\ 10^{6}$ radians.

$\sigma \sim (D\theta/2\pi)\mathrm{Sqrt}(F)$

D = mirror diameter

F = reduction factor (10^{-8} or 10^{-10})

Example: 8 meter telescope, planet separation from star 0.1 arcseconds reduction factor 10^{10}.

Needed precision 0.03 nm (0.3A)

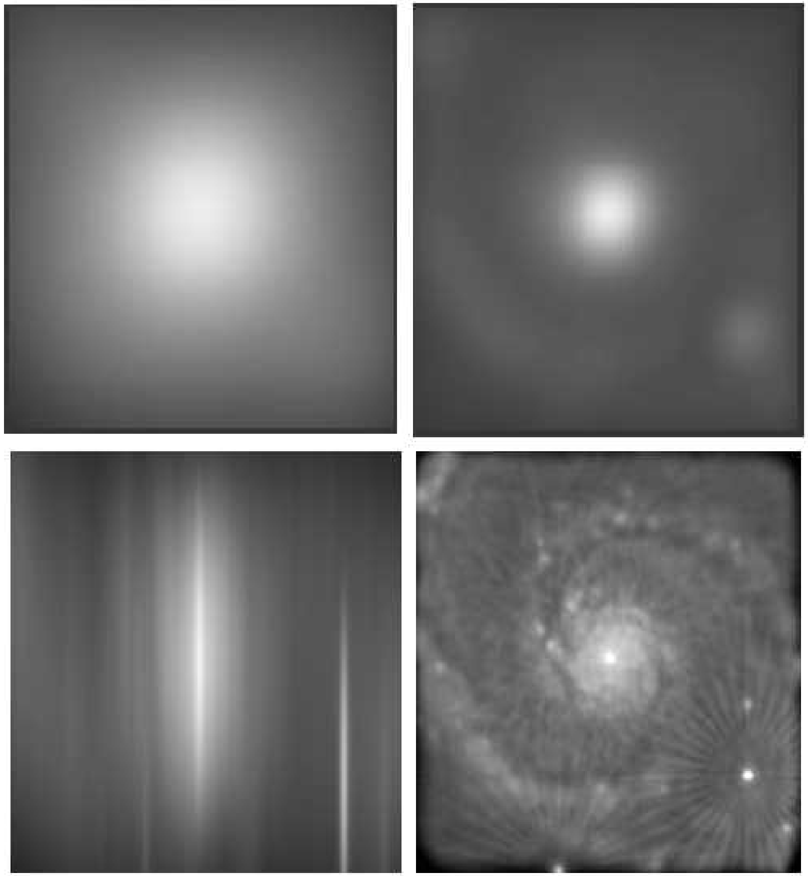
Coronagraph Mirror Shape

- The optimum shape is not round.
- Previous results apply to mirror AREA.
- Most time is spent in taking spectra, where benefit can be taken from an elongated aperture.
- Elongated aperture results in more time in setting up, but that becomes unimportant.
- Elongated apertures are good for astrophysical imaging

Use of a strip/slot telescope

HST

NGST



Slot,
1 exposure

Slot
18 exposures

Comparison with NGST

Life Finder mirror dia. Or eq. area	3.3 μm ($F=10^{10}$)	7.6 μm ($F=10^{8}$)
25m ($500m^2$)	0.9A	9A
50m ($2000m^2$)	1.8A	18A

NGST requirement ~ 80nm or 800A
Life Finder optical surface requirement is 50-1000 times harder than NGST, but with compensating advantage.
The presence of a very nearby bright star allows control of surface by adaptive optics.

The vibration problem I

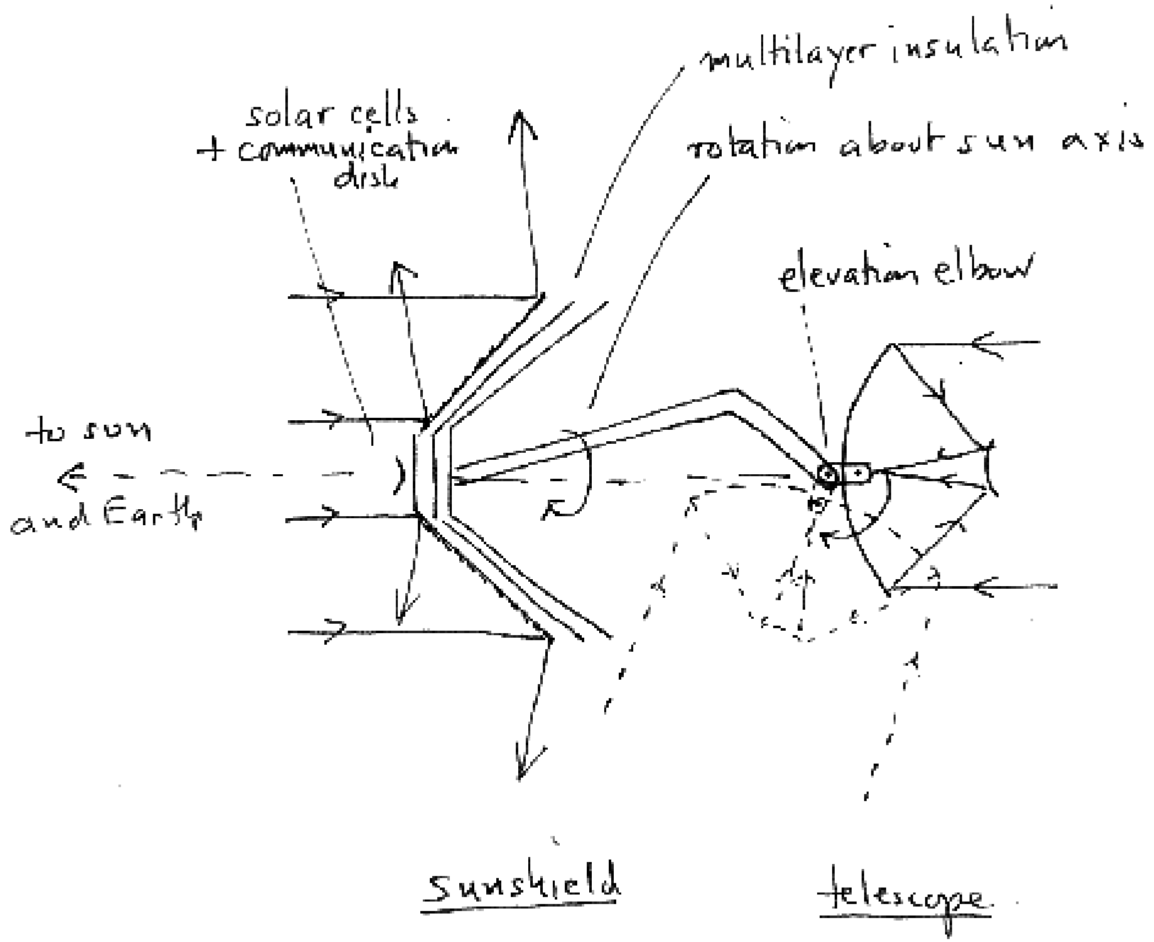
Even with 2 stages of damping, the reaction wheels in SIM produce some 100s of A of vibration!

This exceeds Life Finder specifications by orders of magnitude.

Therefore Life Finder will operate without reaction wheels and with pointing control by solar radiation pressure.

UA will be funded thru Gossamer Initiative for a study, with concept initiated under the NIAC grant.

Sunshade Concept

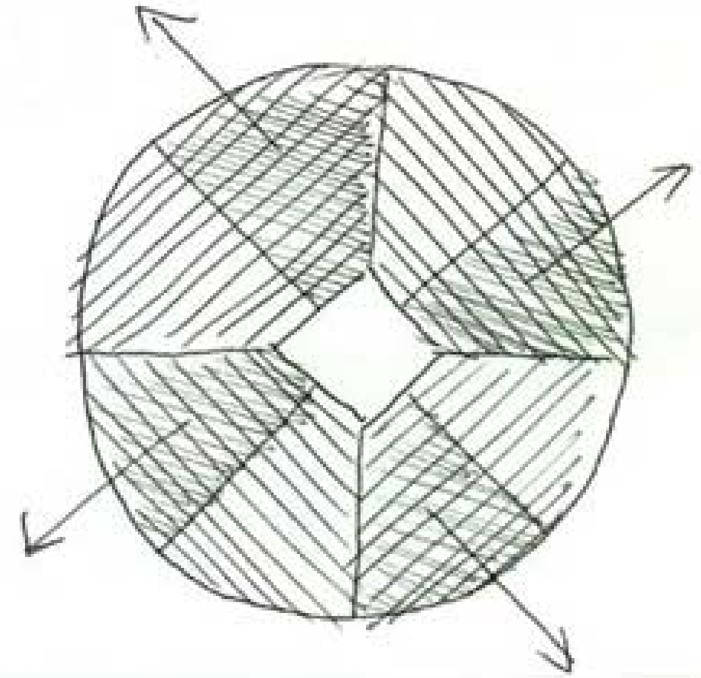


GossamerPassive cooling with sunshields

- Zodiacal dust radiation at 1AU equals in flux a black sphere at 4.1K
- Microwave background adds 2.7K
- Block out the Sun as seen by the telescope. Then if the sunshield is white on the sun side, and shiny gold on the “scope side. The telescope temperature will be set by the telescope sunshield spacing. The telescope and detector could be passively cooled below 10K!
- Power can be beamed to a shielded receiver at the telescope, or transmitted by wire along a physical connection (if warmer telecope is acceptible.
- The big issue is power use in the cryogenic telescope. We have developed concepts where this is negligible.

The vibration problem II

View from the sun. To torque about the sun axis, the lighter shaded louvers are raised, and the darker ones reflect to the side as shown. A clockwise net torque is transmitted into the system.



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The vibration problem III(an example)

Telescope mass assumed 3000Kg at rms distance 7m from the center of mass. I= 1.5x 10^5 SI units.

1 mas = 5 x 10^{-9} radians. Angular acceleration to move 1mas in 100 sec is 10^{-12}

The radiation pressure force is 10^{-5} Newtons/square meter.

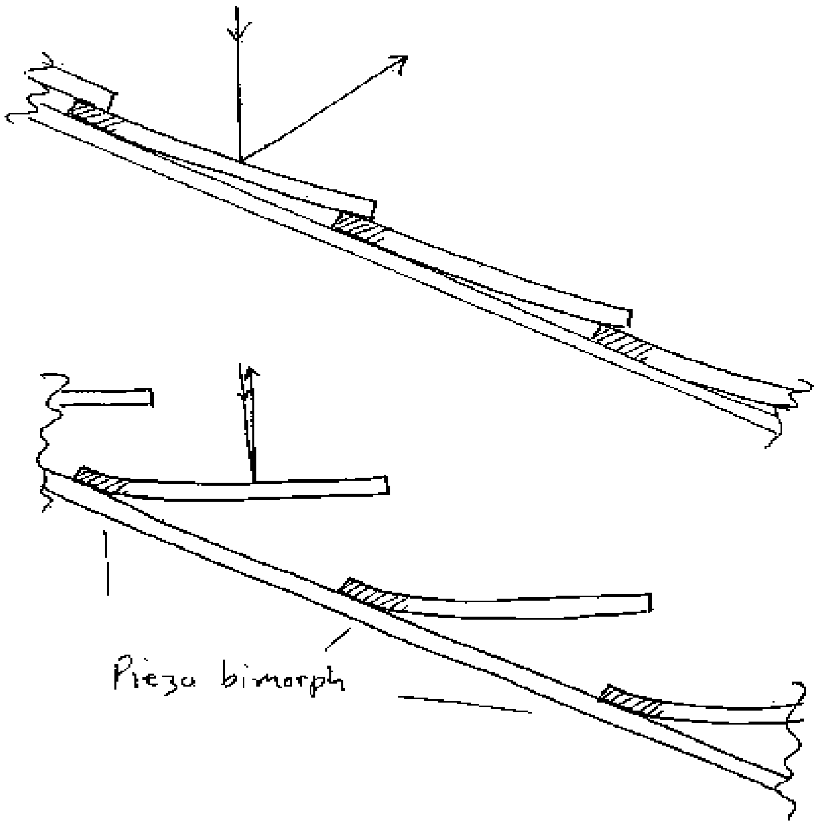
The torque with this force at 10m from the center of mass is 10^{-4} Newton meters per meter of area

The angular acceleration this will cause is 10^{-4}/1.5x 10^5 = 6.6 x 10^{-10} per meter of area and,

The allowable area imbalance is 15 square cm.

The vibration problem IV

Detail of sunshade surface with reflecting tiles actuated by piezoelectric bimorph.



The vibration problem V

Vibration **damping** is a major issue.

Typical space structures have Q ~ 1000.

If amplitudes after acquisition are ~10 microns, and requirements are ~ 1A, then ~12 exponential decay times are needed, or in all ~10,000 times the resonant period. If the period is 1 sec, this is 2.8 hours! So the structure must have a period at most a fraction of a second.

Availability of control information from starlight

Starlight control available from a 5th magnitude star for radiation 0.1 arcsec from diffraction core.

	0.76μm	3.3 μm	7.6 μm
Characteristic length for 0.1 arcsec resolution	1.5m	6.6m	15.2m
Achievable control in 1/20 second	1.24A	0.3A	0.124A

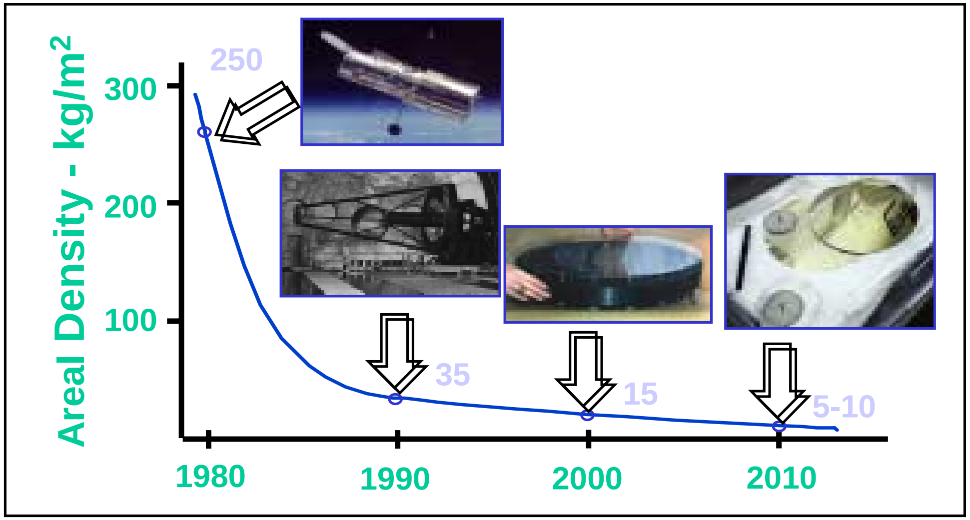
The starlight control information is adequate for an 8m telescope at 3.3 microns, and for an even smaller telescope (too small for the needed resolution) at 7.6 microns, but for the visible, a coronagraph will have problems in getting adequate starlight control if it is less than ~30m diameter. This may make it impossible to consider TPF variants that are a visible wavelength coronagraph, because they would be too large and expensive.

Will normal polish quality be adequate

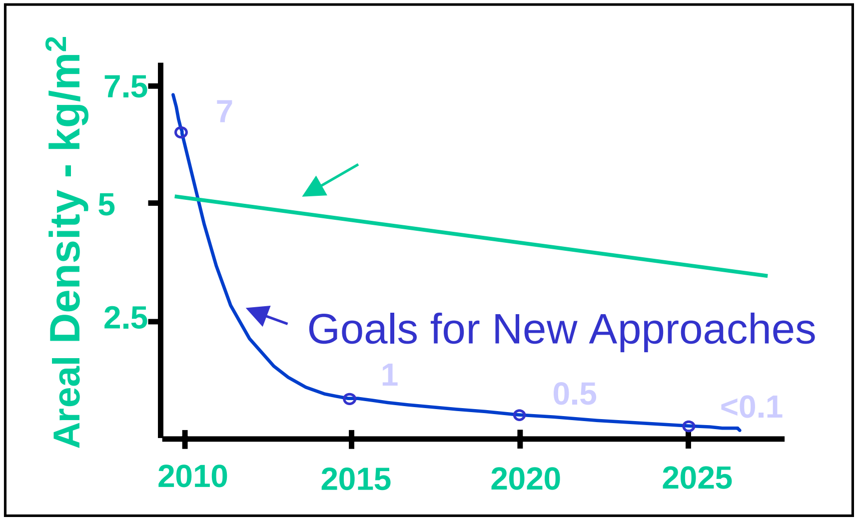
- We will consider a Life Finder that will make observations at all three wavelength regions.
- Normal polish has most difficulty at ~5cmscale, where ~10nm rms can be achieved.
- The tightest tolerance is for visible observations. However, ~20nm rms will be adequate.

Precision Large Optical Aperture Technology

Projected SOA Will Be Inadequate



New Approaches are Required



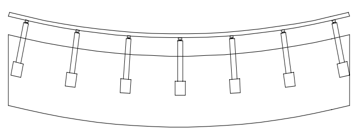
Limit of Current Technology

A 1997 Vintage viewpoint

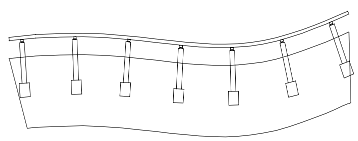
High Authority Glass Mirrors for Space

Mirrors of high optical quality are reduced in thickness to 1-2 mm and incorporated into what is now called a *high authority* mirror. Stiffness is restored by rigidly attaching the thin mirror to an efficient, ultralight and robust structure of carbon composite. Long term optical stability is achieved on orbit by active correction in a cycle of wavefront measurement and correction. The largest such mirror system of optical diffraction limited quality is complete, 2 m in diameter and weighing~ 12 kg/m^2. The space-oriented technologies critical for these mirrors have been developed at the Mirror Lab. They are for the production of facesheets and actuators.

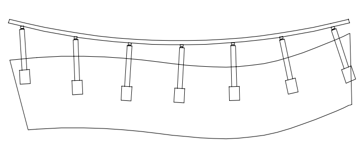
Ideal shape



Structure deforms, taking membrane with it



Actuators are driven to compensate



Why glass is still a good material for ultra-lightweight space mirrors

Glass has been the preferred substrate for ground and space mirrors until now. Should lower density, stiffer materials be preferred for future, lighter mirrors?

If the mirror were to be of a single material, with no active controls, then a material like beryllium forms the best compromise of mechanical, thermal and optical properties. However, once we separate the functions of reflection and stiffness by combining different materials in a high authority mirror, glass is best for the reflection component:

* very mature technology for optical processing

* highest homogeneity of any material

* lowest expansion coefficient of any material

* highest dimensional stability of any material

The 2m x 2mm thick finished glass shell

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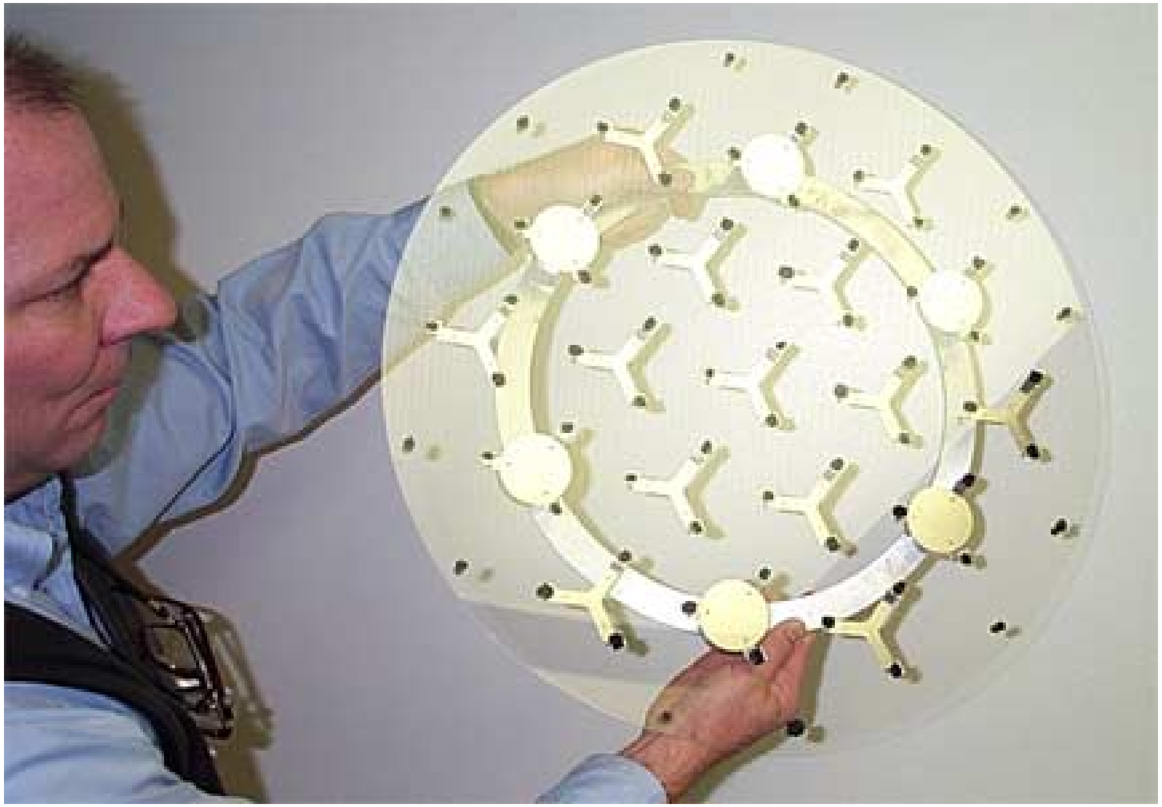
NIAC concept- Push the design for even lower mass-(funded by another agency)

Scales the existing NMSD density by less than half!

	NMSD	**Ultra-light**
Glass thickness	2 mm	1 mm
Actuator mass	40 g	5 g
Reaction structure	3.2 kg/m^2	1.1 kg/m^2
Areal density	12.4 kg/m^2	5.2 kg/m^2
Total mass 8 m mirror + support	**623 kg**	**250 kg**

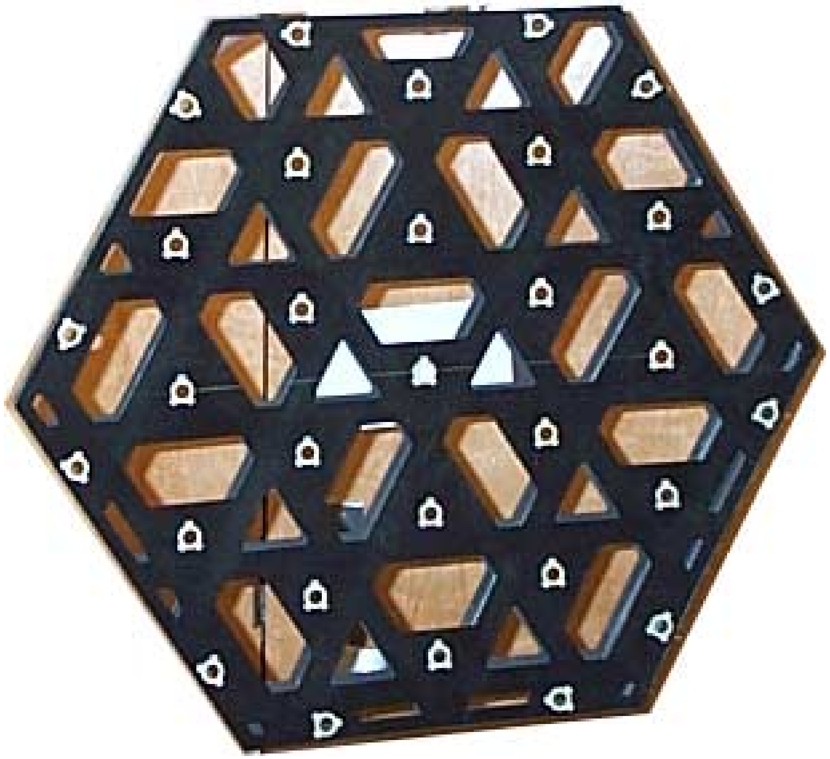
Ultralight Glass Shell

0.5m diameter x 1 mm thick Zerodur

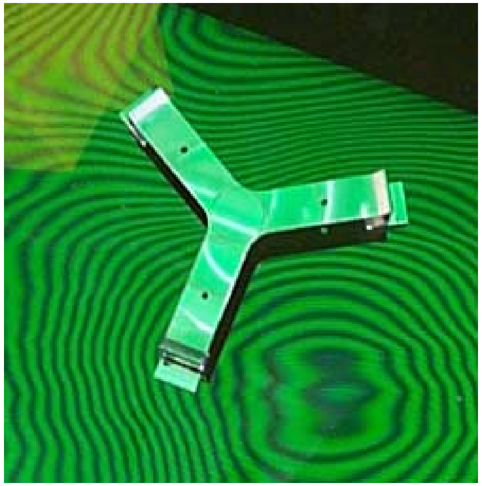


Ultra-light Reaction Structure

Designed at UA, Fabricated at COI
Total mass: 0.3 kg (0.7 lbs)



Ultra-light Loadspreaders



Ultralight cryo-capable actuators

5 grams each

20 nm step size
(these give ~ 4 nm motion of the glass due to attachment compliance)

Use tiny parts.

50 units produced
(needed 31 for mirror)

Several mm of travel available!

How far does lightweight optics save cost? I

- **Our study started to develop the optics, and is only now questioning the assumption.**
- The assumption was made because unless the launched mass/area ratio is low, we cannot afford Planet Imager.
- Mini Life Finder is likely affordable with extensions of the **glass** technology we have developed with NIAC support.
- Very large Life Finders may need new reflector technology, depending on availability of large rocket shrouds.

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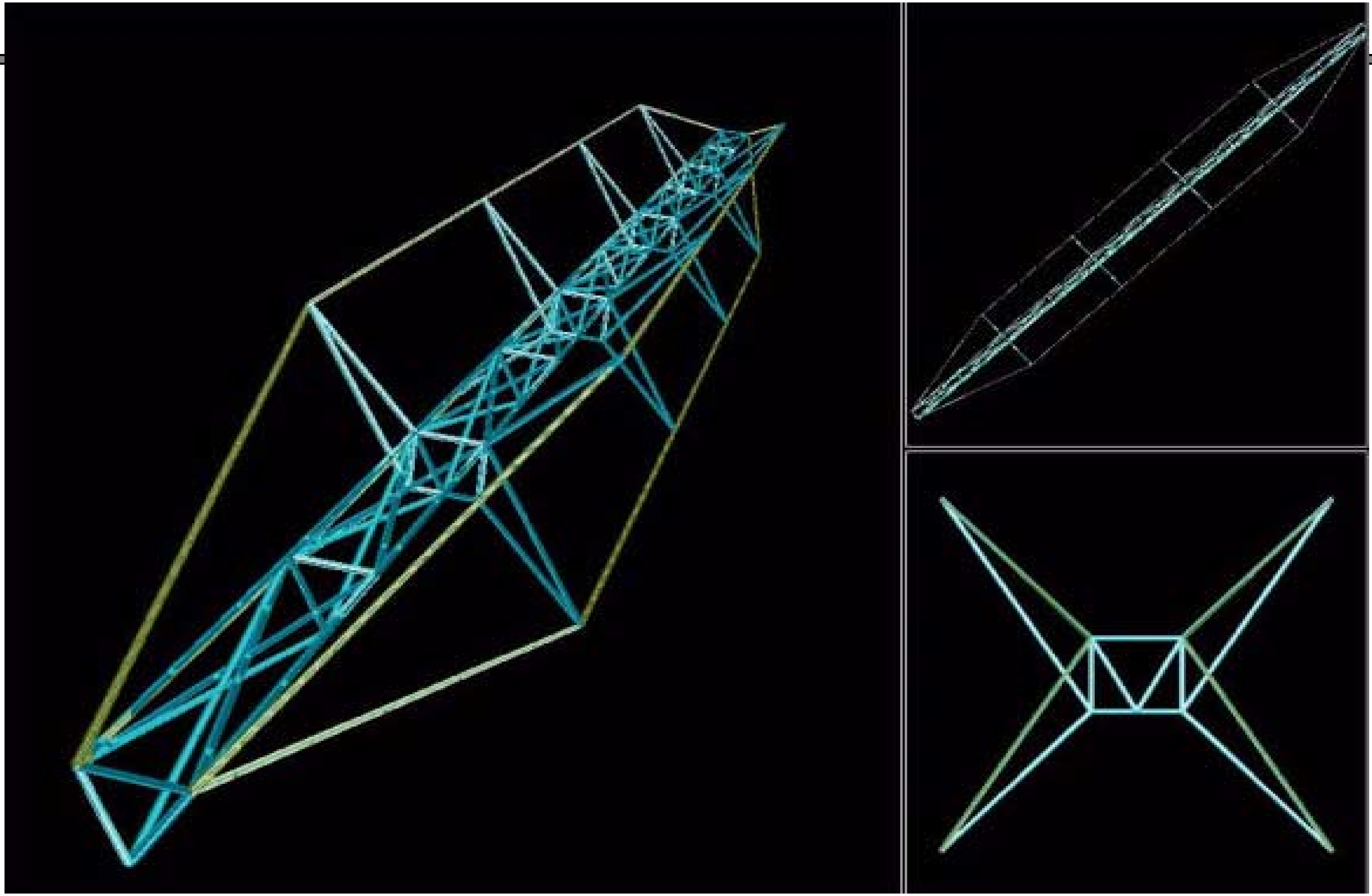
How far does lightweight optics save cost? II

- For ground based telescopes, mirror costs vary as Diameter, **D^2**. Structure and building costs scale as **D^3**. Historically, design has continuously changed as D has increased but scaling any design gives a **cost** varying as **$D^{2.7}$**. That is, the **structura**l costs have dominated. Issues are "tin-canning" and column instability.

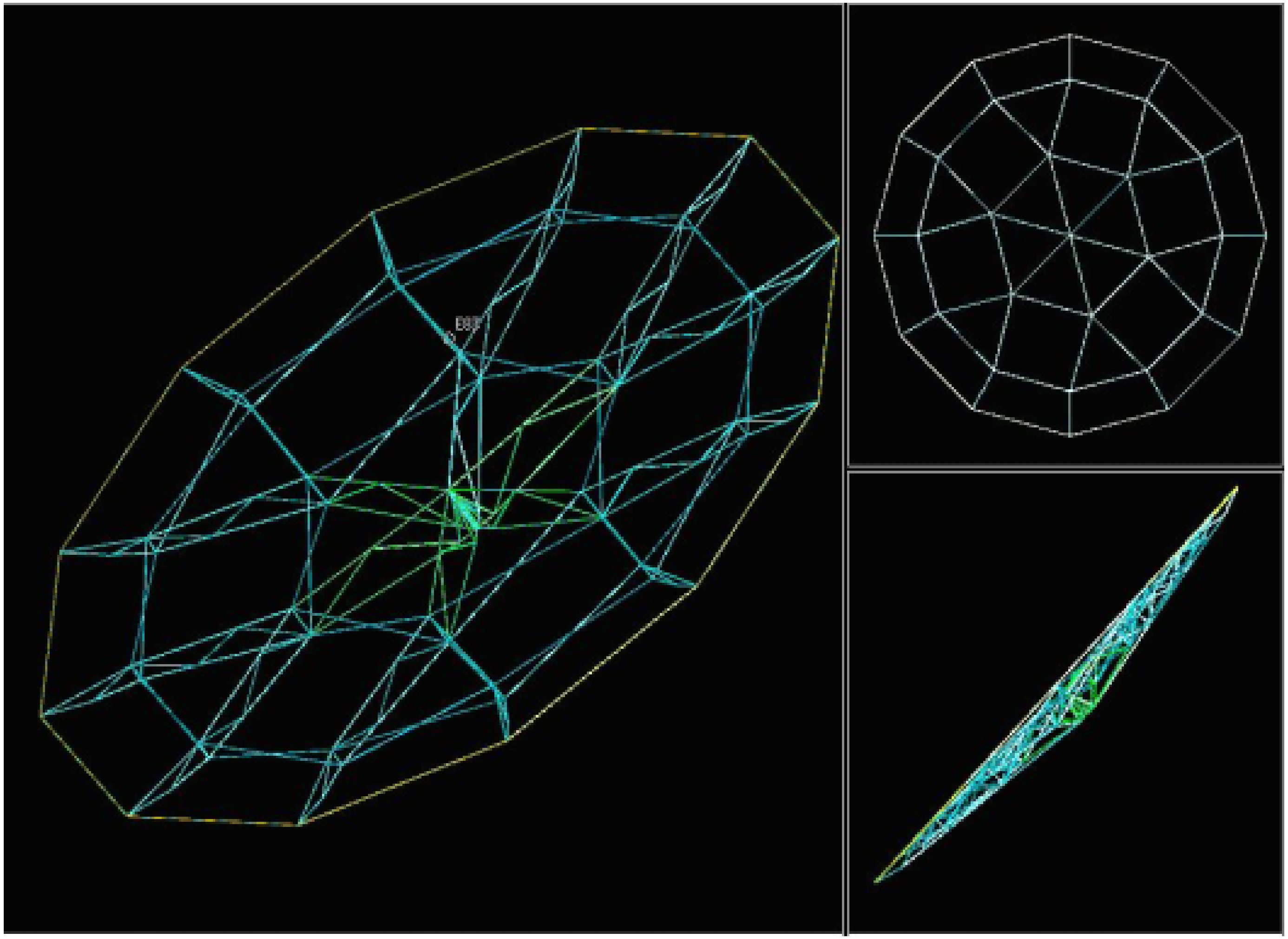
- Complex structures for space could be ultra-light-weighted, but they bresent a huge problem for space assembly. **They belong in an era of space manufacture and testing.**

550ft. 91,00tons 1064 ft 10,100tons

Complex structures I
Truss for strip telescope



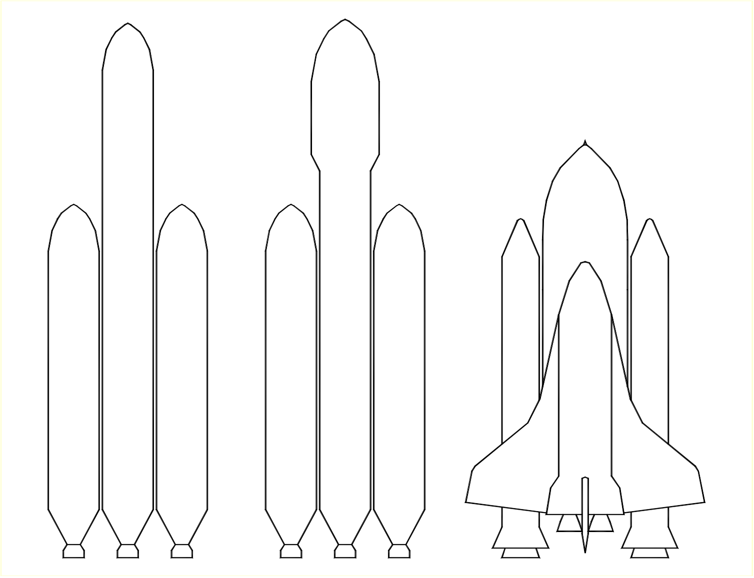
Complex structures II
Truss for Circular Aperture



Weight saving problem in 2001

- Weight savings requires structural complexity.
- If complexity requires space assembly, that itself is expensive with current facilities.
- If complexity requires space control, that is expensive. Currently software is ~20% of the cost of a launched device. If we save weight and add control, then the cost will become mostly software, and could even go up!
- **Cost reduction is a total process change**.

The larger the shroud, the easier the construction



As an example of an EELV configuration, the Delta IV heavy config. (shown on the left) should be able to accept a 7 m fairing to take 6 m optics, as shown in the center. Such a fairing still presents less drag than the STS-Shuttle system with its 8-m external fuel tank, shown to scale on the right. The alternative is space manufacture and testing.

The Gossamer Optics Workshop

- Prompted by the NIAC work, and with funding from NASA, a Gossamer Optics Workshop was held in Tucson 17-20 Janury 2000.
- 75 attendees from Universities, Industry, NASA, Airforce and Livermore etc.
- Discussed optical options, mechanisms etc.

Ultra-Lightweight Telescope Concepts I

An ultra-lightweight telescope is not just a telescope with weight shaved off.

There are two types of surfaces in mechanics that could become telescope mirrors:

Plates or Shells, where the restoring force comes from rigidity.

Membranes where the restoring force comes from tension.

For large apertures the transition comes near $5Kg/m^2$

Tension forces are in a plane and tend to produce flat optics.

Ultra-Lightweight Telescope Concepts II

Flat or near flat optics implies that the incoming light or IR converges slowly to a focus. Thus the focus is many mirror diameters away from it.

Since we are trying to minimize structural mass, the simplest solution is to use a virtual structure, and have the radiation detector as part of a separate free-flying package.

Transition to Membranes

	F/1 systems			F/20 systems	
'Scope diameter	2.6m	8.0m	25m	25m	100m
surface density	150Kg/m^2	16Kg/m^2	5Kg/m^2	1.6Kg/m^2	0.1Kg/m^2
Mass	800Kg	800Kg	2500Kg	800Kg	800Kg
Moment of Inertia	1 unit	10	300	36,000	600,000
Rotation period for same thruster expended	1	3	50	190	800
Rotation period for same reaction wheel use.	1	10	300	36,000	600,000

Membrane telescopes are for long observations of ultra-faint objects only. General Purpose telescopes should be restricted to rigid mirrors.

Membrane Telescope Concepts

We have developed two varieties of plastic membrane telescope concepts.

The easiest surface to produce with a stretched membrane is a flat. The higher the tension, the higher the frequency, and the more rapid the damping.

Electrostatic force can induce modest curvature.

Near-Flat Membrane Optics

If the flat panels of scheme II are warped slightly by electrostatic forces, they can be shaped into parts of a parabola without need for massive re-converging optics. And adjustment of the electrostatic forces will allow the optics to become active. However the edges of the panels must be held mechanically, so these edges must also be mechanically controlled. Systems look more "conventional", though long.

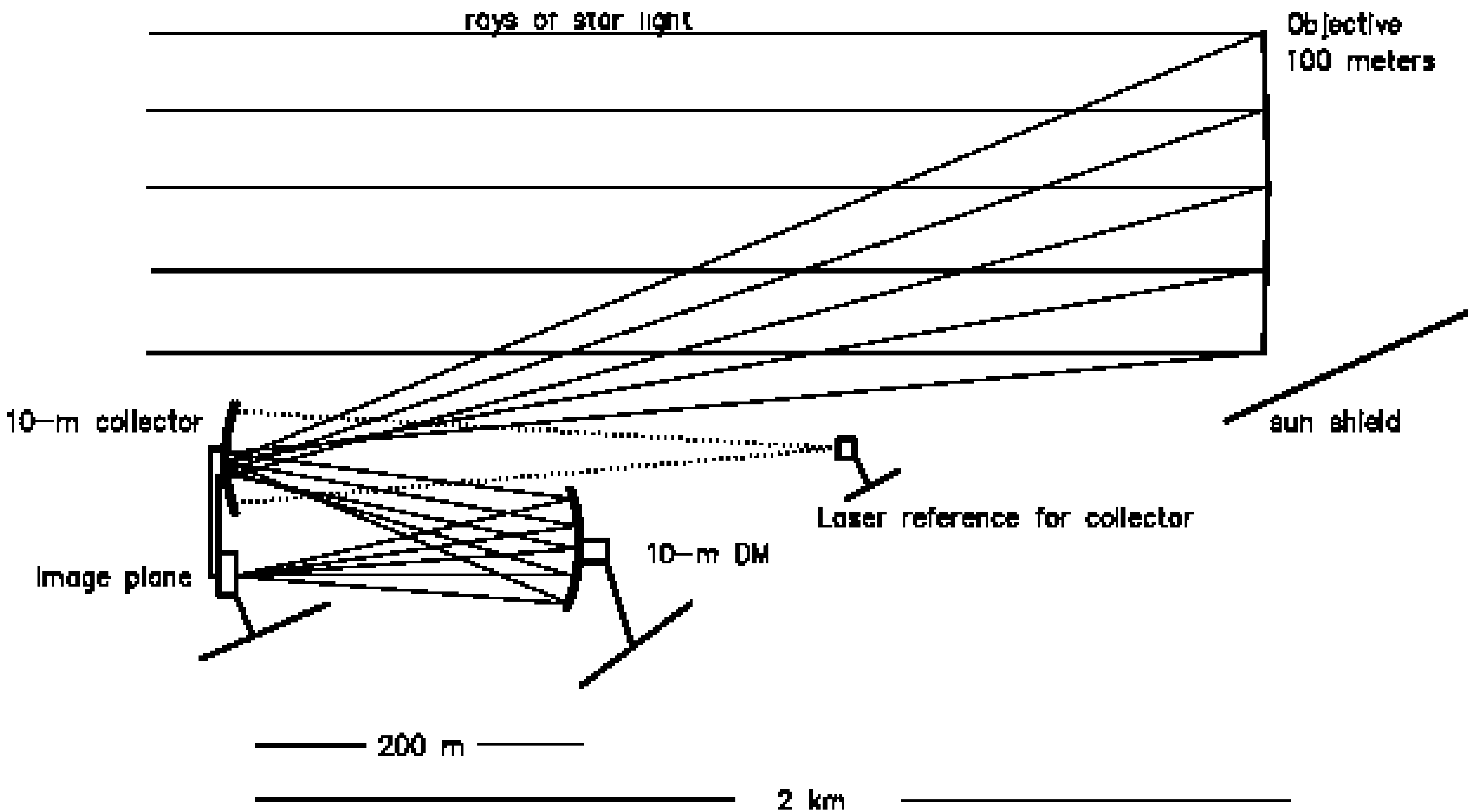
Flat Membrane Optics Concept

Reflective Flat Optics (NIAC Phase I)

Flat panels direct light onto an optic the size of one panel, which images the panels onto a scalloped AO mirror. This inserts the missing paraboloidal curvature needed for imaging.

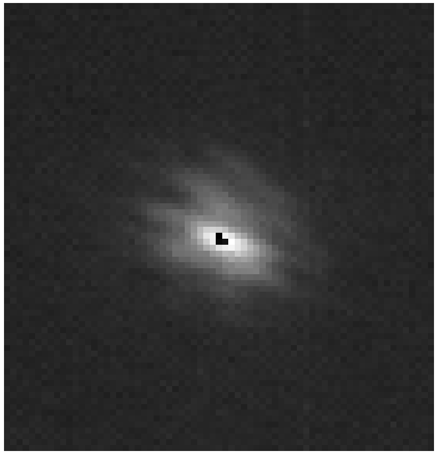
The disadvantages are the large corrective elements, which must be made of rigid material. The concept is totally achromatic, and appropriate for the infrared.

Flat Mirror Telescope Concept



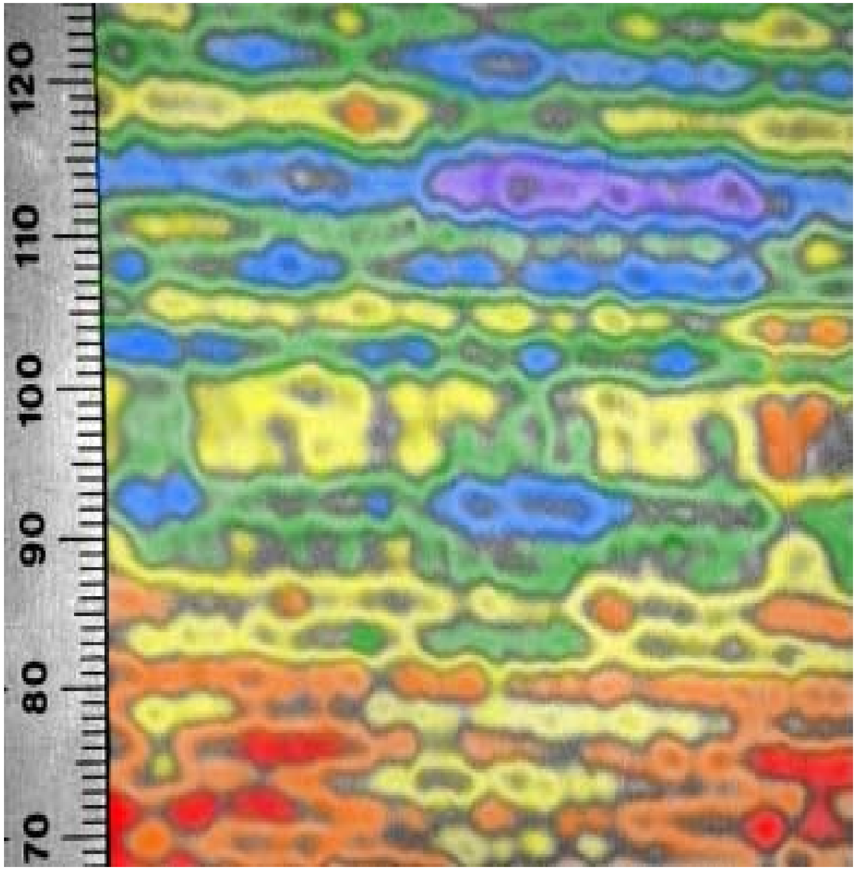
Membrane Studies

1meter diameter membrane mirror being tested



4arc minute field showing double pass image

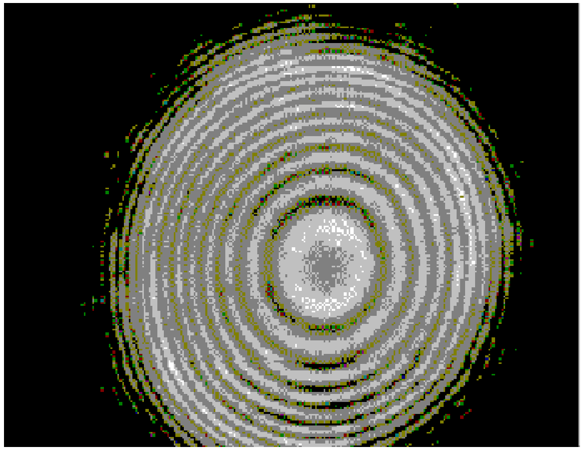
Thickness variations of a film

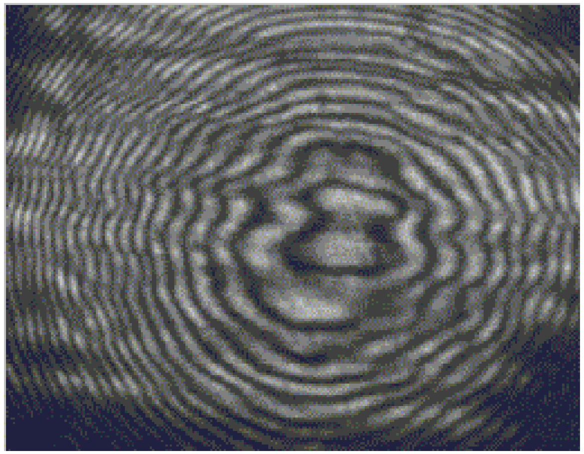


Thickness variations in 25 micron thick commercial DuPont Kapton polyimide film, from a 2 m wide roll. The interferometric map (scale in mm) at 546 nm wavelength gives contours at intervals of 180nm. The peak-to-valley variation is 1 micron over scales of 5 – 10 mm.

Moon picture with 6mm electrostatic membrane

Optical quality of stretched plastic





Interferogram of 0.8 μm mylar stretched and curved by electrostatic field.

Interferogram of 25μm kapton stretched and curved by electrostatic field

Major issues for membranes

- The optical quality of even the thinnest stretched plastic is >20 times poorer than polished glass.
- The mass will be dominated by stretching frames to generate high tension, and so high resonant frequencies.
- Electrostatic damping needs to divert the energy of membrane motion to members that can dissipate.

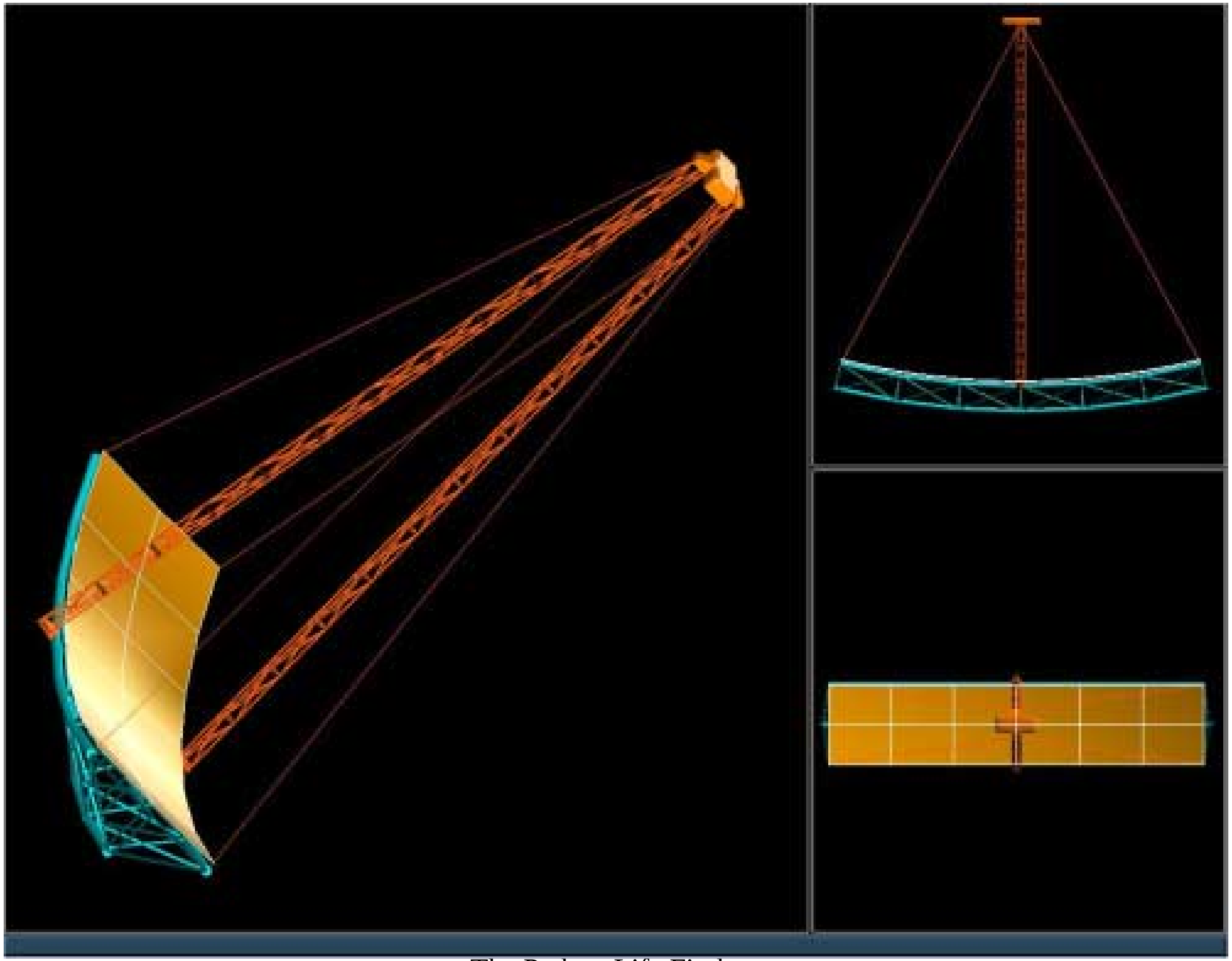
It is possible to plan "Mini" Life Finder now

- Concept would be a 50x10m telescope, made with 12 segments of 8.3X5m mirrors.
- Mirrors would be of 5Kg/m^2 glass.
- Adaptive Optics would be piezo-electric controlled.
- Focal length would be 50m.
- Cooling would be by attached sunshade also used for solar pressure pointing control.
- Total mass would be ~5 tons
- Orbit would be sun orbiting fall away (SIRTF-like) because L2 needs constant thruster use and thrusters generate heat.

Packaging and Testing

- Even for the smallest Life Finder, packaging the structure, and ground testing are a major problem.
- For full scale Life Finders, assembled testing becomes impractical.
- The cryogenic space environment for these complex devices is inappropriate for manned assistance.
- To ensure success, a "mission" must be transformed into an "expedition", with robotic repair and modification built in

“Mini” Life Finder concept



Mini Life Finder concept, view II