The Island Concepts & Technology Readiness

Nick Woolf
Steward Observatory, University of Arizona

Terrestrial Planet Finder (TPF)
Phase 1 Architecture Study Report
Dec 12, 2000

Fixed Angular resolution versus variable. 1

- Angular resolution is a wavelength dependant characteristic of a device with fixed dimensions.
- TPF requirements assume resolution adequate for K7 stars at 15pc. But such resolution is ~ 3x higher than that required to see planets around G2 stars at the same distance.
- Planetary systems will have various inclinations, and earth-like planets, even in round orbits, will be at variable elongation. One half of the systems will be inclined at angles down to 300. For 30 systems the minimum separation will be 0.5 maximum elongation, and the average will be 0.75 maximum elongation. For more inclined systems, confusion will be more marked, but the average elongation will be 0.71.
- We shall assume that resolution of 0.7 of maximum elongation is adequate to find planets.

Fixed Angular resolution versus variable. 2

- Spectral range will also add to the required resolution, since the long-wave end of the spectrum will be more poorly resolved than the short end. We shall assume that the longest wavelength required to observe a spectral feature will be not less than 80% resolved. The required resolution at this longest wavelength is then as if the planet were at 87% of its maximum elongation.
- For fixed baseline devices we require the same # of G stars as in the requirement, and let the other types adjust. This sets ~100 stars as the # for fixed baseline devices
- We define 0.038 arcsec resolution plus ability to cover 100% of the sky plus increase in distance to 16.7pc as equivalent to the 150 star/15pc requirement

Configurations for the nulling interferometers

- In covering a wide spectral range,we need configurations for the nulling interferometer where there is no need to use more than one baseline. Also for fixed baseline devices we need the shortest possible array for adequate null breadth and angular resolution.
- We have developed one such linear array concept, a combined Degenerate Laurance Hexagon (DLH) and a Shrunk Double Bracewell(SDB). However it needs a truss structure to allow for path equalization reflections to occur at other places than the mirrors.
- We need a different array concept for Free-Flyers and Tethered systems. We expect that such a system can be developed, in which we use a regular Double Bracewell, and modify the DLH for the purpose. The array will be somewhat longer than the DLH/SDB version.

Solar System Planets

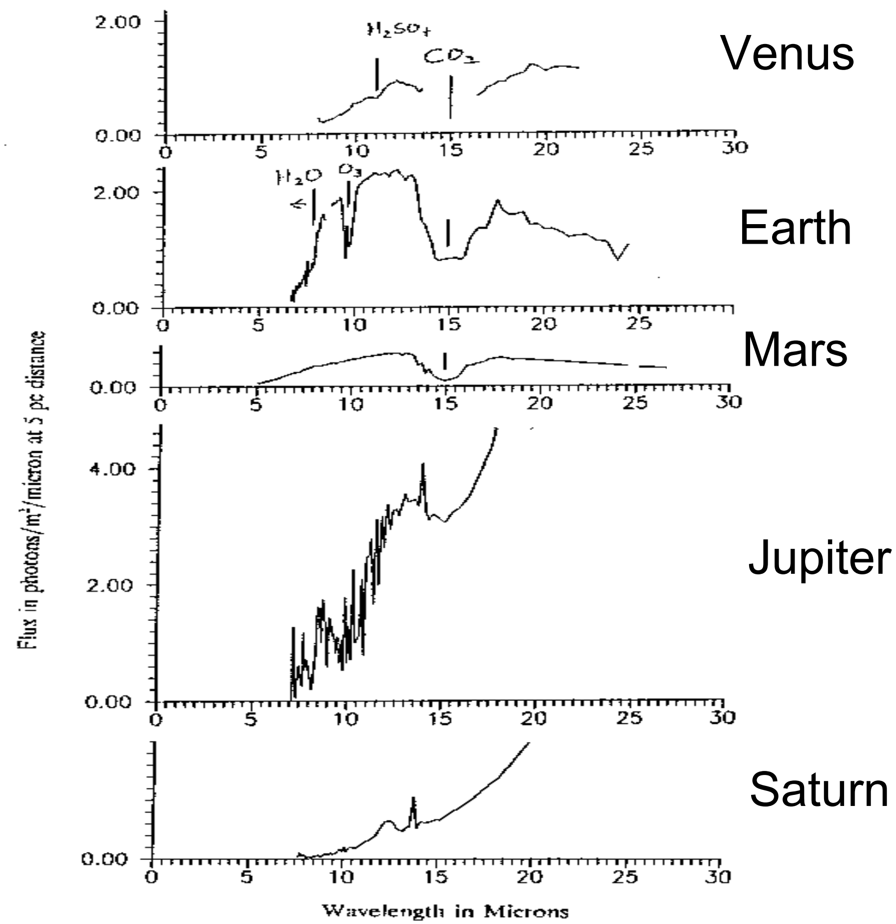


Figure 1 Spectra of thermal emission from planets in the solar system adapted from Hanel, (1983) and Kunde et al (1977). All are plotted to the same scale.

Giant Planets and Close by Stars

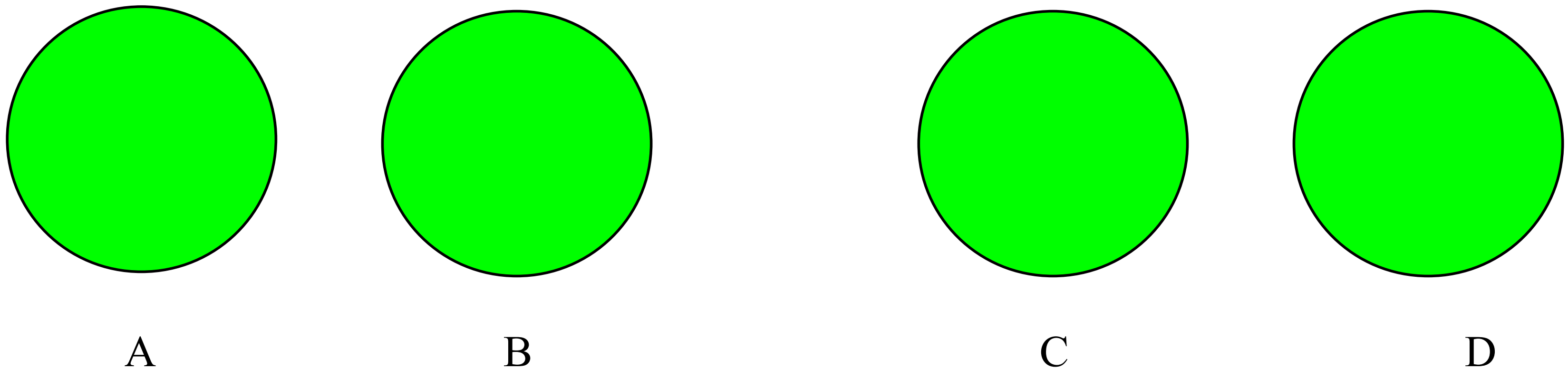
There is a problem with seeing giant planets around closeby stars with nulling interferometers. Interferometer systems with large primary mirrors will have small diffraction cores that leave giant planet images on the outside.

To see Jupiters, the image must be within the diffraction core at wavelengths beyond 12 μm. For Saturns the image must be within the core beyond ~17 μm.

If we exclude A stars, the nearest brighter single stars have Earth-temperature planets no further away than 0.18 arcsec, thus Jupiters are closer than 0.94 arcsec, and Saturns no closer than 1.7 arcsec. Thus to include these planets in the diffraction core, the aperture cannot be larger than 2.6 m and 2.0 m respectively.

To see such planets, there needs to be a nulling mode available in which the pupil is diaphragmed down to 2m at least in one dimension.

DLH/SDB concept



There are two groupings of three mirrors, ABD and ACD. Each of these is used as a Generalized Degenerate Angel Cross. Thus we take the signal from B, and to it add antiphase 3/4 of the amplitude of A and 1/4 of the amplitude of D. Then similarly to C we add 1/4 A and 3/4 D. Each of these then produces a central null.

For a Double Bracewell, we have A+C as one interferometer pair and B+D as the other. Because of the spacing, the chopping uses +/- $\lambda/6$.

Degenerate Laurance Hexagon Response

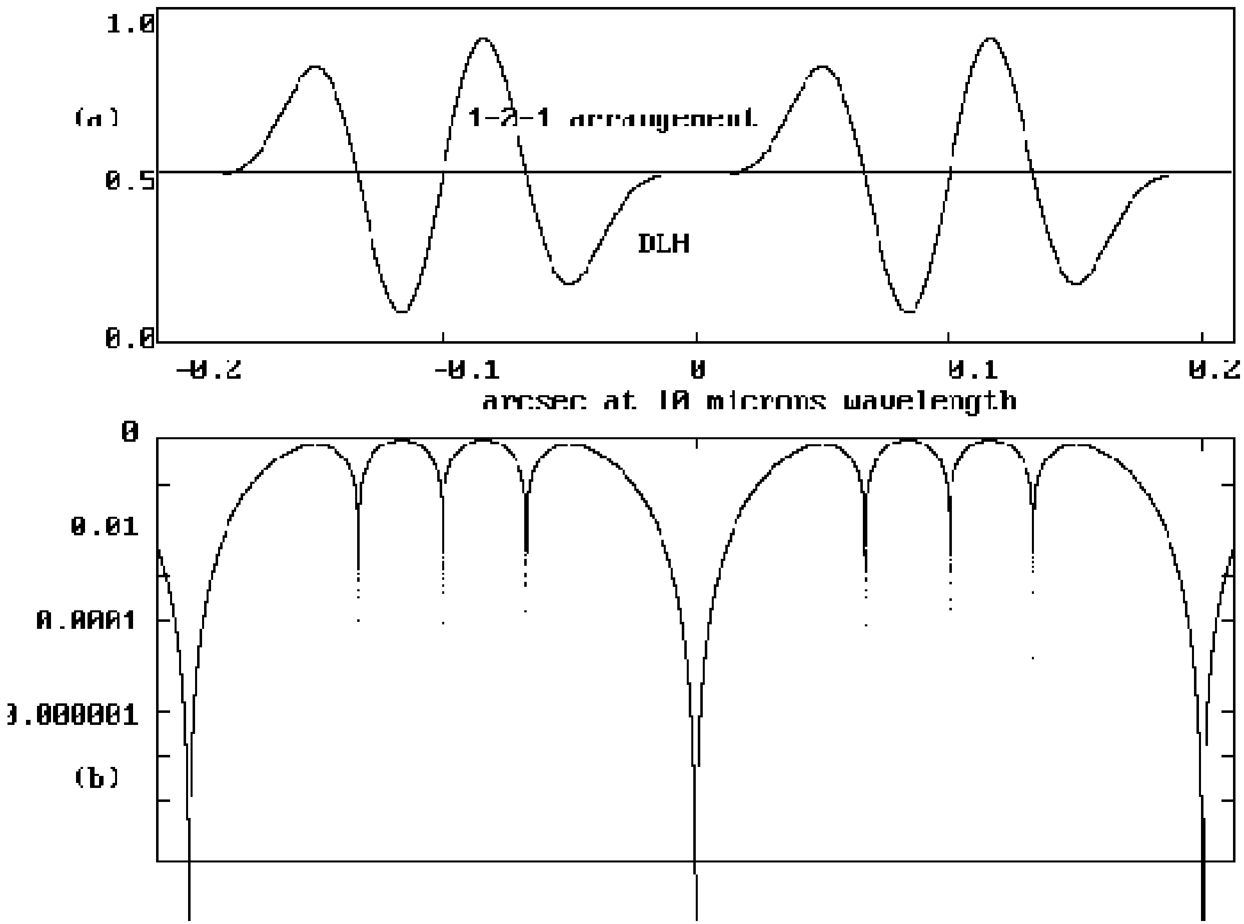
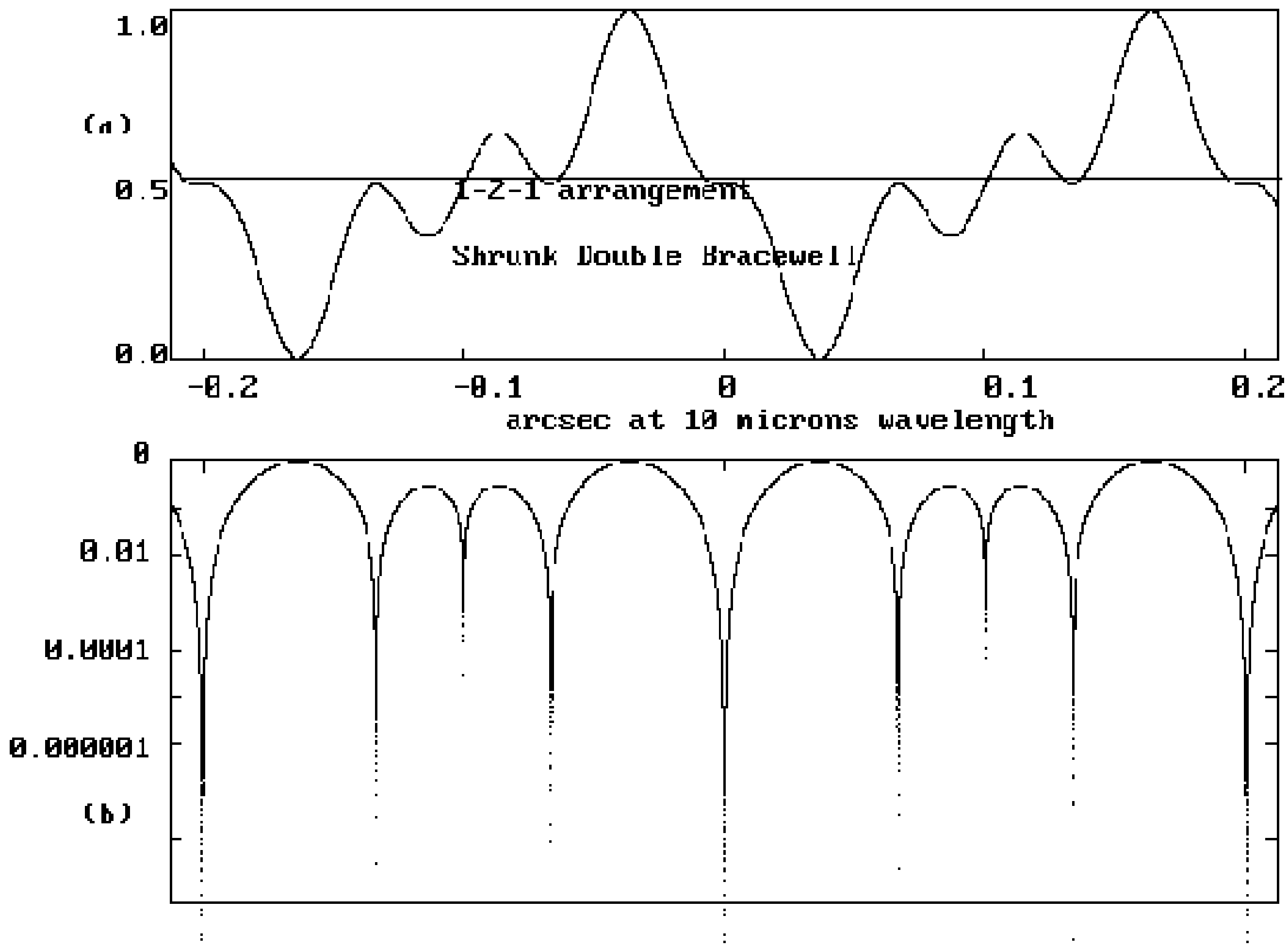


Figure 1 The response of the DLH configuration. The signal is centered on the 50% line, and the peak-to-peak scale is set by the response of the Shrunk Double Bracewell configuration (see below) which is itself only 80% of that of the regular Double Bracewell

Close Spaced Double Bracewell Response



Island 1 Considerations [Free-Flyer]

All configurations, 1D and 2D were considered to be variants of the degenerate or generalized Angel Cross with θ^4 nulling.

When all the mirrors are the same size, then the benefit in time for sending up more mirrors is exactly proportional to the number of mirrors.

Weight of a single mirror system without fuel is W
Number of mirrors is N.
Then weight sent up = WN + Fuel x Time of use x N
Time = K / N
So Weight sent up = WN + K

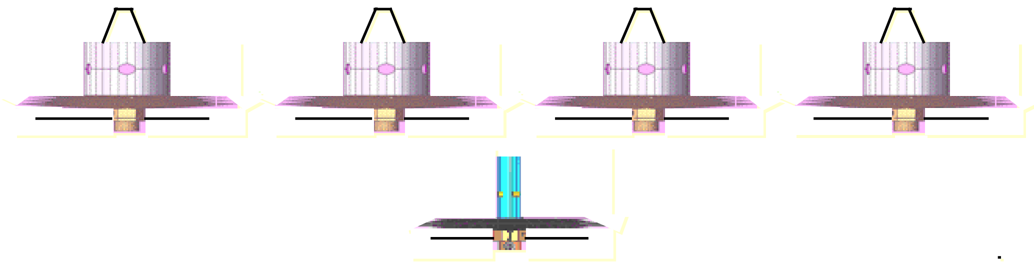
The fuel weight is independent of the number of mirrors, but there is a weight penalty for sending up more units. The **weight is then minimized** by making N as small as possible, and the minimum to achieve chopped deep nulls is 4. This is the number we have adopted and implies a **linear interferometer**.
[written discussion available]

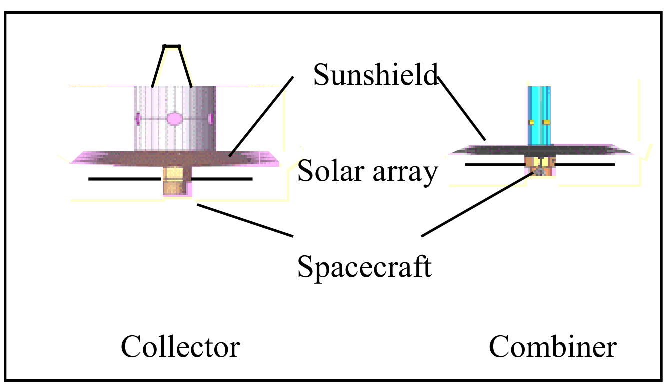
Island 1 Details

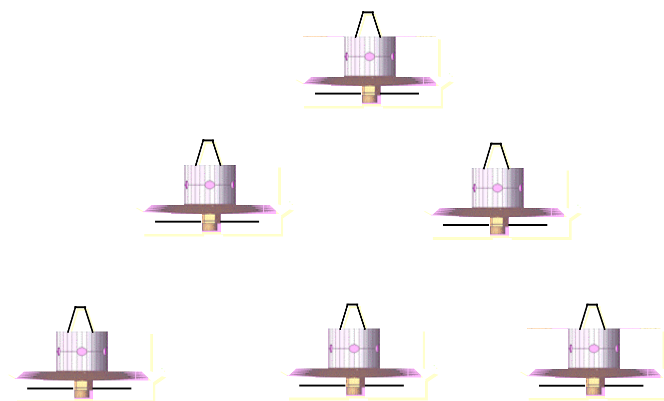
- Mostly our Island 1 concept follows the design shown in the TPF book. However we use just two optical concepts, the modified Degenerate Laurance Hexagon, and the Regular Double Bracewell. When MDLH is used for short wavelengths, RDB is used for long wavelengths

- Our second variant is to offer safety redundancy. The beam combiner is also useable as a telescope, and one of the other telescopes is also useable as a beam combiner

Island 1 Sketch





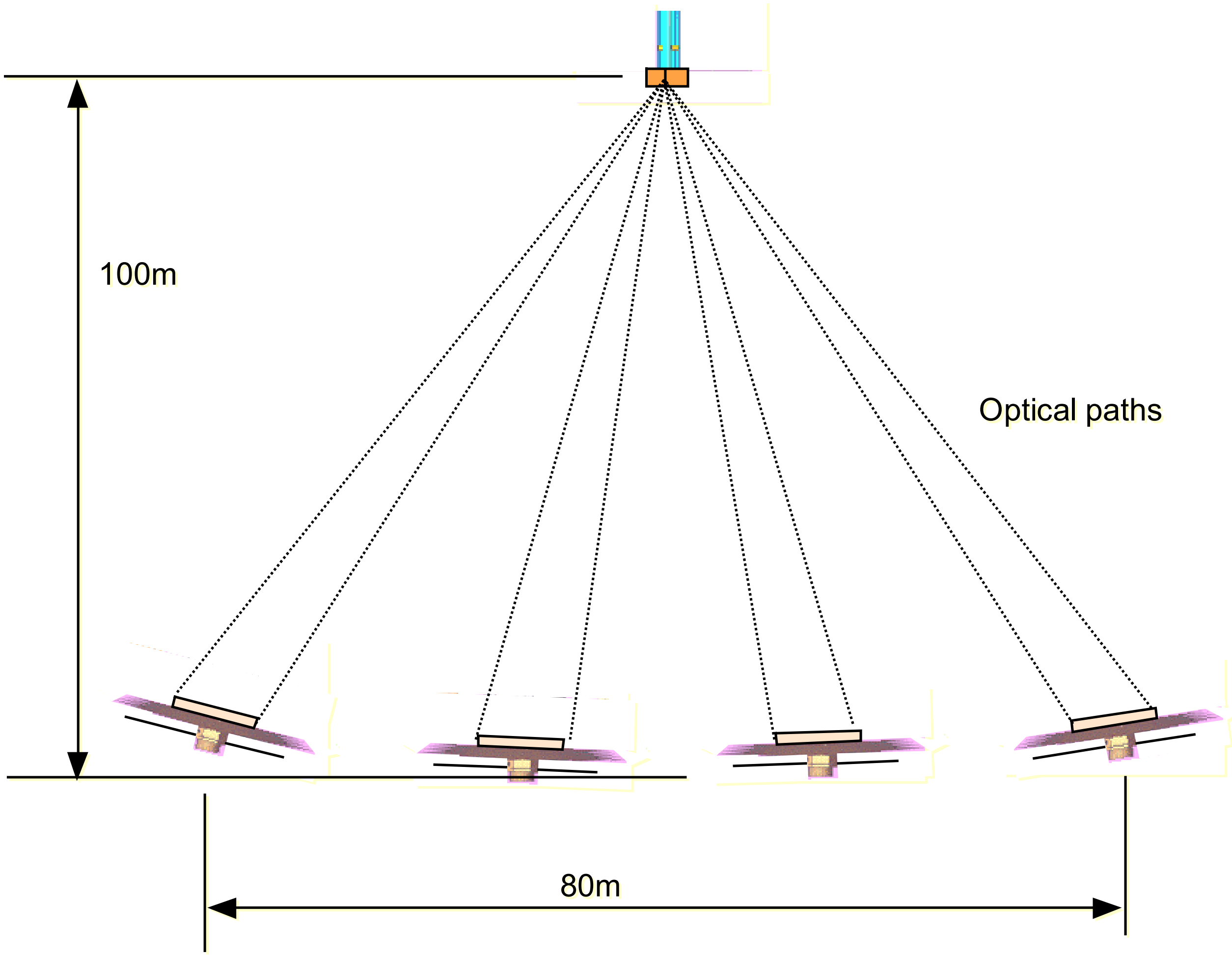


Mariotti Configuration

Island 2 concept [primary mirror segments]

- We found that use of mirror segments is not substantially harder than use of afocal telescopes, but it was difficult to take advantage of this mass reduction without expensive complexity.
- We developed a concept where the segments are moveable along a truss, with one sunshield for the entire truss. We use 4m. round mirrors, and the DLH/SDB configuration.
- The secondary package is a separate free-flying system with its own sunshield.

Island 2 sketch



Island 3 [Truss Nuller] Optics
The Multiple Elongated DLH

For the truss nuller we have 8 mirror segments used as 4 mirrors. This concept with long mirrors was optimized for astrophysical imaging. A less expensive variant just for planets would use 8 3m round mirrors.

Options are: ABCD as a DLH, + EFGH as a spare DLH.

ABCD and EFGH as a Shao/Velusamy double interferometer. This is for nearby stars and short baselines.

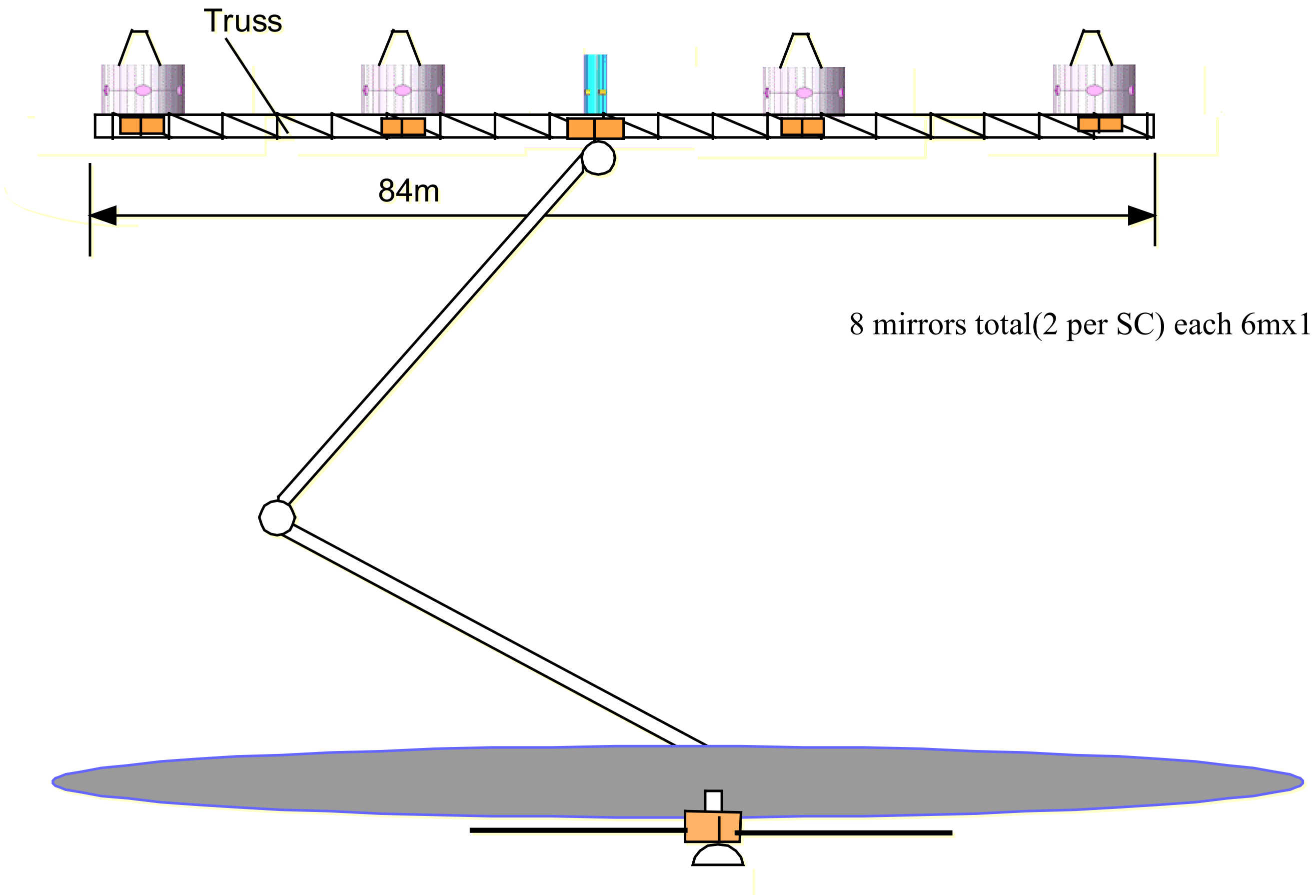
A+B, C+D, E+F, G+H gives a long baseline DLH.

Equally each set of 4 mirrors can be used as a Double Bracewell with effective baseline 1.5 x that of the DLH.

Island 3 Details

- Island 3 is an 84m long truss with 8 mirrors each 6m x 1.1m, each just off-axis so as to require no central hole. Segment pairs use a common secondary on a 12m truss.
- The truss is divided into 7 sections each 12m long on to which the mirrors are mounted before launch.
- A solid hydrogen cryostat is inside the truss.
- The sunshade is presently planned to be coupled to the main truss with a slender truss. An alternative version with the sunshield free-flying is still under consideration.

Island 3 sketch



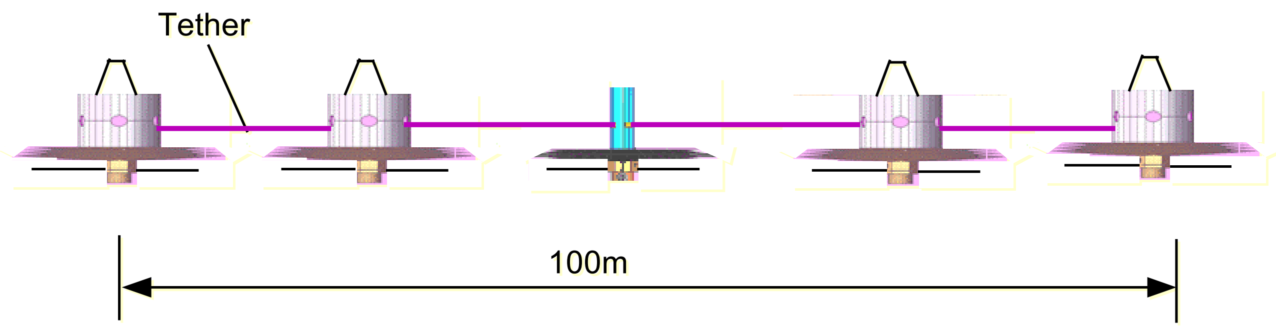
8 mirrors total(2 per SC) each 6mx1.1m

Island 4 Specification [Tethered]

- The arrangement of telescopes with tethers to connect them to the beam combiner seems to save fuel, but at the expense of considerable mechanical complexity. We were unable to find an arrangement of tethers for 4 telescopes that worked both to permit astrophysical observations, and to allow a linear interferometer. A better configuration for this would be a Laurance Hexagon.

- The arrangement shown has the individual units very similar to island 1.

Island 4 Sketch



Island 5 Concept [Coronagraph]

- We analyzed the required mirror area by estimating the optical efficiency, including the apodizing mask and the spectrograph. We assumed that N star photons are collected with each planet photon.
- We separately calculated the needed mirror area and long dimension. The mirror needs to be long and thin.

N	*Square meters at 0.072 efficiency*	*Equivalent primary mirror diameter*
1	*50*	*8m*
2	*60*	*8.7m*
5	*97*	*11.1m*
10	*165*	*14.5m*
20	*306*	*19.7m*

Inefficiencies include a factor ~5 in the apodizing mask, and a factor 2 between the spectrograph and detector.

Island 5 slide 2

The exteme diversion of starlight requires:

- apodization (perhaps with nulling) to reduced the diffraction rings and
- reduction of scattered light by

  a) excellent polish

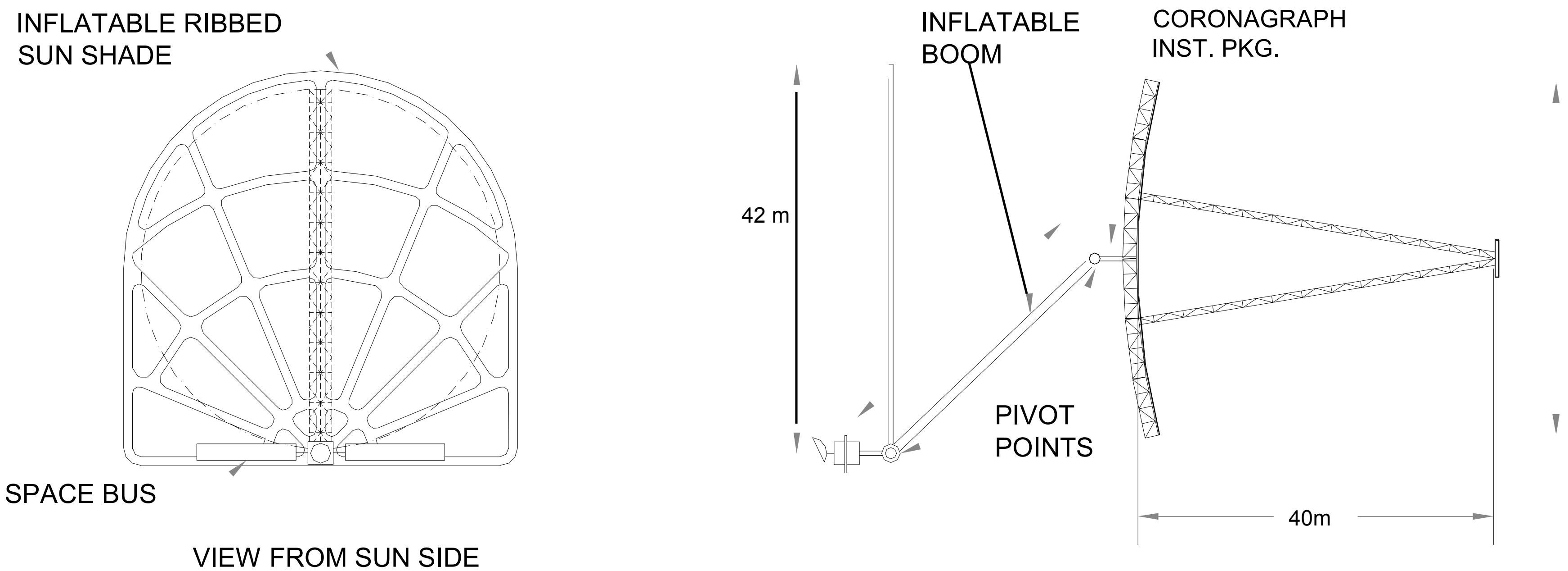
  b) UV phase diversity to adjust figure to ~ 1nm.

  c) 100,000 to 1,000,000 AO actuators and electronics sets

  d) Special treatment of mirror segmentation

  e) Balance reflectivity over every surface to ~ 0.1%

Island 5 sketch



Technological Readiness Issues

- Primary mirror technology - All Islands
- Nulling - Islands 1,2,3&4
- Coronography - Island 5
- Passive cooling + sunshades - All Islands
- Free-flying control - Island 1
- Space truss structures - Islands 2 and 3
- Tethers - Island 4
- Magnetic coupling - alternate option for Islands 1 and 4

TPF Relation to Origins

TPF is one of three planned ORIGINS missions to find and study Earth-like planets around other stars.

The others are :

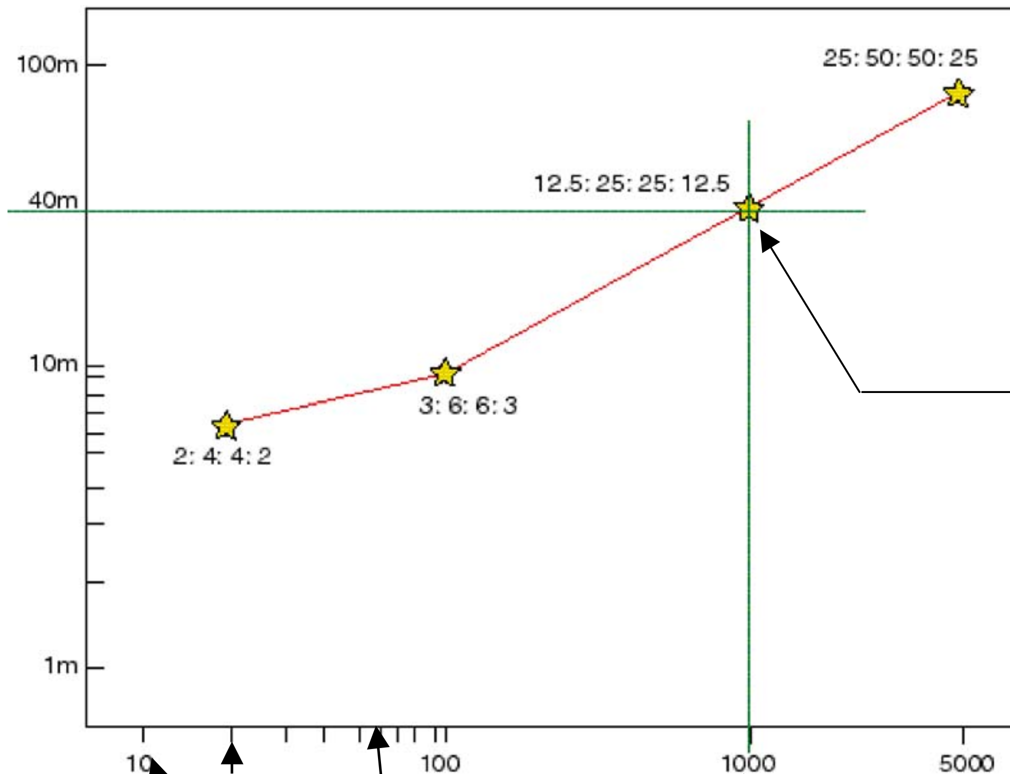
Life Finder *to look for additional bio-markers, and*

Planet Imager *to make images of any Earth-like planets found to be habitable and have bio-indicators.*

TPF is intended to leave a technological legacy for these missions, but because PI is far in the future, we have focussed on legacy for Life Finder.

Developing One Concept for Life Finder

"Effective" Aperture Diameter



total collecting area equal to a 40m aperture

Spectral Resolution

bulk gases: carbondioxide, ozone

temperature profiles

trace gases: terrestrial methane

<u>Assumptions</u>
λ = 7-17 μm
10^{-6} starlight nulling
1 month of integration
exozodi = 1 Solar zodi

Life Finder Potential Technologies

Life Finder potential technologies are:

1) Interferometry

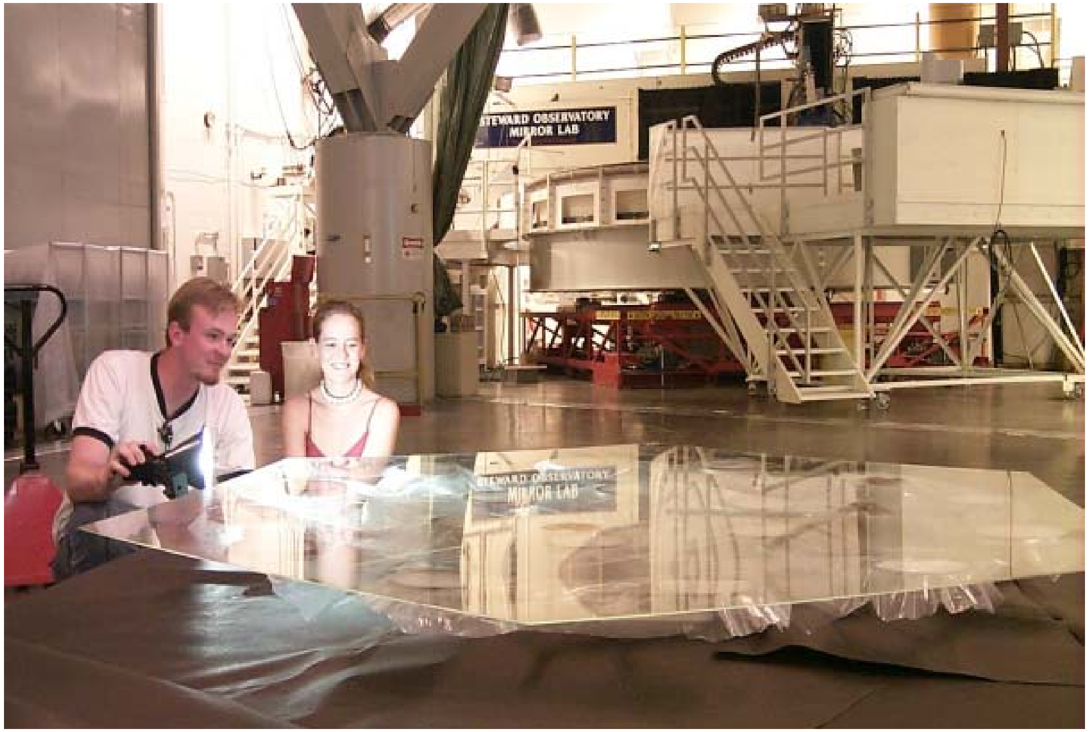
2) Large Space Telescope structures

3) Possible coronagraphic isolation of planets

4) Possible free-flying spacecraft

All these are key techniques being considered for TPF (and PI).

NMSD Glass Membrane

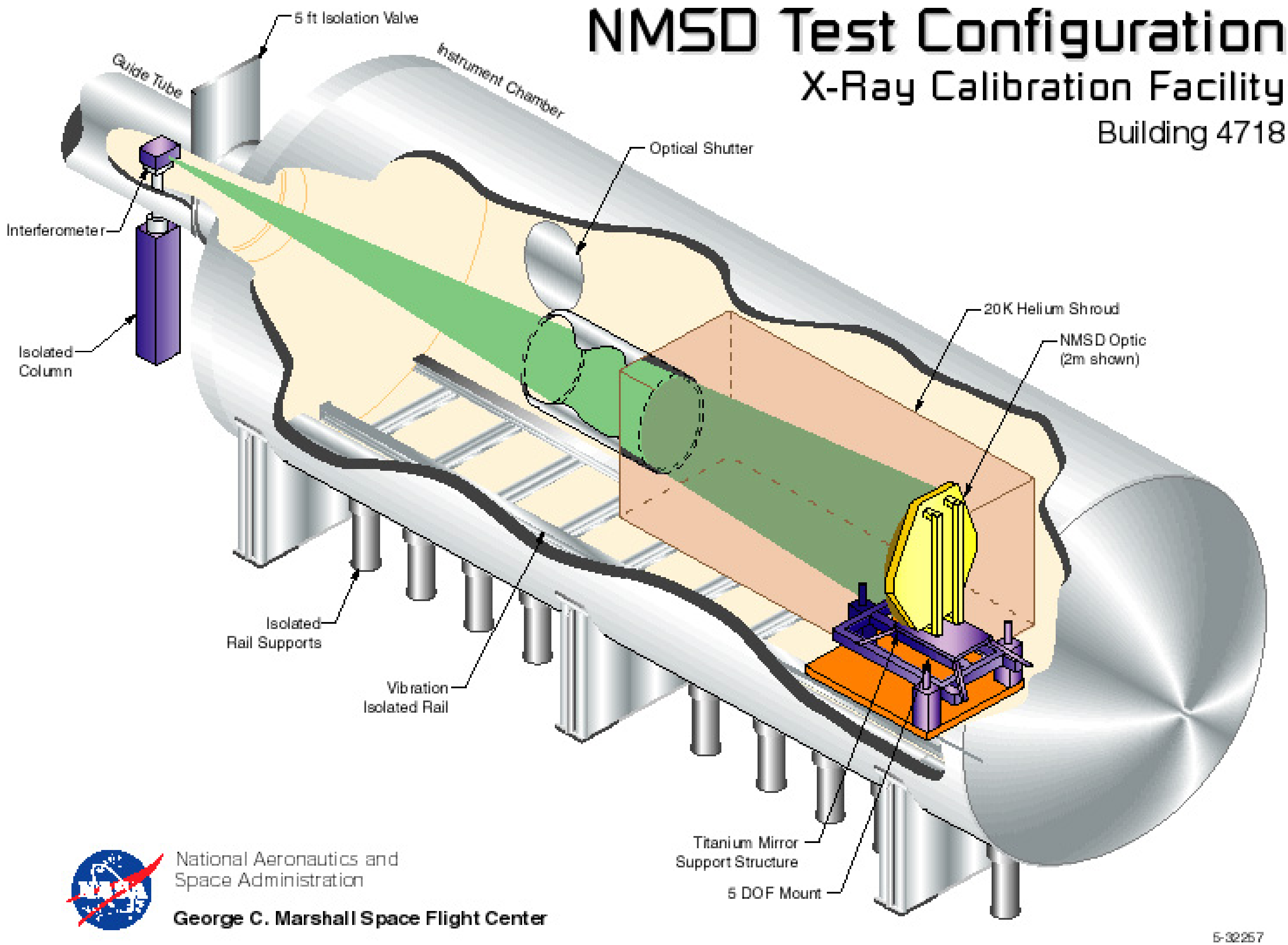


2m across

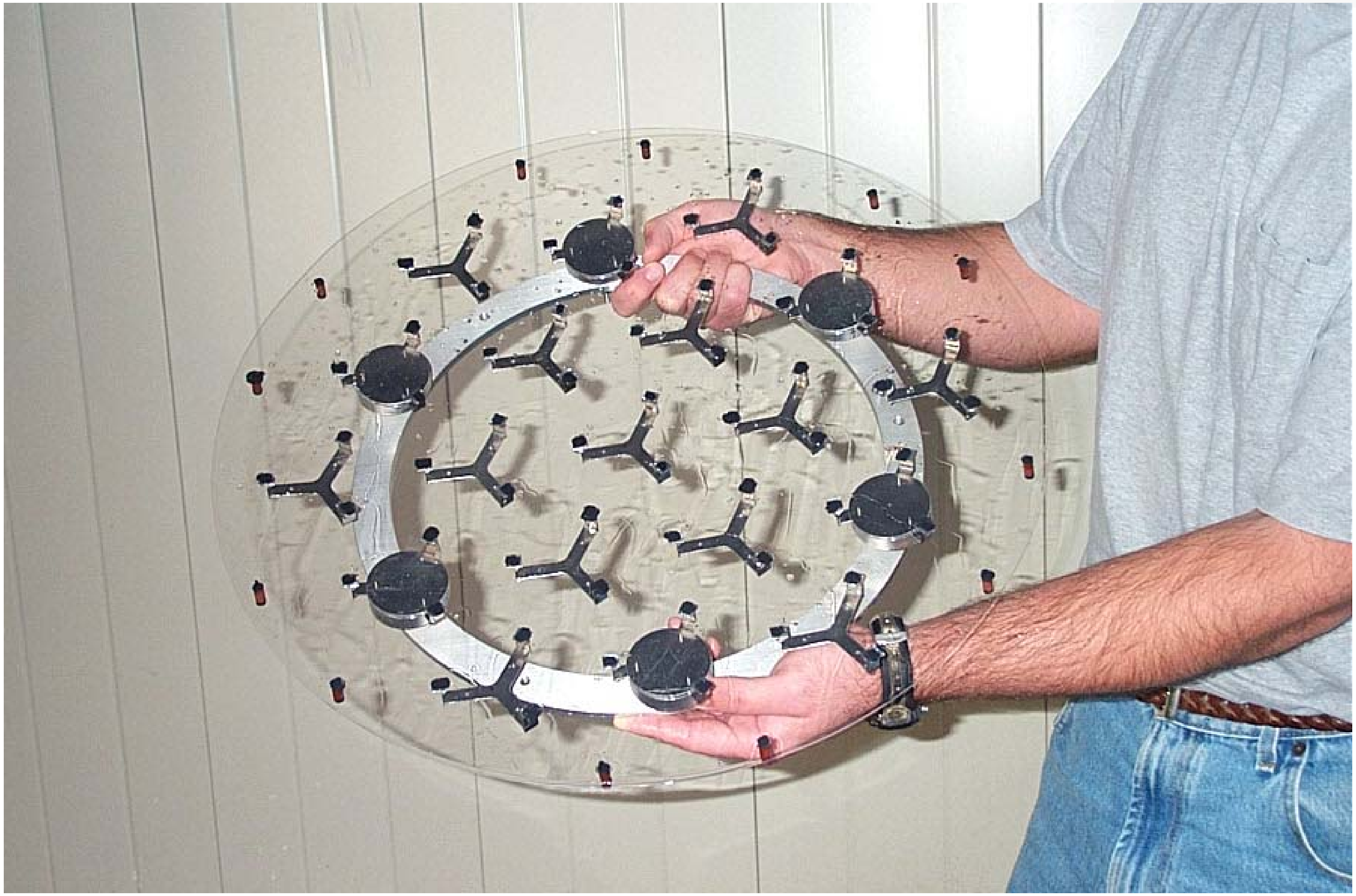
2 mm thick (4.4 kg/m^2 by itself for a ~15 kg/m^2 system)

Borosilicate glass -- 0 CTE at NGST 35 K operating temperature

Cryo testing of NMSD at MSFC to start 2001



0.5 m Polished Mirror, 0.9mm Thick



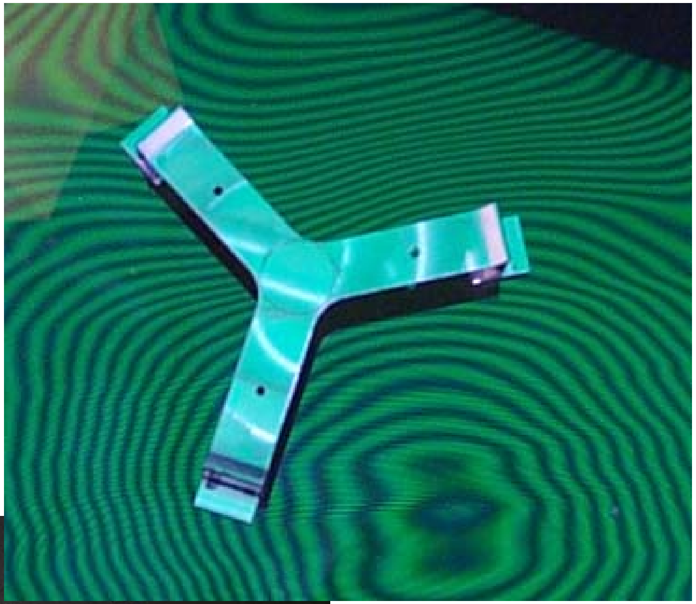
NRO actuators

- 5 grams each
- 20 nm step size (these give ~ 4 nm motion of the glass due to attachment compliance
- Use tiny parts, hard to manufacture!
- 50 units in production (need 31 for mirror)
- Actuators developed with support by NIAC (7g). Reduction to 5 grams done in NRO program

Loadspreaders that connect actuators to glass

- No stray forces from attachments

- parts are ready, waiting for glass



Primary Mirrors Status

- Need cryo testing
- Need space testing

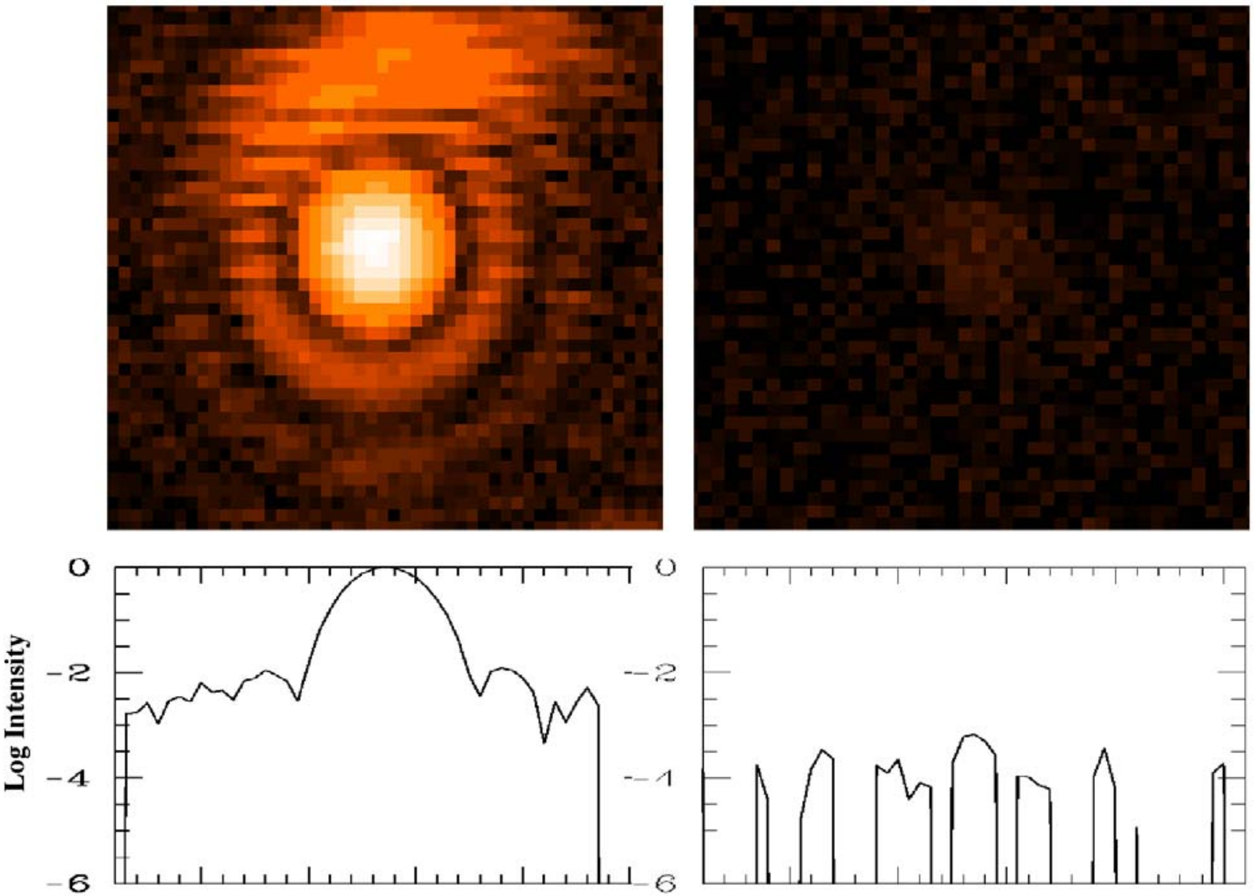
Moving towards TRL 5

Components have been developed towards NGST/TPF application and for the appropriate level of performance.

This is the most advanced of the new technologies to be used, but because it needs a flight demo first, it is suggested that this should NOT be used for a precursor mission.

Initial Nulling Laboratory Results

0.5 s exposure images at 10.6 μm. Log scale



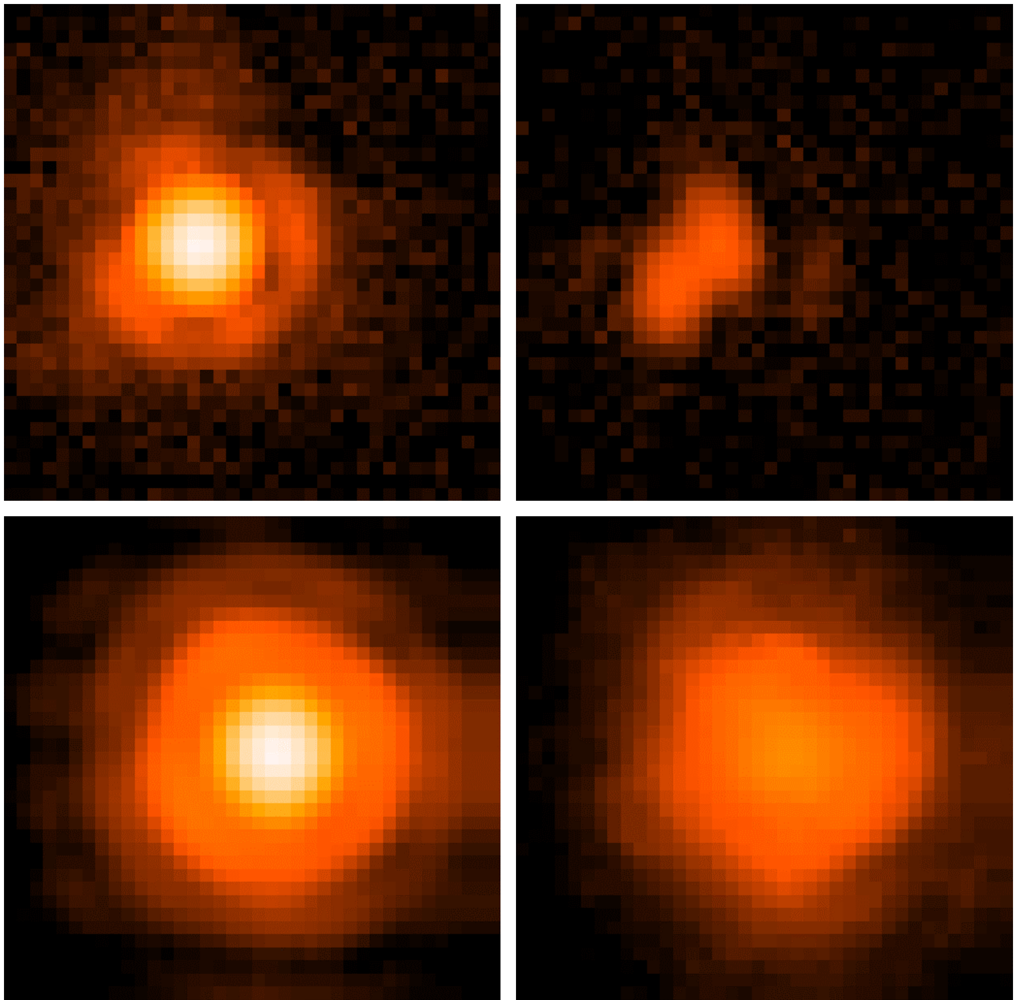
Results from our first trial with a CO_2 laser yielded a null with an integrated flux of **3×10^{-4}**
We have also achieved a **2%** null over a 50% bandwidth, limited by The spatial coherence of our source.

Cryogenic Nulling Imaging at the MMT

constructive | destructive

α Boo

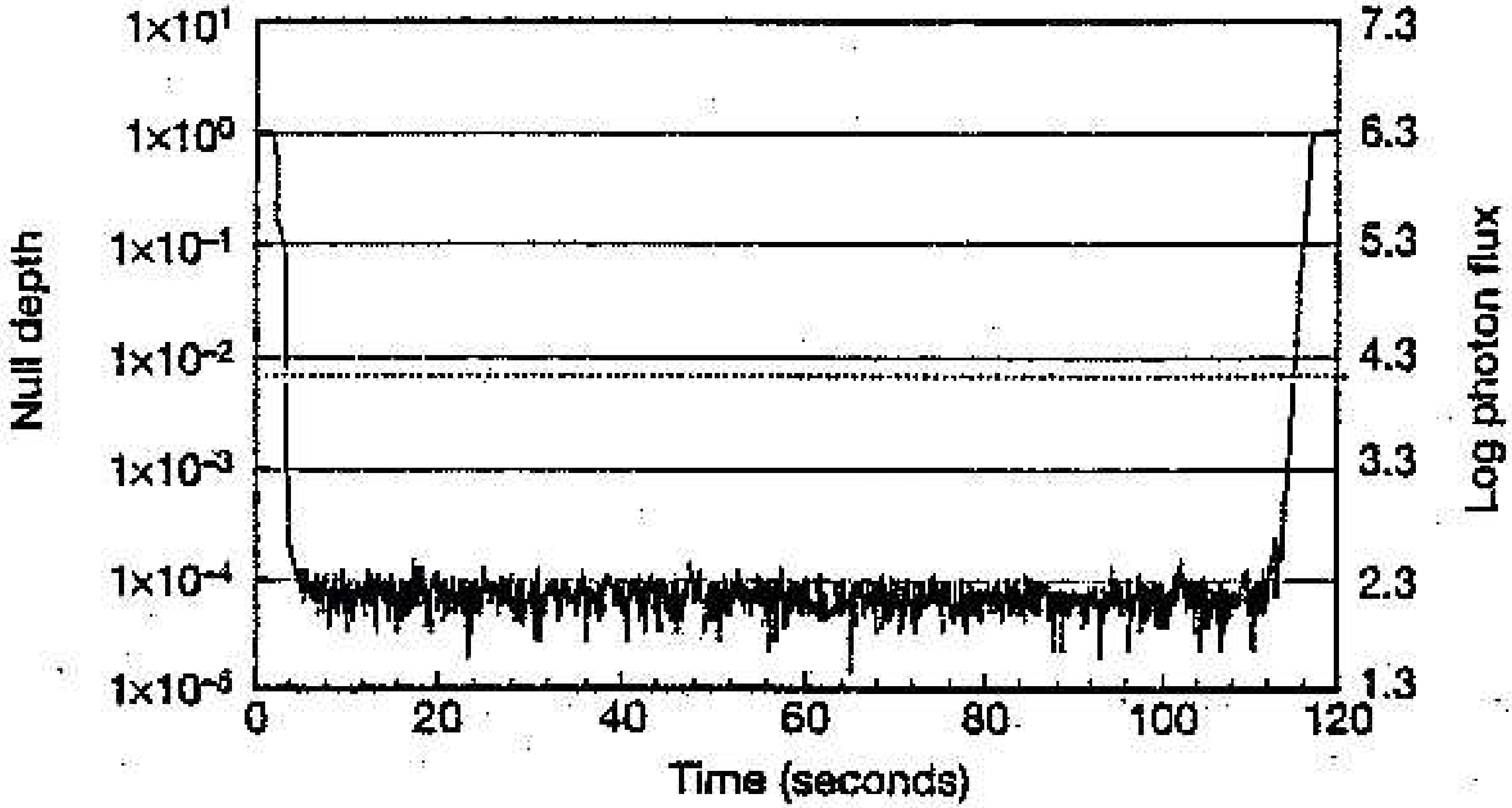
α Sco



Best nulls of α Boo have a peak ratio of 3%. The integrated light is 6% of the constructive image.

The nulled images of α Sco are 25% of the constructive images. Suppression of the starlight allows us to form direct images of the dust outflow around the star

Nulling Phase Stability Demo by Serabyn (JPL)



How Nulling Needs Change with Wavelength and to Precursor

We consider a sun-like star at 8pc, and the nulling requirements for total apertures of ~50m² (TPF) and 2.3m² (PDI=TPF-precursor).

	7µ	8µ	9µ	10µ	12µ	14µ	18µ	20µ
2.3 m²	64,000	28,000	15,000	8,700	**4,000**	2,300	1,500	1,100
50 m²	**1.4 10^6**	600,000	340,000	190,000	90,000	50,000	33,000	24,000

The nulling required is such that the star gives half as much flux as the solar system zodiacal dust.

Each nulling precision is associated with a needed rms phase control e.g., 1.4 10^6 at 7µm needs +/- 1nm   4000 at 12 µm needs +/- 30nm Likewise at 7µm with TPF there is a need for 0.1% amplitude control. At 12µm with PDI there is a need for 1.6% amplitude control.

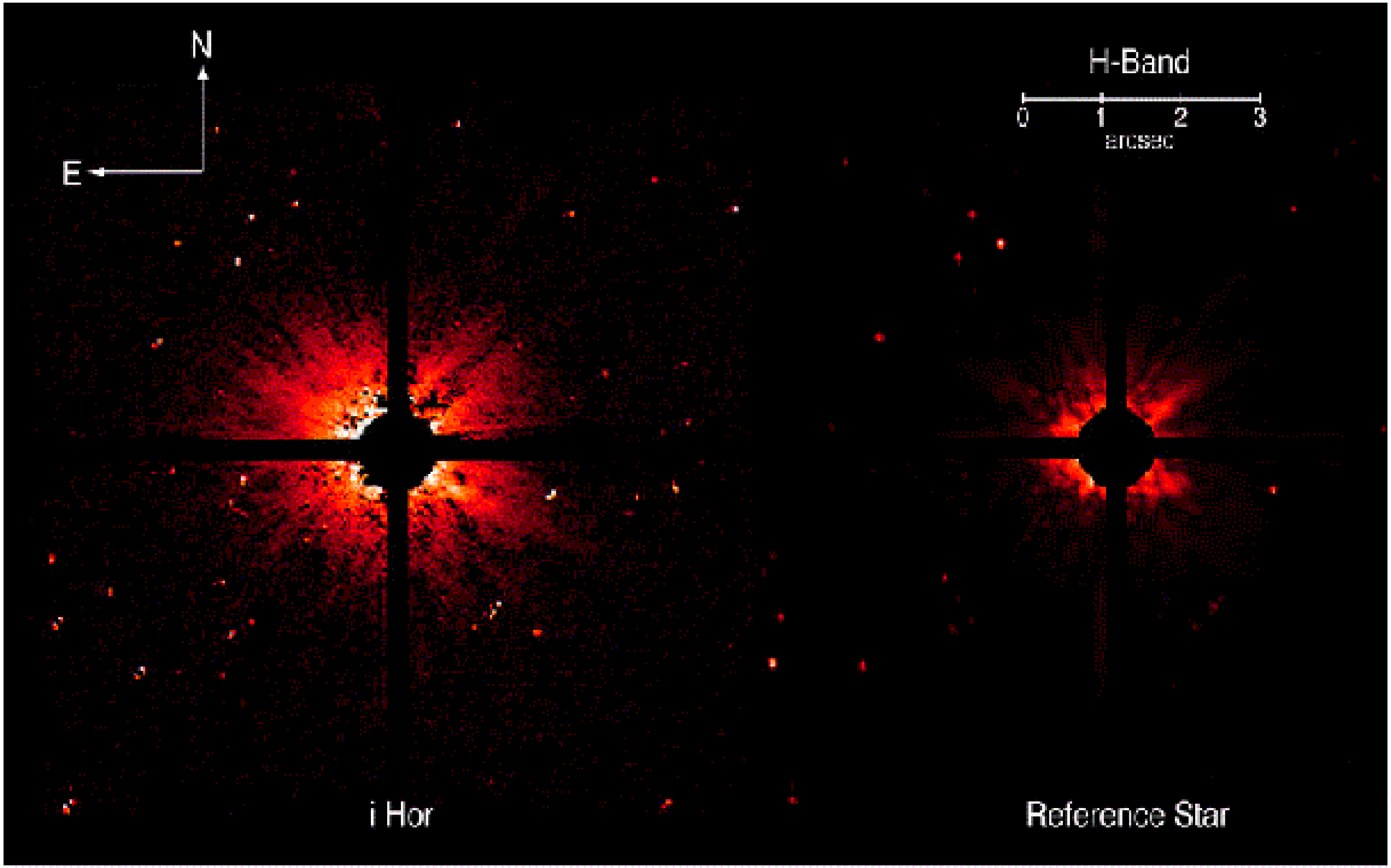
Nulling Status

- Null quality at single wavelength adequate ~10^{-5}
- Null broadband at appropriate wavelength - components do not yet exist.
- Nulling components not yet developed for good optical efficiency
- Nulling components not yet tested for cold and space performance
- Broad-band beamsplitters of other than 1:1 ratio and >1% precision do not exist even in design.
- **TRL3**

Components have NOT been developed towards this application NOR for the appropriate level of performance. New technology may be needed.

Because demands are so reduced for a precursor, the needed performance is much closer to being available.

AO Coronagraph Result



The Disk around Iota Horologii (ESO 3.6-m Telescope + ADONIS)

ESO PR Photo 27/00 (13 October 2000)

Coronagraph Status

Diffraction ring reduction to ~10^{-9} not yet demonstrated

Scattered light reduction to ~10^{-9} not yet demonstrated

~10^{-5} has been demonstrated at a telescope.

TRL 3

The stability of the mirror surface at the ~1nm level is not known.

Unknown what time scale correction will be needed, and whether appropriate AO exists.

Unknown whether low surface density optics can reach the appropriate surface finish at reasonable cost.

The handling of cracks between mirror segments not yet developed.

Passive Cooling

Passive Cooling and Light Shielding Status

Passive cooling demo for GEO existed (1980).

A large inflatable sunshield has been deployed on the ground.

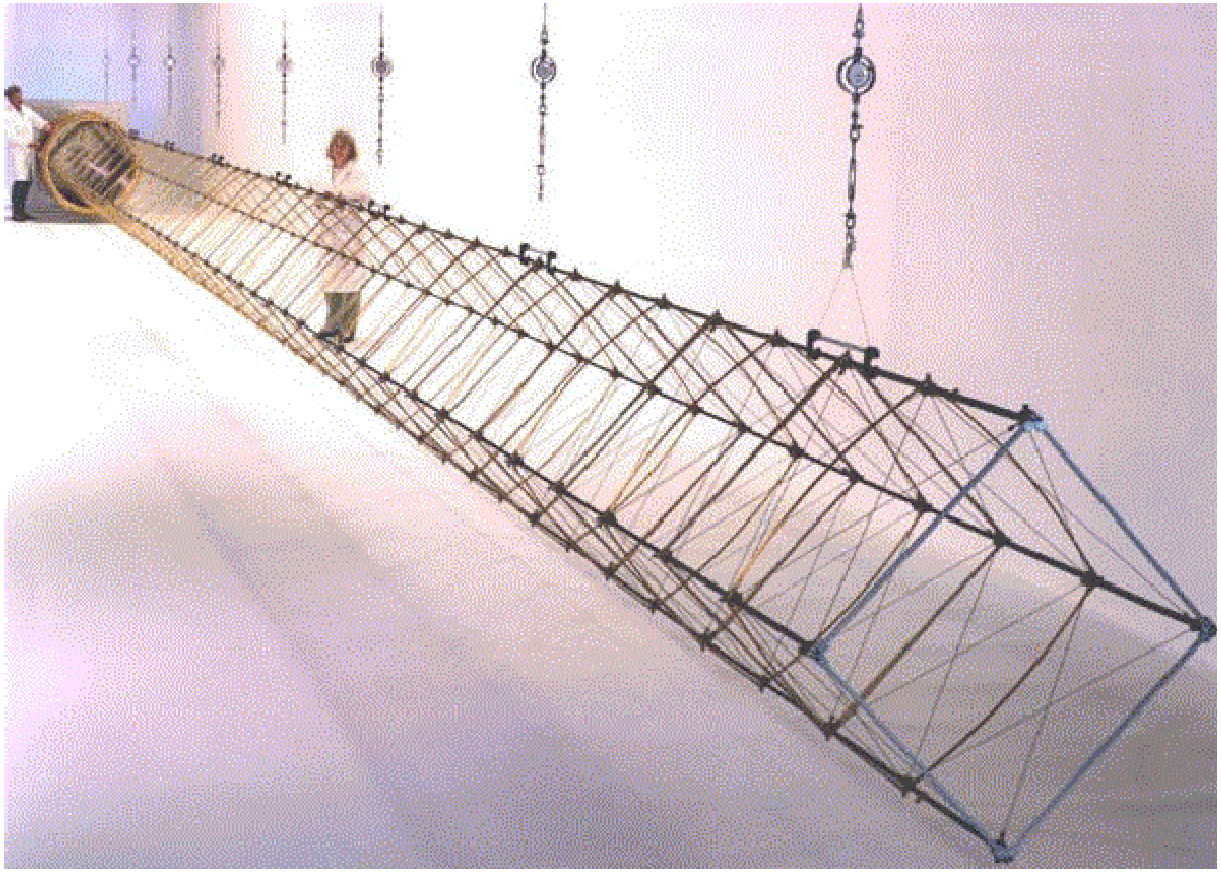
Passive cooling of a telescope structure will fly with SIRTF.

Designs appropriate for TPF (and other large space telescopes) only exist as primitive concepts.

TRL 3

This technology seems to be the least adequately developed for TPF. New inventions may well be needed.

Space Truss Structures



Space Trusses Status

Large not-very-rigid trusses in space have been demonstrated

Either a means of connecting telescopes to a truss, or a way of sending up portions of a truss with telescopes pre-connected have not yet been demonstrated.

Nor have variants such as tethered components or magnetically connected components been demonstrated.

TRL 5 for trusses

TRL 1 for magnetic coupling

TRL 2 for tethers

Appropriate concepts seem promising, and do not seem to require any novel technological inventions

Will Other Missions Develop what TPF Needs?

ST-3 and SIRTF will help.

De-scoping of SIM and NGST leave more ground to make up for TPF. The total descoping will probably change with time and will be difficult for TPF to plan on.

At these low TRL levels, the work needed is not just linked to the level, but also to the intrinsic difficulty of the task.

Overall, the low TRL for TPF technological needs suggest that we will not be ready for TPF in 2012, even if funds are available. The readiness towards a precursor is considerably greater, and could meet this time scale.

Islands and Requirements Conclusions

- We have developed concepts for 5 islands
  - unlike the 6 concepts we have rejected, all of these 5 seem to have considerable scope for implementation.

- We have made progress towards understanding the technology needs for the concepts. If there is to be a 2012 launch of TPF, a suite of substantial technology development programs need to be implemented rapidly.

- For nulling at least, the precursor requirements are substantially reduced, and an early precursor mission is achievable with a modest technology development.