Optical and Mechanical Options Development

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Terrestrial Planet Finder (TPF)
Pre-Formulation Phase Architecture Study
Pre-Architecture Review (PAR)
December 12-14, 2000

Evaluation Procedure

1) All devices to be compared at this stage must satisfy the TPF requirements of numbers of stars to be observed, Signal/Noise ratio of habitability determination and Signal/Noise of Biomarker(s). [We will need a separate discussion to compare fixed baseline/resolution and variable baseline/resolution devices]
2) Quality of information about the terrestrial planet (spectral region, spectral resolution and signal/noise limit) is compared.
3) New technology needed, especially development time and cost and assessed risks are compared.
4) Weight, size, packing and deployments are compared.
5) **Relative benefits,costs etc are weighed to give a single number.**

Evaluation Items

- RISK is the danger that the concept will encounter a major technological hurdle that prevents it being implemented in cost and time.
- RELIABILITY/ROBUSTNESS is the mean time to failure/the amount of redundancy placed in the system without change in performance with a failure.
- HERITAGE is the ability to make technological and experiental progress towards Life Finder and TPI.
- ASTROPHYSICAL IMAGING presented problems for every concept considered. Free flying systems required an additional mission to fill in short baseline information. Fixed baseline systems were unable to supply the long baseline information. In all cases, optimization for planet studies de-optimized astrophysical abilities and vice versa.

Method of Architecture Development

Phase 1 (Complete)

- Stage 1 Categorization of design space.
- Stage 2 Development of Evaluation Matrix by use of reference design and a priori "good" options.

Phase 2 (Not yet started)

- Stage 3 Development of optimum designs within each unit of design space.
- Stage 4 Development of structural and packaging architecture etc.
- Stage 5 Discussion of the differences of optimized designs with science team.
- Stage 6 Re-optimization of designs.

Types of Observation Considered Worth Study/discussion

- Visible - planet atmosphere observed while planet occults star.
- Visible or IR - planet observed during artificial occultation of star.
- Visible - planet observed with coronagraph.
- Near IR - planet observed with coronagraph
- Mid IR - planet observed with nulling.
- Radio - planet observed with nulling.

Toolkit

We consider a suite of tools to use with these concepts, though not all tools will fit all concepts, and other sets may play together very well.

The ways of getting rid of starlight are nulling (including schemes such as that of Gay), coronography (internal occultation), pupil masking and apodization, and external occulting.

Other tools available are use of lower mass-per-unit-area optics, shaping apertures, using single mirror apertures rather than afocal telescopes, separation or partial separation of the sunshield from the telescope.

Tools to avoid the likelihood of thruster contamination of optics include lowering the mass of separated telescopes or use of a single connected optical support structure. Note that this is not inconsistent with long range NASA plans for large telescopes and interferometers, which do or may use large mechanical structures, and in which those structures are far separated from other similar structures.

TPF Optical Architecture
Optical Configuration Options

Starting point:

- Angular resolution
- Wavelength range
- Field of view for planets
- Adequate rejection of starlight
  - All of these depends on desired system distance range
  - Maximum and minimum distances both important

Architectures divide into three broad categories:

1. Rejection of starlight by nulling, i.e., superposition of out-of-phase stellar wavefront pupils at a semi-transparent beam-splitter.
2. Rejection of starlight by coronography - a combination of apodization (pupil shading) and focal plane blocking or phase manipulation.
3. Separately orbited occulting disk associated with interferometer (infrared) or more normal telescope (optical).

TPF Optical Architecture
Optical Options continued

1) Nulling aperture configurations:
   - A) Separate elements in a line; e.g., OASES
   - B) Separate elements in a two-dimensional array; e.g., DARWIN
   - C) Superposed wavefronts derived from a continuous filled aperture; e.g., rotation shearing interferometer

In the TPF book, in the table on p58, we see that lines 1,2,3,5 are all of category A; lines 4 and 6 category B. No versions of type C were studied.

TPF Optical Architecture Optical Options - 3

2) Coronagraphic systems

D) Near-filled round aperture
e.g., the apodized aperture discussed by Angel Cheng and Woolf (1986)

E) Elongated filled aperture
e.g., the NGST version discussed by Angel, et al. Proc SPIE 2807

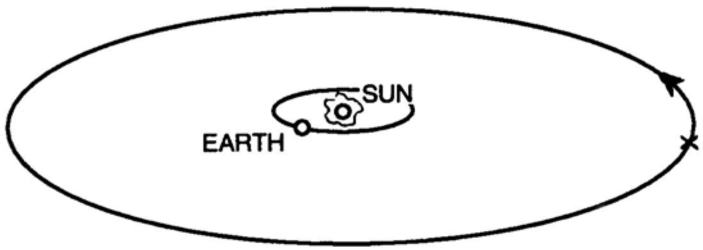
F) Dilute aperture
e.g., the dilute aperture recently discussed by Labeyrie

3) Occulting systems

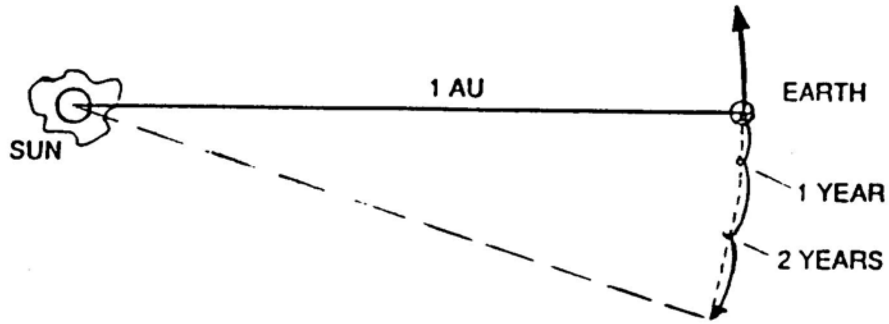
G) e.g., BOSS by Glenn Starkman

H) Natural occultations

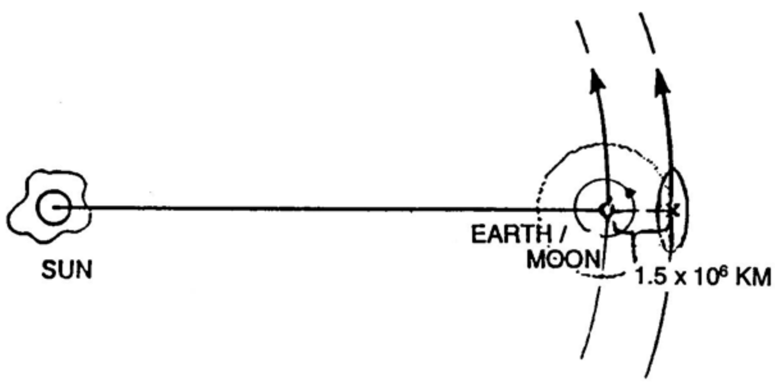
Candidate TPF Orbits (slide series from Sherrill LMSSC)



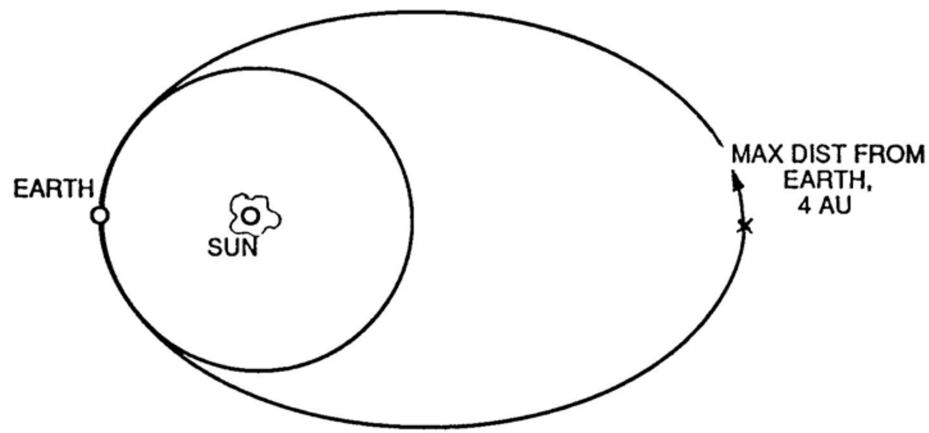
5-AU SOLAR ORBIT
(11.2 - YEAR PERIOD)



1-AU EARTH-TRAILING ORBIT
(~0.55 AU FROM EARTH AT 5 YEARS)



L2 LAGRANGIAN POINT HALO ORBIT
(~1 AU FROM SUN)



1 AU X 3 AU SOLAR ORBIT
(2.83- YEAR PERIOD)

High-Level TPF Orbit Comparison

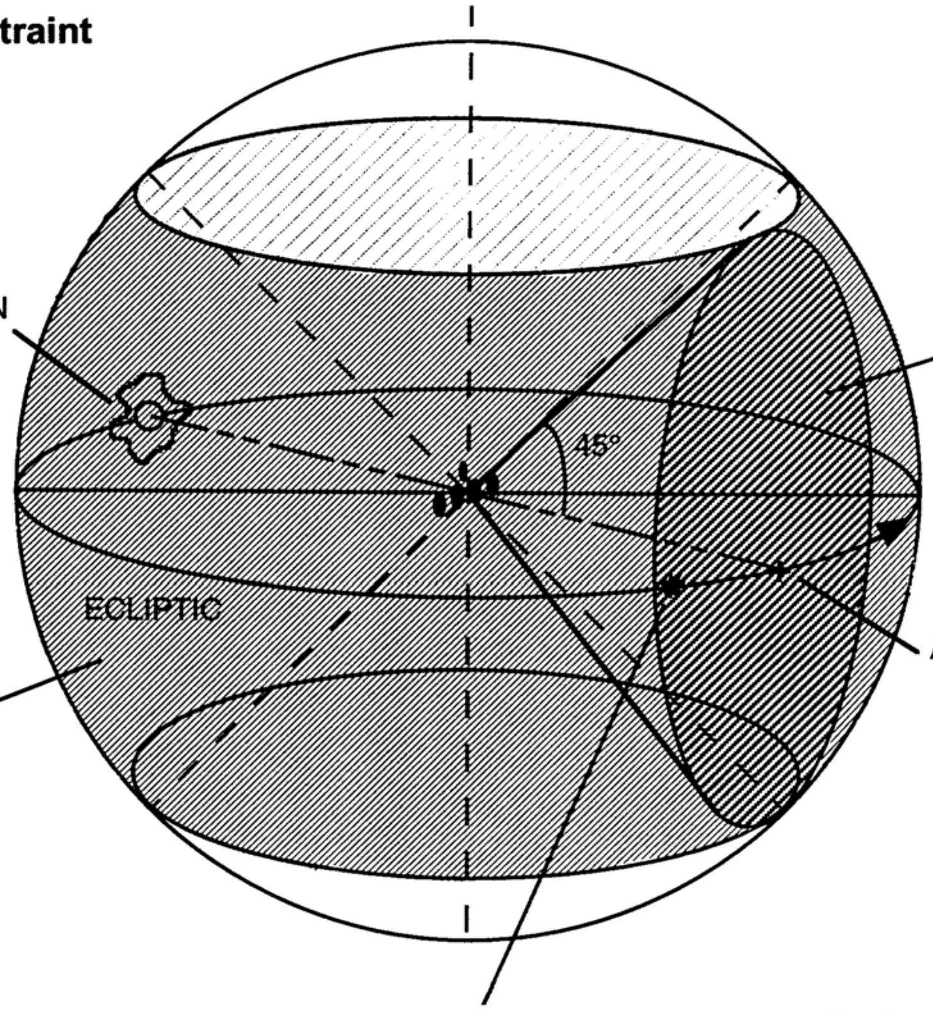
	L2	EARTH TRAILING	1 x 3 AU	5 AU
Launchable Mass	moderate	moderate	less	least
Postlaunch Propulsion Req'd?	station-keeping	no	no	aphelion burn
Time To Optimal Operation	106 days	end checkout	1.41 yrs	2.60 yrs
Size Of Collector Primary	large	large	smaller	smallest
Is Constellation Expandable?	yes	no	no	no
Sky Accessibility	uniform	uniform	nonuniform	uniform
Ease of Passive Cooling	harder	harder	easier at aphelion	easiest
Solar Power Availability	lots	lots	mostly less	much less
Zodiacal Dust Environment	dusty	dusty	good at aphelion	outside of dust cloud
Communications	easy	harder	harder at aphelion	hardest

Representative Launch Vehicle Capabilities

	Candidate Orbits		
	Lunar Swingby to L2	L2 Direct	Drift Away
	C_3 Energy (km^2 / s^2)		
	(-2.24)	(-0.69)	(0.40)
Candidate Launch Vehicle	Maximum Payload Mass (kg)		
Arianespace			
Ariane 5	4998	4855	4617
Boeing			
Delta III	2835	2754	2650
(EELV) Delta IV Heavy	TBR	TBR	TBR
(EELV) Delta IV Medium (0 SRMs)	TBR	TBR	TBR
(EELV) Delta IV Medium (? SRMs)	TBR	TBR	TBR
Lockheed Martin			
Proton M Breeze M	4410	4284	4074
Atlas IIIB	3808	3213	3056
(EELV) MLV A	3859	3749	3565
(EELV) MLV G (0 SRMs)	3381	3284	3123
(EELV) MLV G (5 SRMs)	5807	5641	5364
(EELV) HLV-G	11,800(TBR)	11,500(TBR)	10,900(TBR)
VentureStar RLV	6600(TBR)	6400(TBR)	6100(TBR)

Sunshield Issues:Anti-Sun Viewing and Sky Coverage

(±45° viewing constraint example)



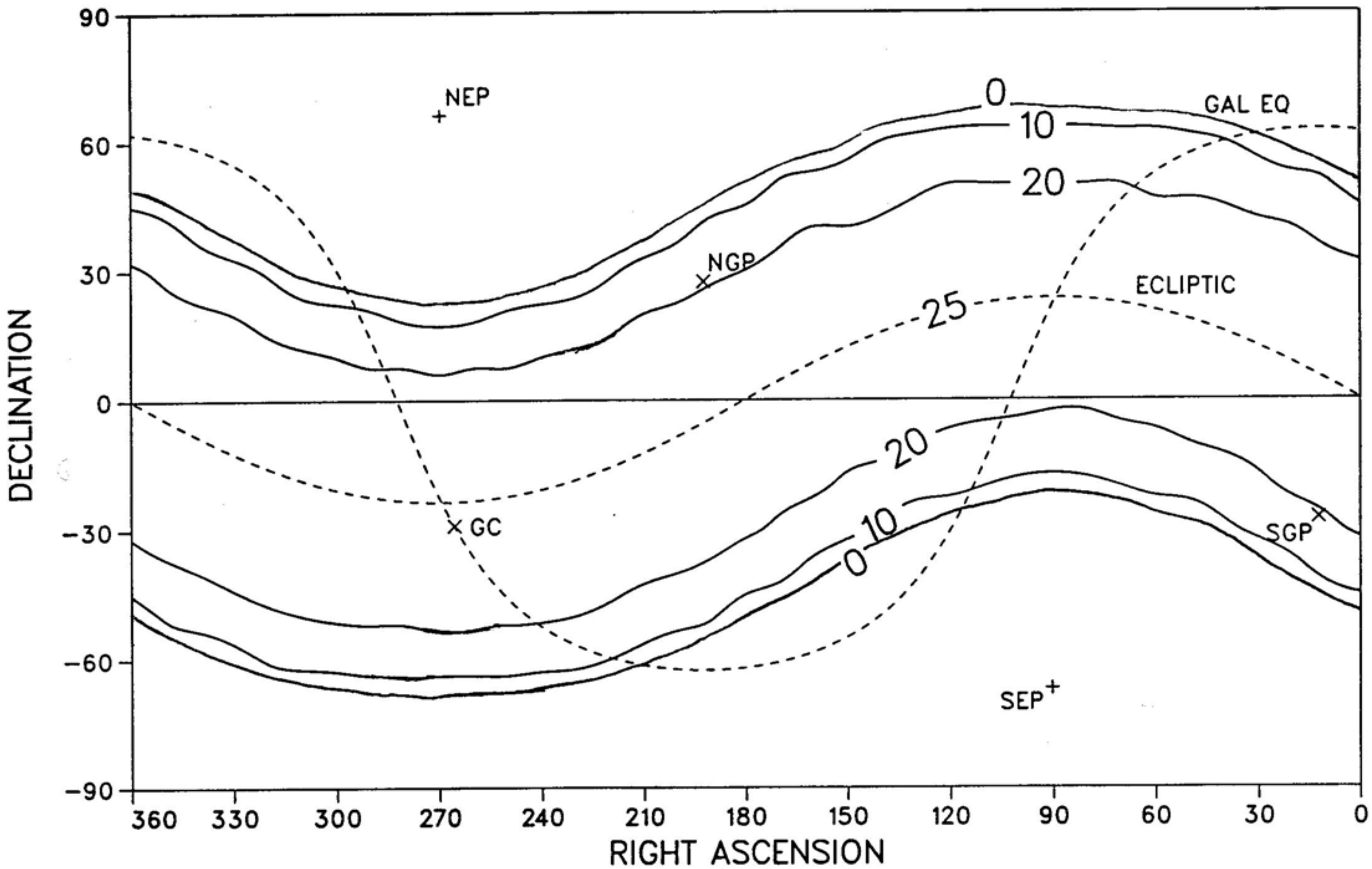
15% of the sky is accessible within 45° (half-angle) cone at any time

For the 1-AU orbits, 71% of the sky is accessible at some time during the year

For the 1-AU orbits, any given target on the ecliptic is visible for 91 successive days (25% of the year), once a year

45° Anti-Sun Constrained Viewing Time Contours Over 1 Year

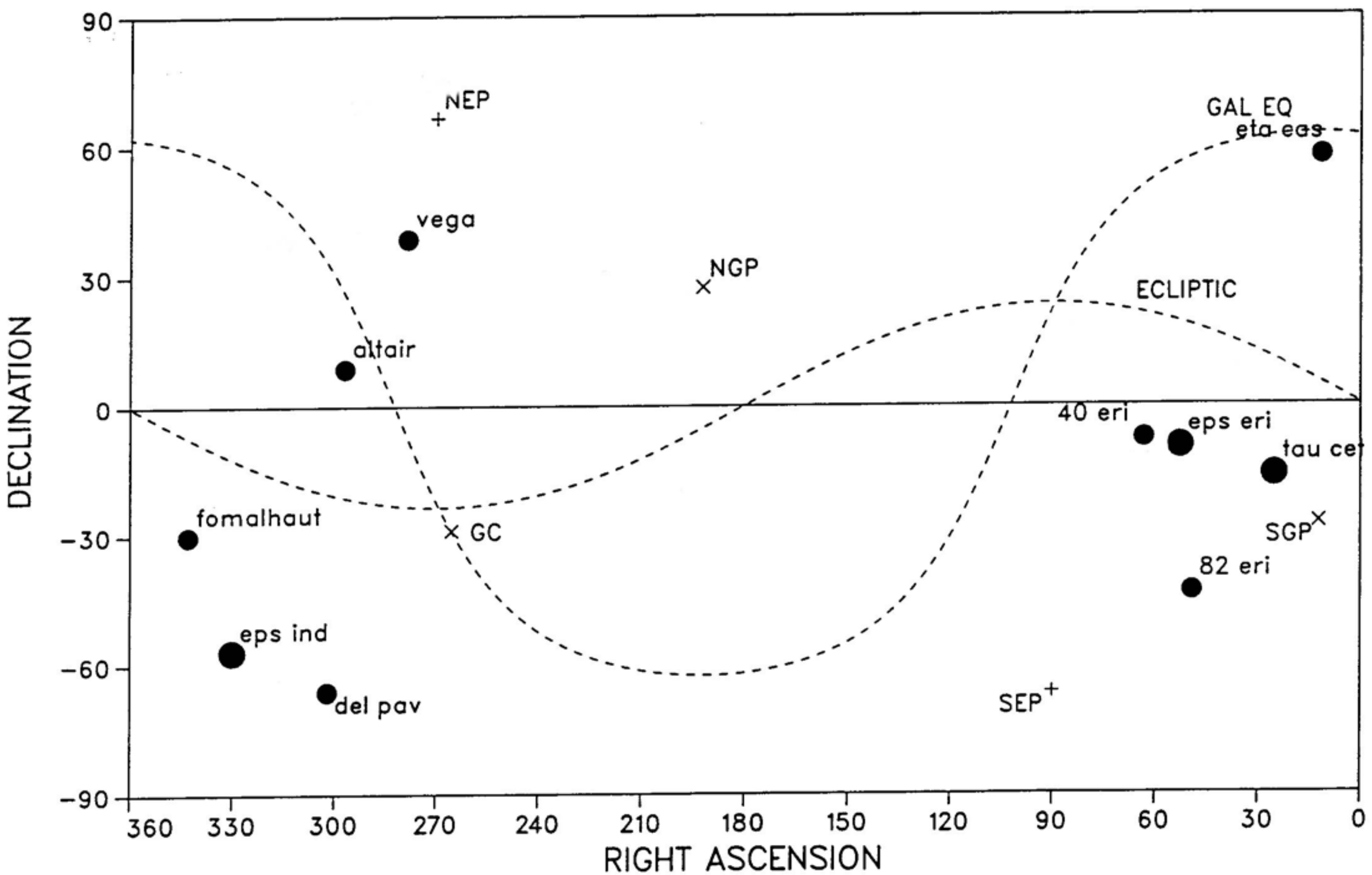
(Percentage of year that target direction is accessible) **(Either 1-AU orbit)**



Result: **25% viewing accessibility on ecliptic**
20% viewing accessibility 26° off ecliptic (cf SIRTF on ecliptic)
No viewing accessibility beyond 45° from ecliptic

Sky Locations of 10 Targets of High Interest

(Stars closer than 8 pc, with potential earth-temperature planet at separation > 0.13 arcsec)



KEY:

- ● 5 pc < star distance ≤ 8 pc
- ⬤ star distance ≤ 5 pc

Viewing Accessibility of 10 Targets vs. Sun Constraint (for 1 AU Orbits)

(Consecutive days per year target is accessible to TPF)

No.	Name	Viewing Constrained to Anti-Sun Direction... ±45°	±60°	±90°	±120°
1	ε Eri	72	108	183	257
2	ε Ind	36	88	183	277
3	τ Cet	76	111	183	254
4	40 Eri	71	107	183	258
5	Altair	69	106	183	259
6	η Cas	0	76	183	289
7	82 Eri	0	31	183	334
8	δ Pav	11	81	183	284
9	Fomalhaut	81	114	183	251
10	Vega	0	0	183	365

More Toolkit Items

- Orbit
  - L2
  - fall-away variants
  - 1x3AU (places more emphasis on deep nulling and increases
  - 5.2A effect of systems own zodiacal glow)
- Variants on sunshield/thermal shield
  - Direct connected
  - Connected by a spar with knuckle(s)
  - Free-flying with a thruster to balance radiation pressure
  - Light shield alone alone vs dark + cooling
- Connections between optics
  - truss
  - free-flyers
  - tethered
  - magnetic or electrostatic connected

Initial Rejection Process

- We began by throwing out a number of concepts that seemed to us to have such basic problems that we were unlikely to find solutions for them.

- Some of these schemes have champions. We thought it more likely that if some way of overcoming these apparent flaws could be found, it was more likely that they would be found by their champions rather than by us.

Natural Occultation of the Star Rejected.

This was analyzed in Pale Blue Dot 1 workshop.

The required energy collection is > 1015 photons from the star in a spectral resolution R~ 200 during an occultation lasting a few hours. This is to bring the star photon noise down to a level in which the planet atmospheric signal can be detected

To get equivalent # of stars we have to look out to ~80pc. At this distance in R=200 we need to receive 5000 photons/sec/m2 during an occultation. Thus we need >106 square meters of collector.

That is a space telescope ~1 km diameter.

Occulting Disk Rejected

Even at the distance of the Moon 4x 10^8m, the angular resolution is ~ 0.008 arc sec at 700nm, and the width of a Fresnel zone is 14m.

We need resolution of many Fresnel zones to get adequate contrast, and so we must have the separation of the occulter and the collector >10^9m.

If we move 10^0 from object to object, then the occulter must move ~2 x 10^8m between observations, which needs to happen at intervals of ~2 days, and should not take more than 1/2 day for the motion. Thus the occulter has to **accelerate and decelerate to ~10km/sec every two days for a few years**. This seems an unreasonable demand on propellants.

MM Wave Nulling Rejected

The apertures of a 4-mirror interferometer needed to detect the 13.5mm water line in a planet at distance p parsecs are about 2p km diameter each! For p = 15 pc this is

30 km diameter each aperture.

This seems unreasonable with near future technology.

[See the discussion in 1999 Bioastronomy conference.]

The Coronagraphic Round Aperture Rejected

Because of the need for apodising, we will need the telescope resolution to be 5-10 times that needed to resolve the star and planet. So we are asking for a telescope with a resolution of 0.004-0.008 arcseconds at 1μm.

For $\theta = 1.22\ \lambda/D$ this gives **telescope mirror diameters from 30-60m.** This is 15-60 times the area currently planned for NGST.

The Coronagraphic Dilute Aperture Rejected

- There are currently two problems with the dilute aperture coronagraph discussed by Labeyrie.
- First, **the nulling method proposed is both very chromatic, and secondly the null depth produced is very shallow.** So it **does not meet a key requirement.**
- In addition there are huge logistic problems in managing a swarm of telescopes.

We have not found any solution to overcome these problems

Options Rejected

- Near IR observations (2.5-5 microns) [from spectrum discussion]
- Natural occultations
- MM wave nulling
- Coronagraphic round aperture
- Coronagraphic dilute aperture
- Occulting Disk

Remaining Variants

1) Nulling aperture configurations:

A) Separate elements in a line; e.g., OASES

B) Separate elements in a two-dimensional array; e.g., DARWIN

C) Superposed wavefronts derived from a continuous filled aperture; e.g., rotation shearing interferometer (Needs to become a MIXED nulling-coronagraphic system),

2) Coronagraphic systems

E) Elongated filled aperture, e.g., the NGST version discussed by Angel, et al. Proc SPIE 2807

We have considered variants (C) and (E) together, including mixed systems.

Islands (of Sanity?)

1) Free-flying nulling afocal telescopes in the IR, either 1D or 2D.

2) Nulling primary mirror segments in the IR, 1D or 2D

3) Truss with elongated primary mirrors for nulling in the IR and astrophysical imaging.

4) Tethered telescopes for nulling in the IR, either 1D or 2D.

5) Truss with elongated primary mirror(s) as a coronagraph in the visible. [We grouped nulling coronography with Lyot coronography]