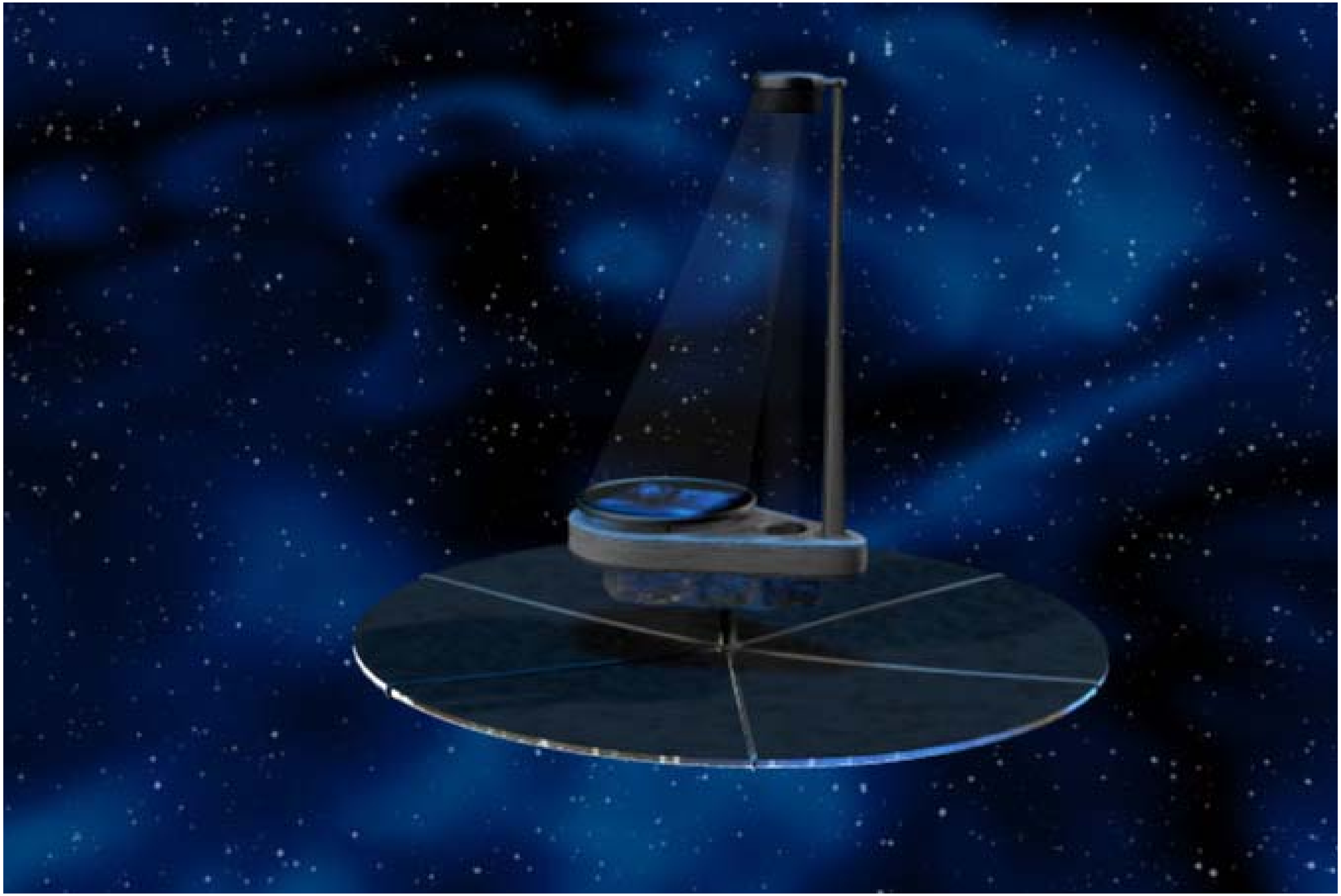
TPF Mission Architectures

Architectures

- Apodized Square Apertures
- Densified Pupil Arrays, AKA Hypertelescopes
- Redundant Linear Arrays
- "Book Design"
- Laser Trapped Mirror
- Occultors

Apodized Square Apertures (ASAs)

ASA Artist Rendering



Types of ASA Systems

- **ASA 3** - a 3m class ASA system operating in the visible that is focused on directly detecting planets and demonstrating this new approach
  - Survey out to 4 to 6 PC for Earths
  - Detection and Characterization of Solar Systems to 20 PC
  - Early Performance with Relatively Low Cost and Risk
- **ASA 10** - a 10m class ASA system operating in the visible and near IR that is focused on performing all TPF detections and some spectroscopy
  - Could accomplish entire TPF plane detection mission
- **ASA 30** - a 30m class ASA system operating the visible and IR that performs all TPF detections and all TPF spectroscopy

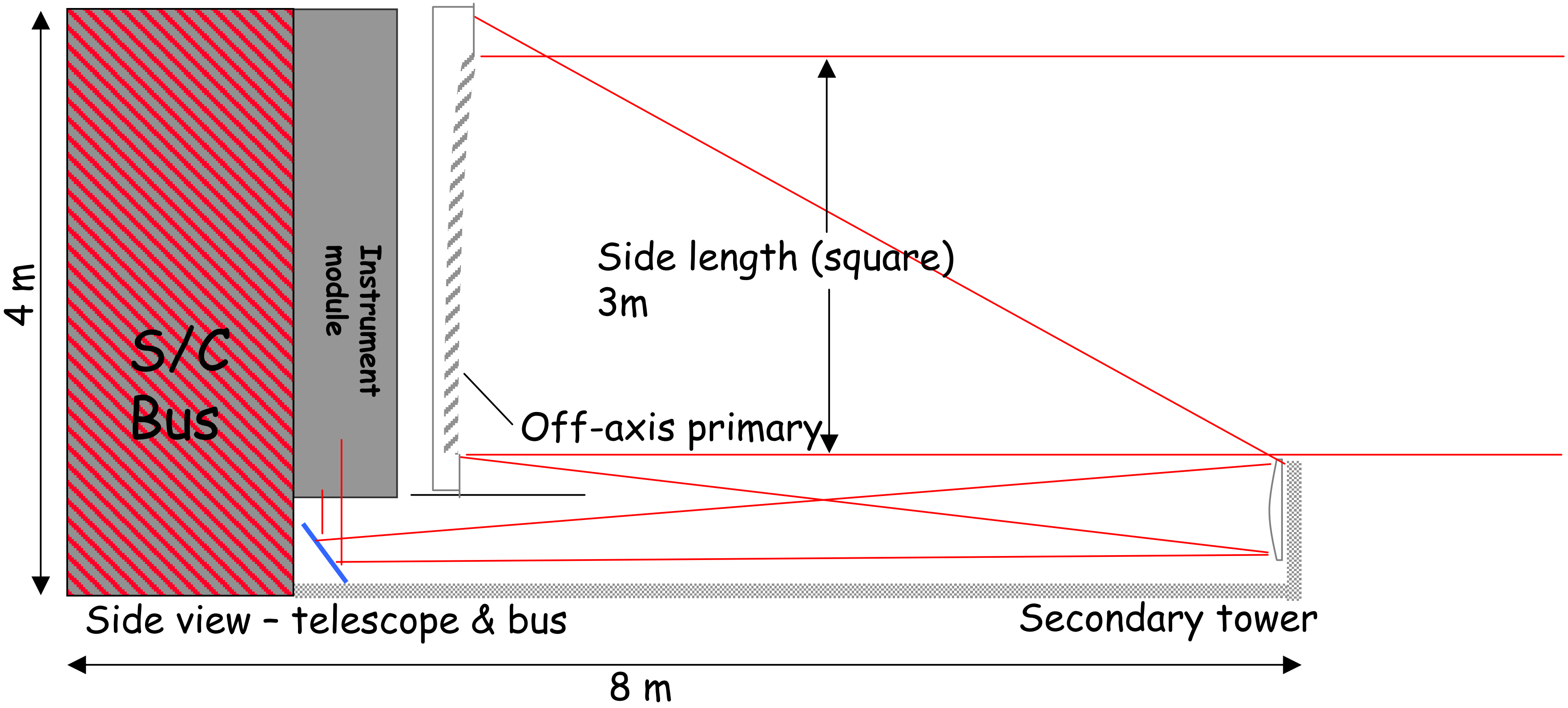
ASA 3 Animation

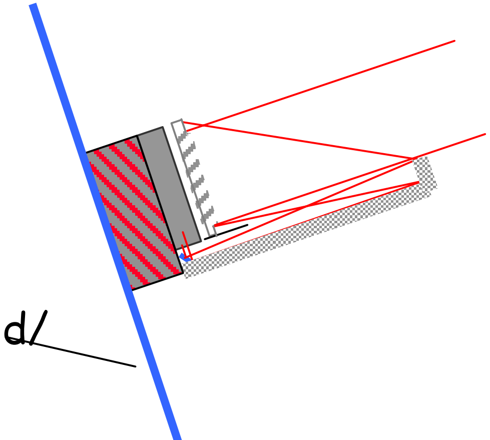
QuickTime™ and a
Sorenson Video decompressor
are needed to see this picture.

Physical Characteristics

	ASA 3	ASA 10	ASA 30
Aperture Diameter	3 m	10 m	30 m
Aperture Type	spherical	spherical	spherical
Optical Geometry	off axis	off axis	Cassegrain or off axis
Wavelength	0.6-1 μm	0.6-3 μm	0.6 - 20 μm
Angular resolution	40 mas @ 0.6μm 67 mas @ 1 μm	12 mas @ 0.6 μm 60 mas @ 3 μm	4 mas @ 0.6 μm 133 mas @ 20 μm
Orbit		L2	
Attitude Control		Cold Gas Jets	
Sun shade		Also serves as solar collector	

ASA 3 configuration





S/C mass:
Rough estimate
< 2000 kg
+ kick motor

ASA 3 Concept (1 of 2)

- Telescope needs EFLs ~ 30 m: afocal front end (10-20X) + focal backend
- Optical design: Off-axis secondary highly desirable; design TBD in Phase 2
- Primary square, non-segmented: joints cause additional diffraction sidelobes,[but, spatially correlated → predictable]
- Option for Phase 2 study: use circular aperture (equivalent area) and apodize at pupil relay plane
- Notes:
  - Effective transmission w/apodization ~ 15 %
  - Angular resolution ~ 80 mas along PSF diagonal (0.76 micron)
  - Maximum detection range (resolution-limited) for planets (@ 1 AU) ~ 10 pc

ASA 3 Concept (2 of 2)

- Spectral region for detection/planet characterization 0.5 – 1.0 μm
- FOV (CCD array): > 40 arcsec
- Operating temperature: FPA ~250K; optics 300K
- Sensitivity (planet-finding): distance ~ 3 pc for SNR = 7 in 10 hrs (Earth at 1 AU),
- Note: star rejection = 10^8
- Spectral resolution:
  - R = 1 for candidate planet-finding (imaging)
  - Planet characterization: low R imaging (filters)
  - or offset guiding to feed planet signal into spectrometer
  - R ~ 10 probably a realistic limit to keep detection times small
- LOS pointing tolerance ~ $\lambda/10D$ with low disturbance environment

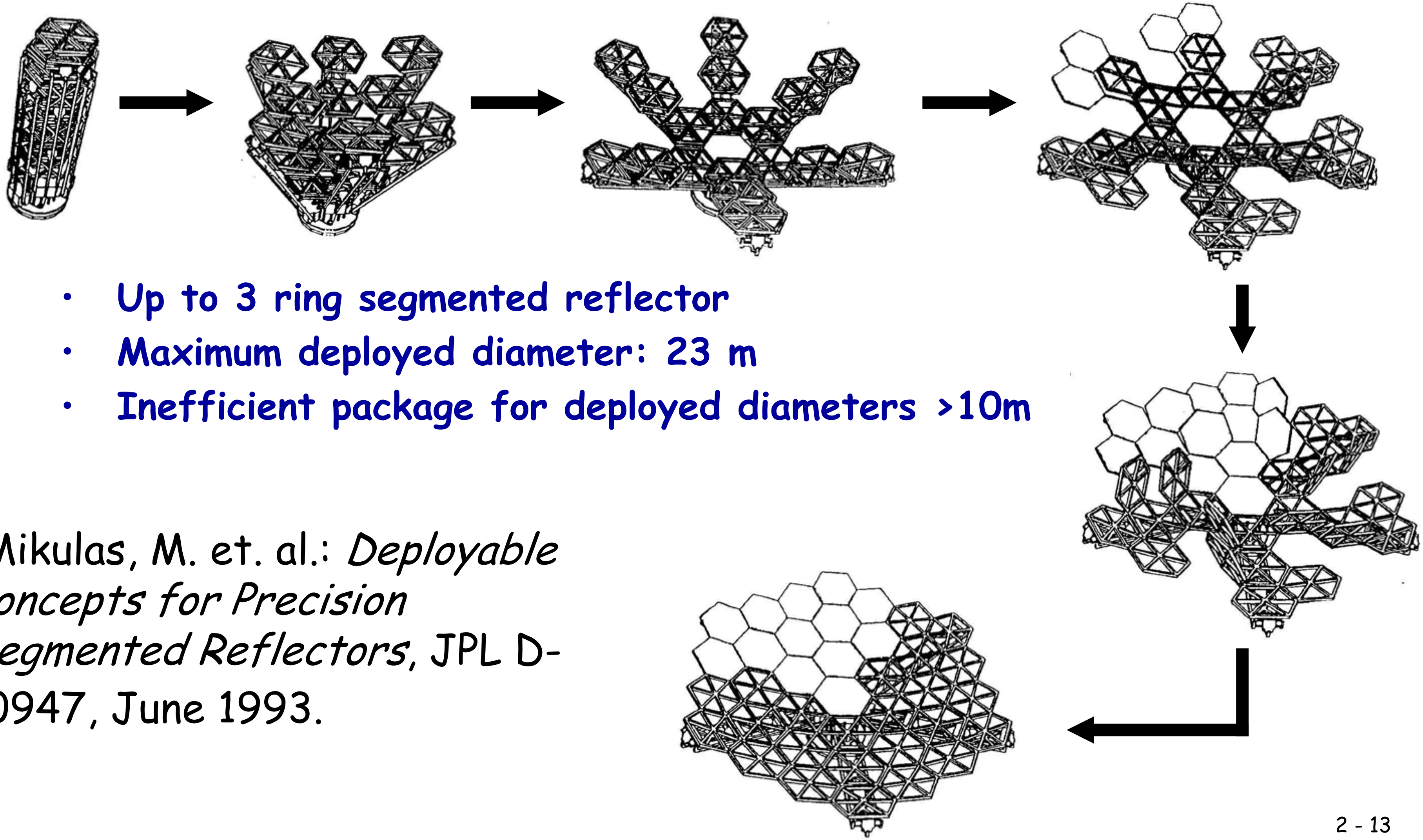
ASA 30 Concept

- The basic concept is a large, segmented monolithic telescope
  - Either deployed robotically, or
  - Assembled via EVA/EVR techniques
- One concept examined in Phase 1 has the segments are held in place by magnets and adjusted in tilt and piston by use of electromagnetic actuators.
- Use wavefront sensor to test the surface.
- Control loop to make corrections in tip and tilt

Deployable Design

- Deployable Segmented Full Aperture Reflector:
- Advantages:
  - No or limited LEO assembly tasks
  - Allow for up to 4 rings of segments
  - Note: 4 ring design: TRW's HARD concept- "High Accuracy Reflector Deployment")
- Disadvantages:
  - Large reflectors have complex kinematics
  - Packaging volumes can be inefficient
  - Lower 1st frequency than same size erectable design

Deployable Reflector: "Starburst"*



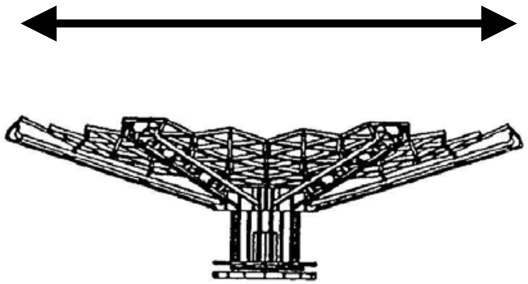
- Up to 3 ring segmented reflector
- Maximum deployed diameter: 23 m
- Inefficient package for deployed diameters >10m

*Mikulas, M. et. al.: *Deployable Concepts for Precision Segmented Reflectors*, JPL D-10947, June 1993.

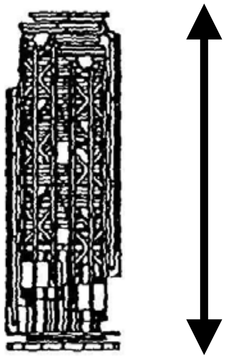
Preliminary Deployment Analysis

- Three rings of segments, 36 reflector panels
- Areal density 15 kg/m2
- Maximum panel diameter 3.8 m
  - (1) Maximum reflector diameter 23 m
  - (2) Packaged height 14.8 m
  - (3) Packaged cross-sectional diameter 4.9 m
- Packaged volume 283.4 m^3
- Reflector mass 5200 kg

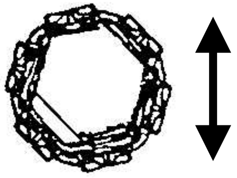
(1)



(2)

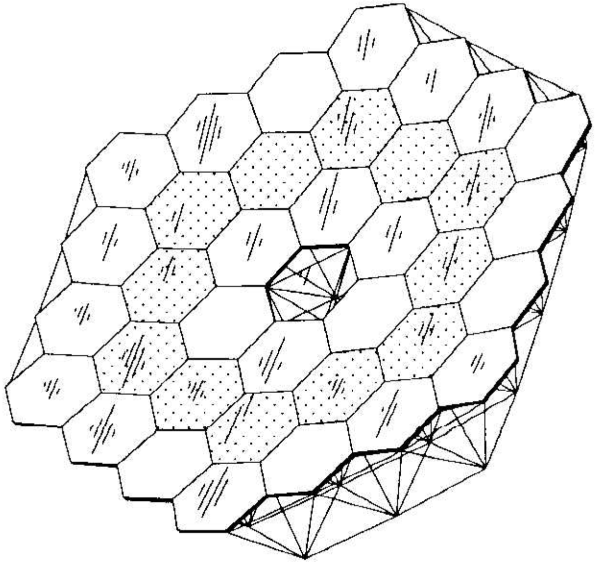


(3)



Erectable Segmented Reflector

- **Advantages:**
  - Can be packaged efficiently
  - 1st Frequency ~10 Hz
- **Disadvantages:**
  - Cost and time associated with on orbit construction
  - Associated orbital transfer loads (LEO to L2) applied to the structure



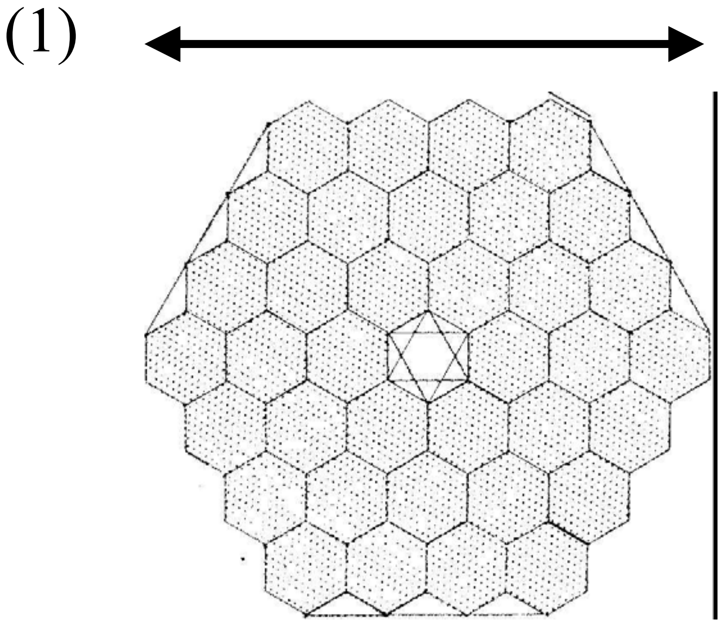
Basic model assumptions

- Panel characteristics:
  - Graphite/epoxy with honeycomb core
  - Borosilicate glass face sheet
- Truss characteristics:
  - Graphite/epoxy struts
  - Aluminum and graphite/epoxy nodes

Packaging analysis: 3 ring reflector

- 36 panels having maximum diameter 4 m, thickness .09 m
- Panel mass 74.5 kg, Total panel mass 2680 kg
  - Total packaged height 6.2 m **
  - Total packaged panel volume 92 m3 **
- 399 truss components, 315 struts, 84 nodes
  - Strut mass 1.7 kg, Node mass 3 kg, Total truss mass 790 kg
- Total packaged truss volume 21 m^3 **
- Secondary mirror and tower truss not included
- **Panels and struts are packed in twice their thickness

Assembled reflector : 3 ring



- (1) Maximum diameter 24.3 m
- Reflector mass 3470 kg
- Reflector surface area 374 m^2
- Moment of inertia 130,850 kg m^2

Frequency analysis: 3 ring

- **To a first approximation, the erectable reflector can be considered as flat circular sandwich plate. (Curvature effects are negligible in the determination of the lowest natural frequency)**

Approx. 1st resonant frequency ~19 Hz **

** Tower truss and secondary mirror not included

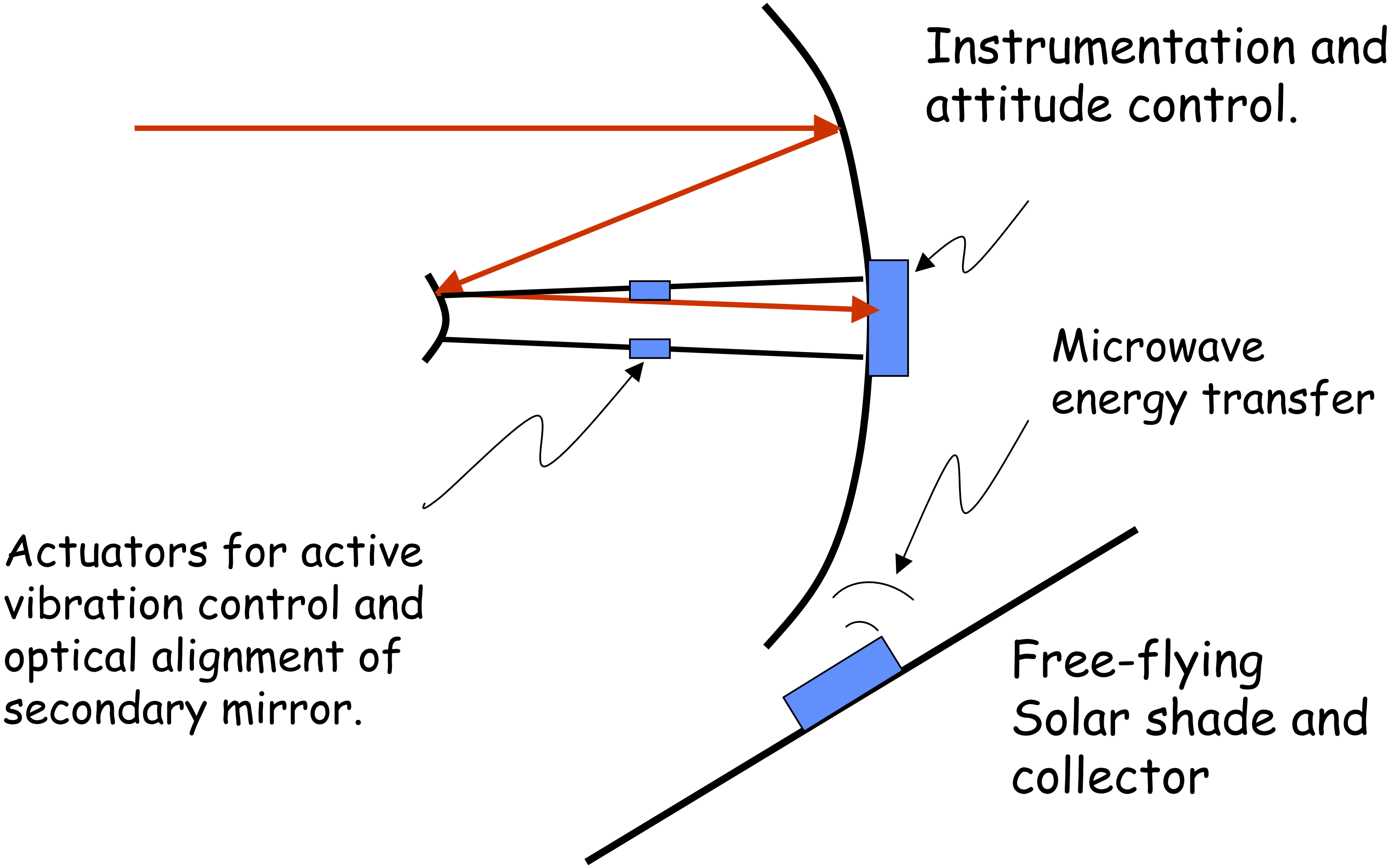
Packaging analysis: 4 ring reflector

- 60 panels having maximum diameter 4 m, thickness 0.09 m
  - Panel mass 74.5 kg, Total panel mass 4470 kg
  - Total packaged height 10.4 m **
  - Total packaged panel volume 153 m^3 **
- 663 truss components, 528 struts, 135 nodes
  - Strut mass 1.7 kg, Node mass 3 kg, Total truss mass 1310 kg
  - Total packaged truss volume 35 m^3 **
- Secondary mirror and tower truss not included
- **Panels and struts are packed in twice their thickness

Assembled reflector : 4 ring

- Reflector mass 5780 kg
- Maximum diameter 31.2 m
- Reflector surface area 624 m^2
- Moment of inertia 356,430 kg m^2
- 1st resonant frequency ~11 Hz

ASA 30 Configuration (1 of 5)



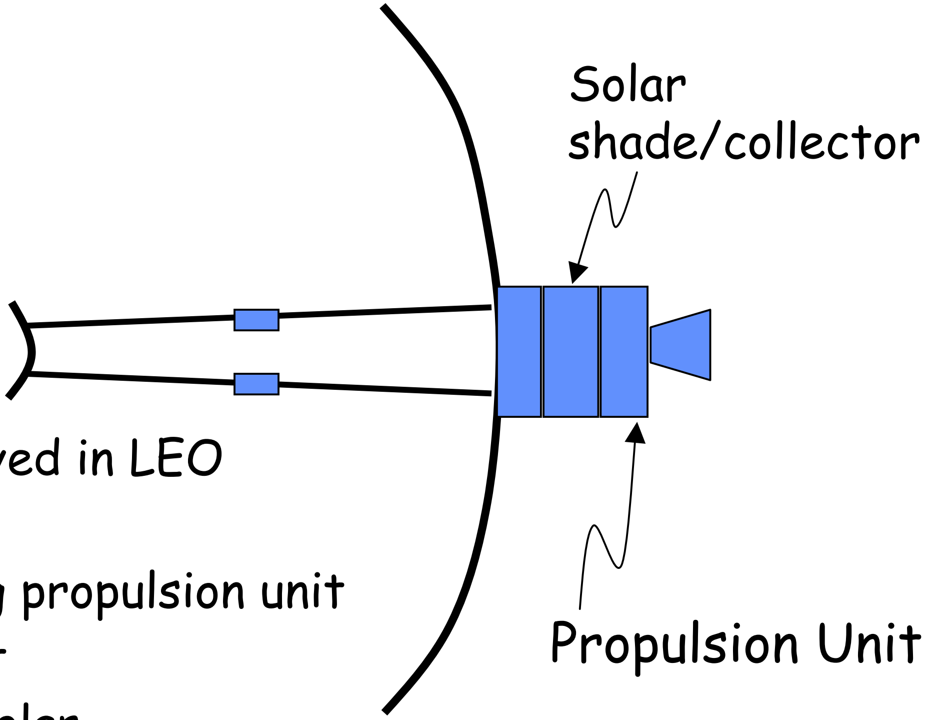
Instrumentation and attitude control.

Microwave energy transfer

Actuators for active vibration control and optical alignment of secondary mirror.

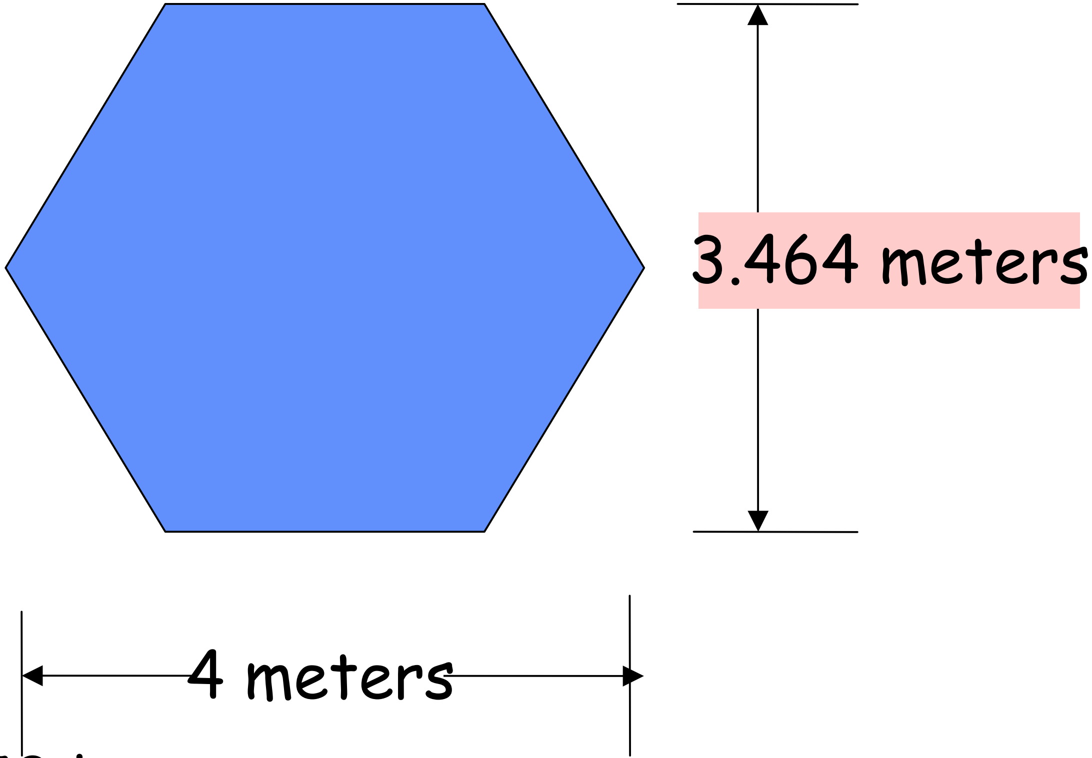
Free-flying Solar shade and collector

ASA 30 Configuration (2 of 5)



- Assembled or deployed in LEO
- Latch tile in place
- Transfer to L2 using propulsion unit
- Eject propulsion unit
- Deploy free-flying solar shade/collector
- Unlatch tile

ASA 30 Configuration (3 of 5)



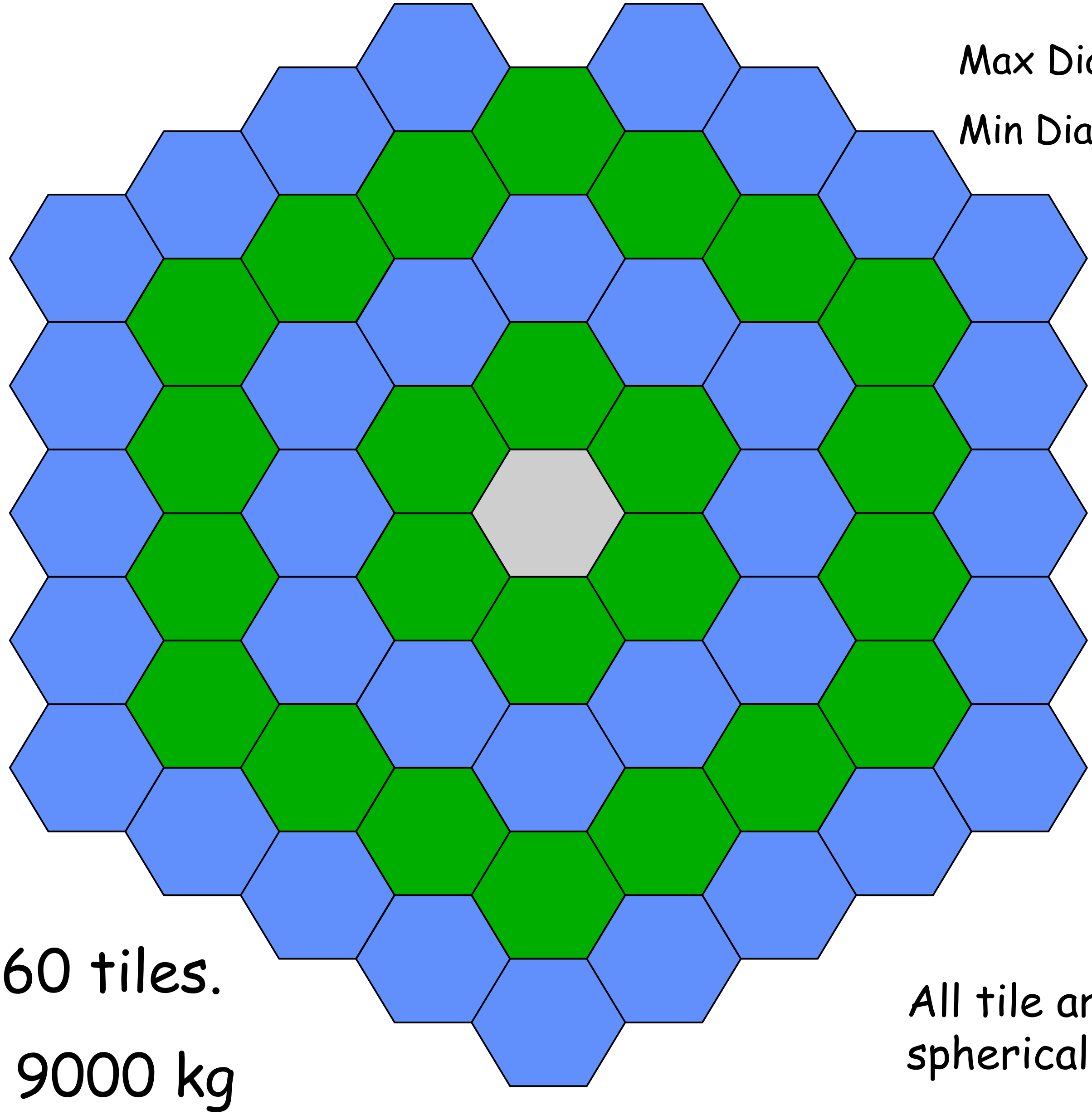
Assume SiC material.

Estimated weight = 150 kg.

Spherical shape

BOEING SVS

ASA 30 Configuration (4 of 5)



Max Diameter = 31.4 m

Min Diameter = 28 m

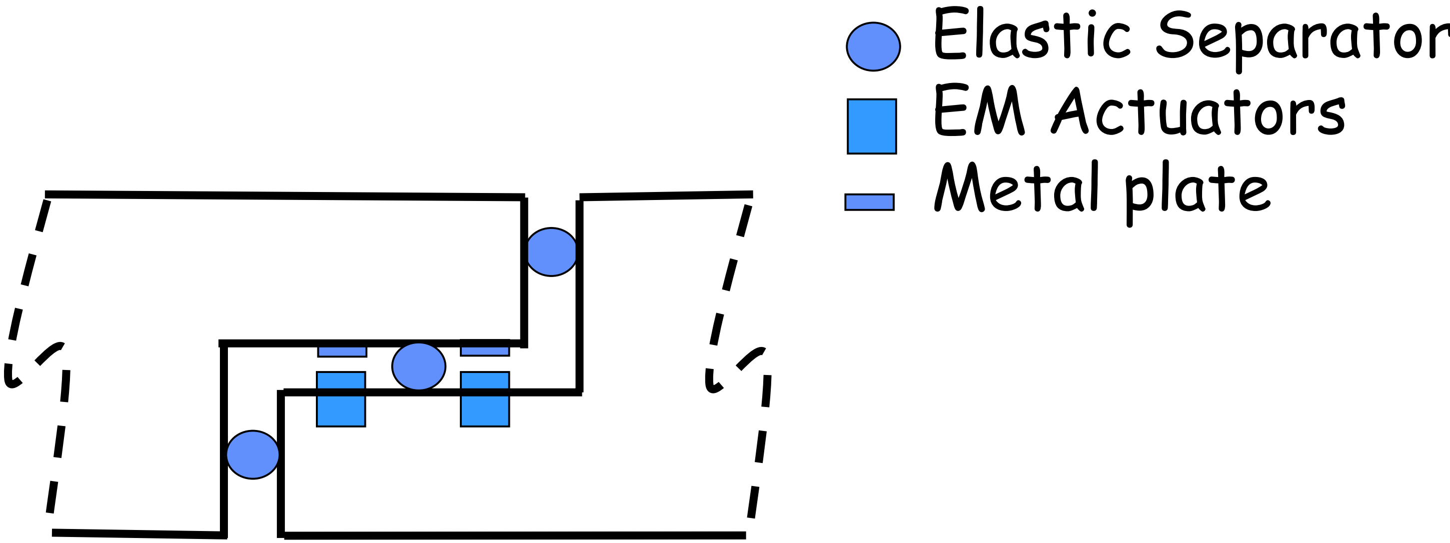
Requires 60 tiles.

Weight = 9000 kg

All tile are identical spherical shapes.

ASA 30 Configuration (5 of 5)

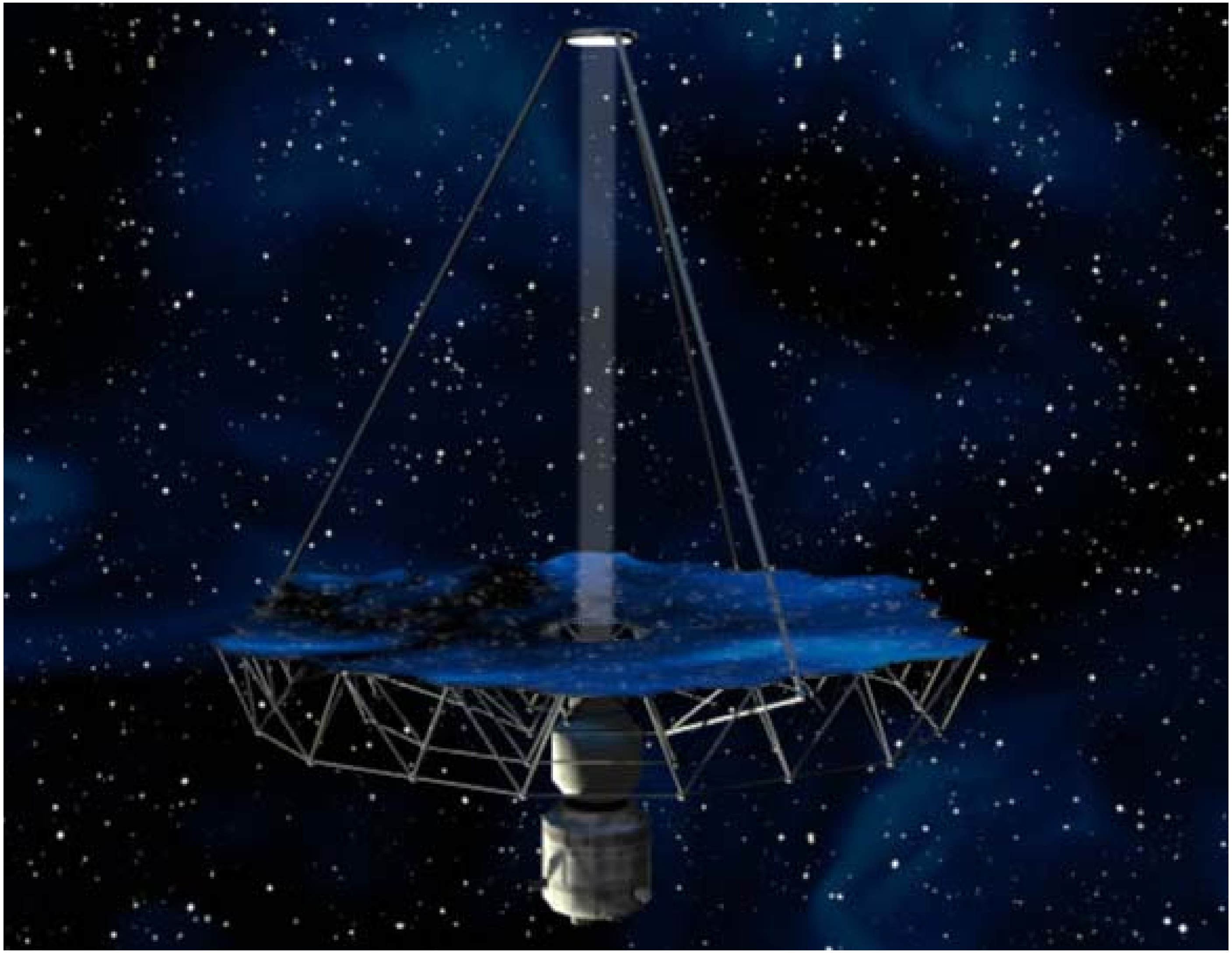
Detail of dove-tail fitting & Actuator control



● Elastic Separator
■ EM Actuators
▬ Metal plate

Electromagnetic actuators have some permanent magnetism for holding tiles in place, and are used for both piston and tilt corrections.

Artists Rendering of ASA 30



BOEING SVS

ASA 30 Animation

QuickTime™ and a
Sorenson Video decompressor
are needed to see this picture.

ASA 10 Configuration

- Details to be worked out in Phase 2
- Hybrid between ASA 3 and 30

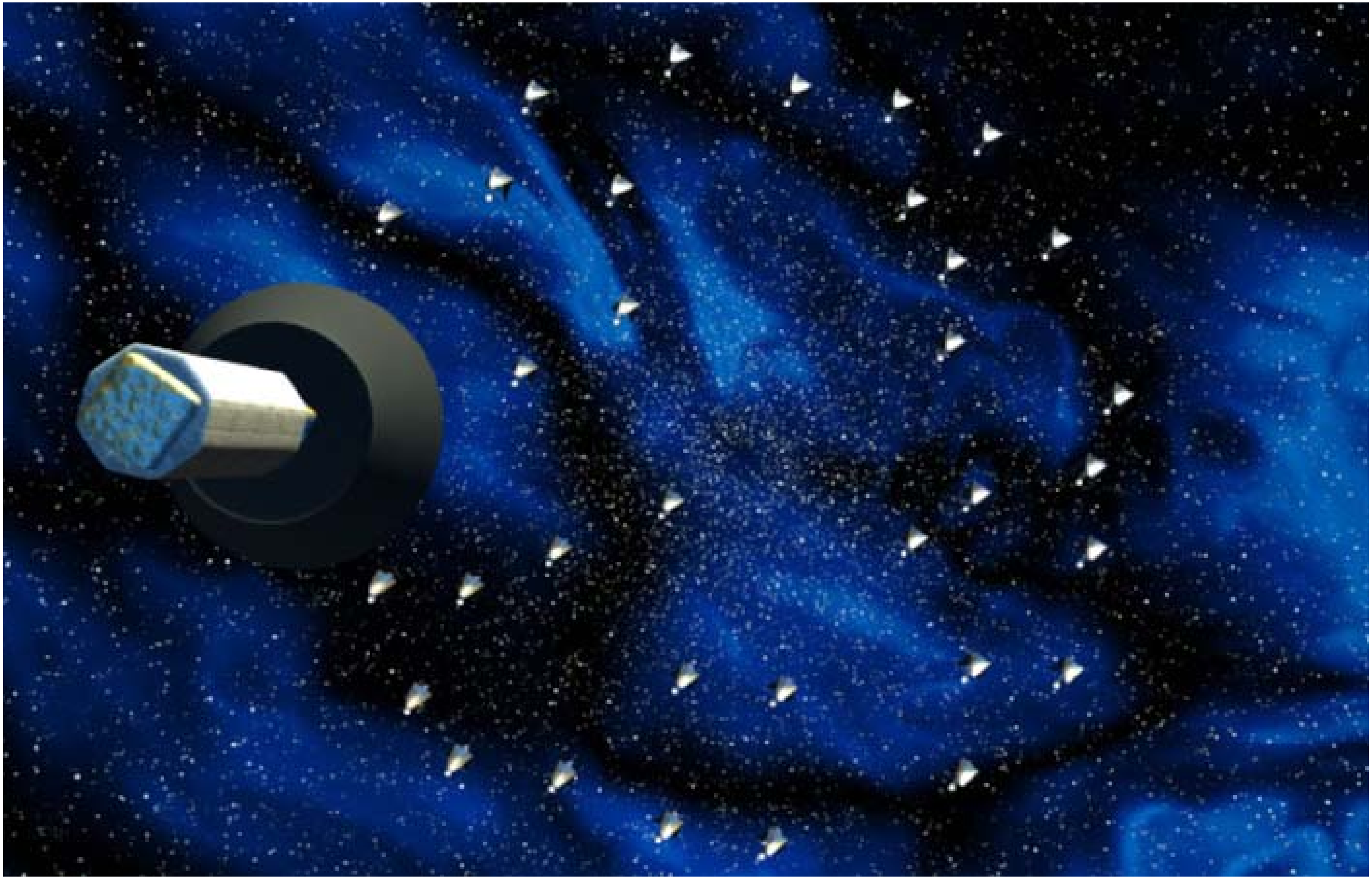
Densified Pupil Arrays, AKA, *HyperTelescopes*

Two Conceptual Approaches

- ***Snapshot Hypertelescope Imager*:** Large number of small elements
- ***Rotational Hypertelescope Imager*:** Smaller number of larger elements

Hypertelescope:
Snapshot Imaging Array

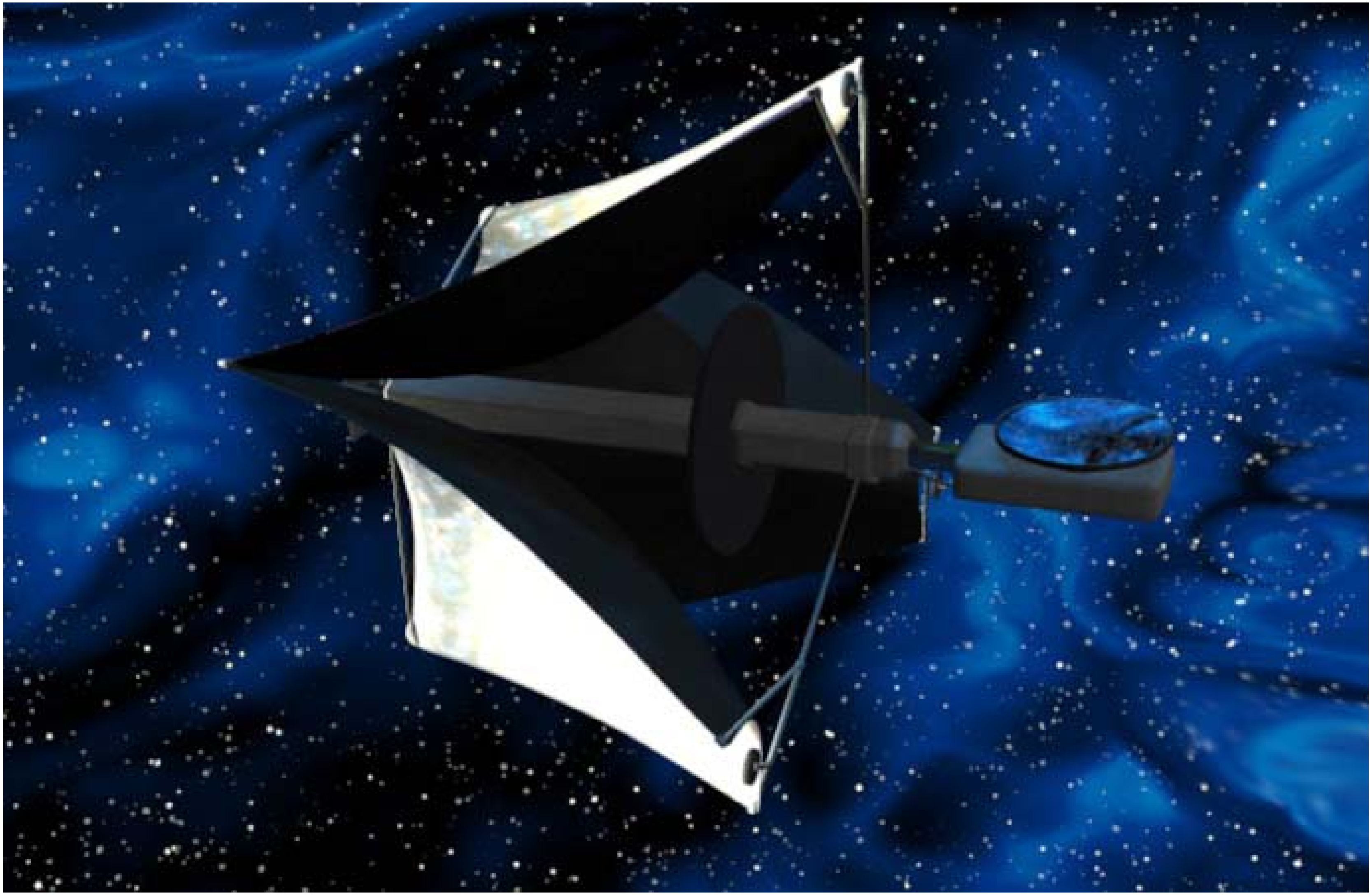
Artist's Rendering of the Snapshot Imaging Array



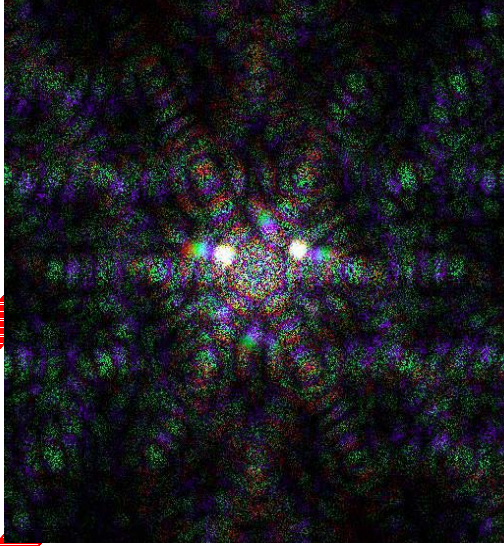
Animation of the Snapshot Imaging Array

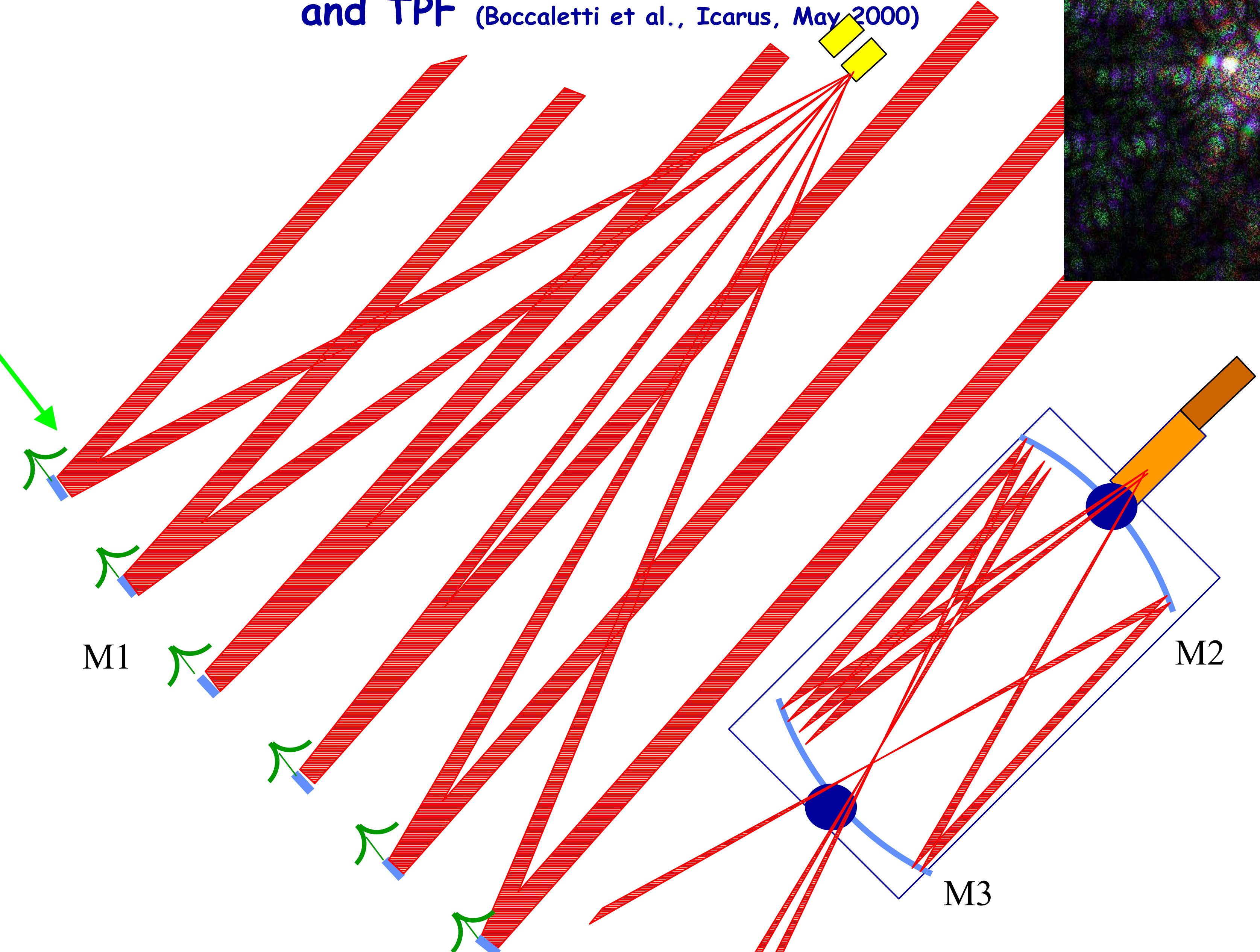
QuickTime™ and a
Sorenson Video decompressor
are needed to see this picture.

Artist's Rendering of the Single Array Element

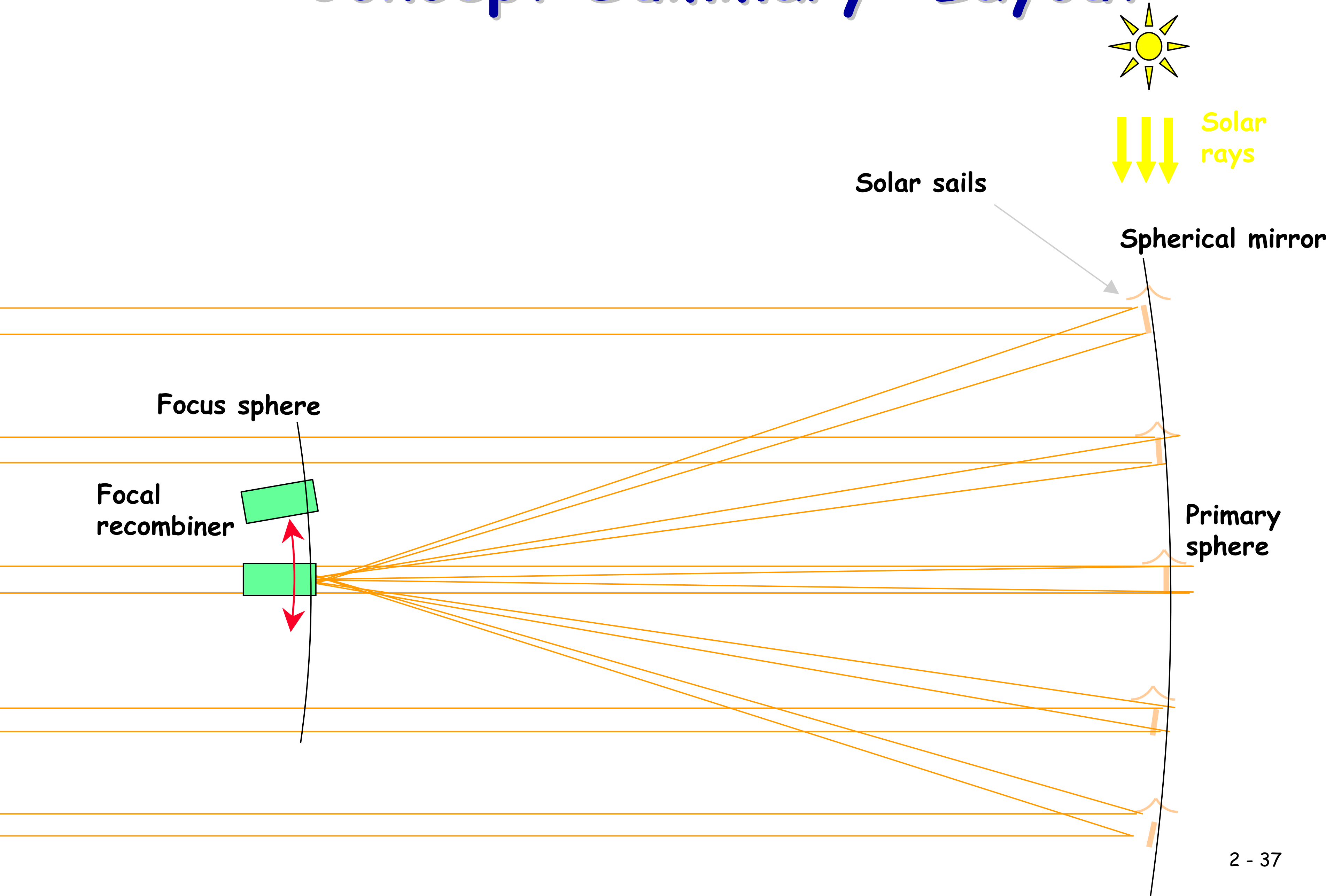


Hypertelescope architecture concept proposed for DARWIN and TPF (Boccaletti et al., Icarus, May 2000)



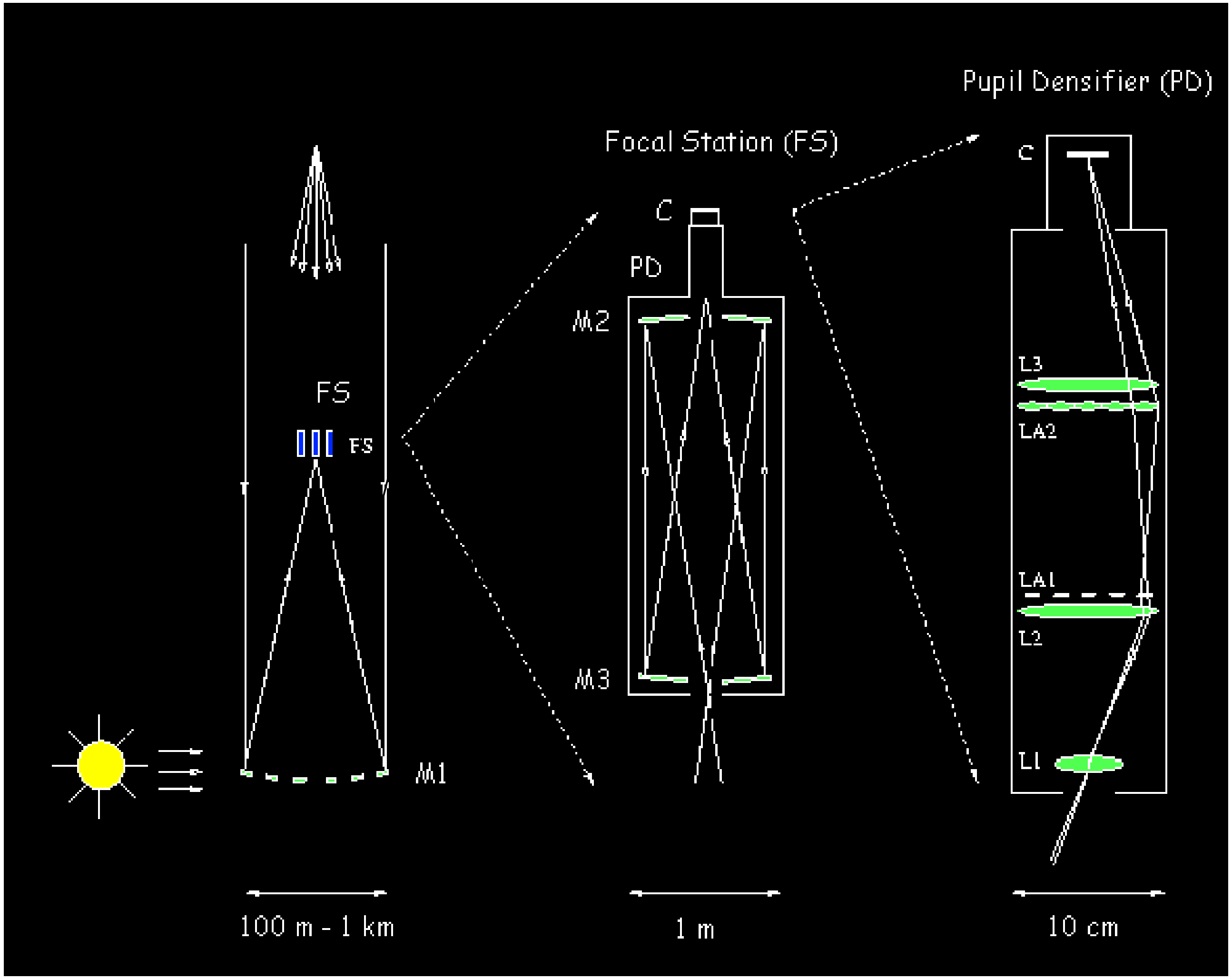


Concept Summary: Layout



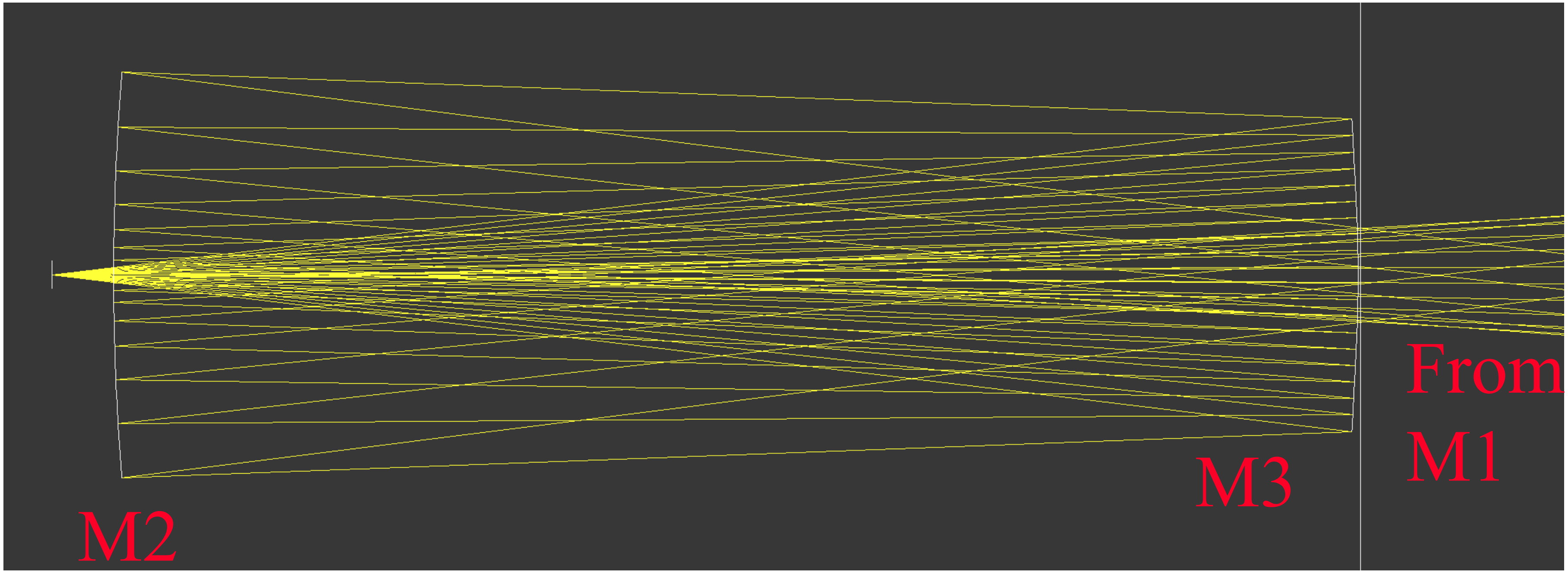
Beam Combiner

- Fizeau stage + densifier
- Corrector of spherical aberration and coma
- Pupil densifier: micro-lenses or micro-mirrors
- Usable primary median field size is D/2F (7,2° if F/4 aperture)



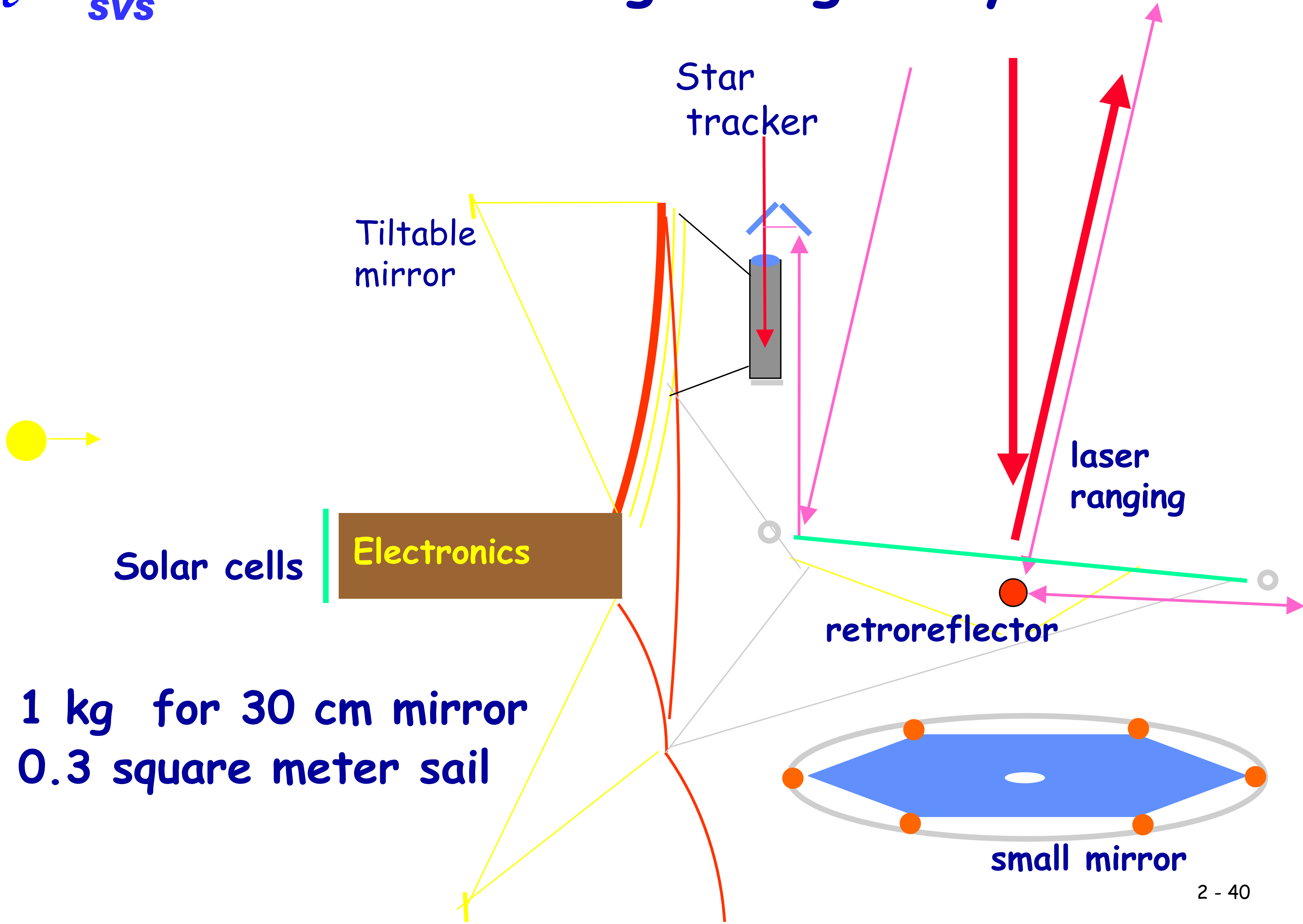
SVS

Corrector of Spherical Aberration and Coma from F/4 Spherical Array



- 0.21 m diameter, 1.34 m length for 100 m array at F/4
- 25 % central obscuration, reducible by increasing size
- Pupil obscuration up to 10% tolerable for Rouan coronagraph : possible with larger (3x) corrector

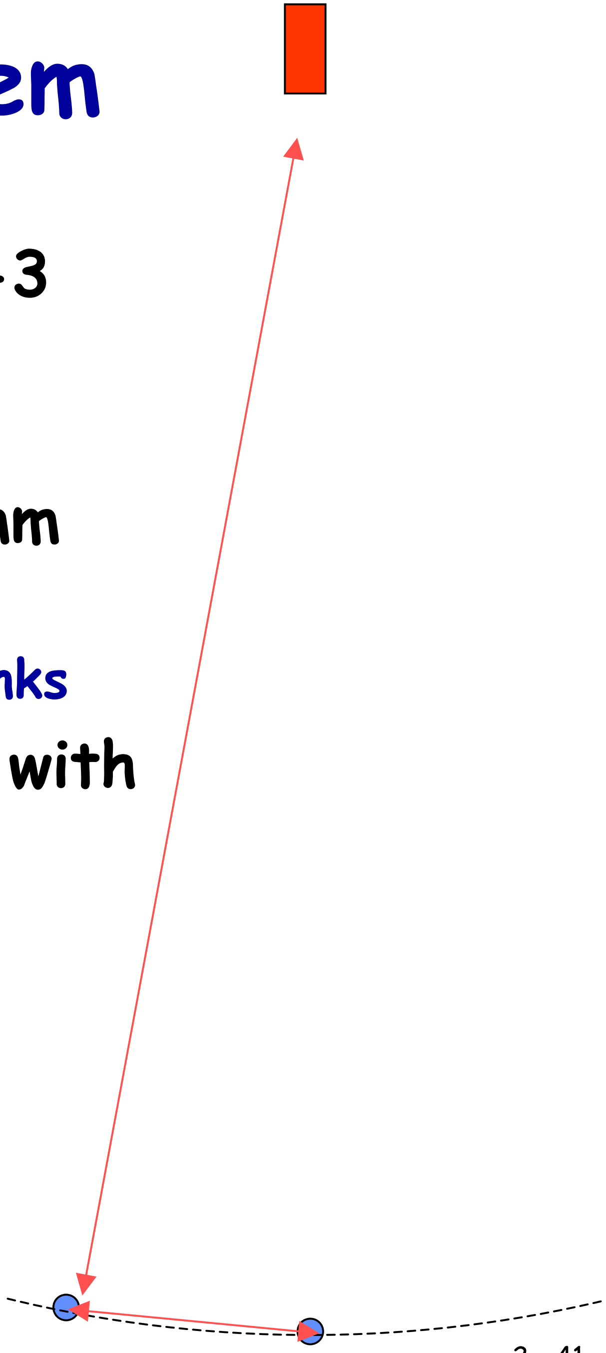
Small ultra-lightweight flyers



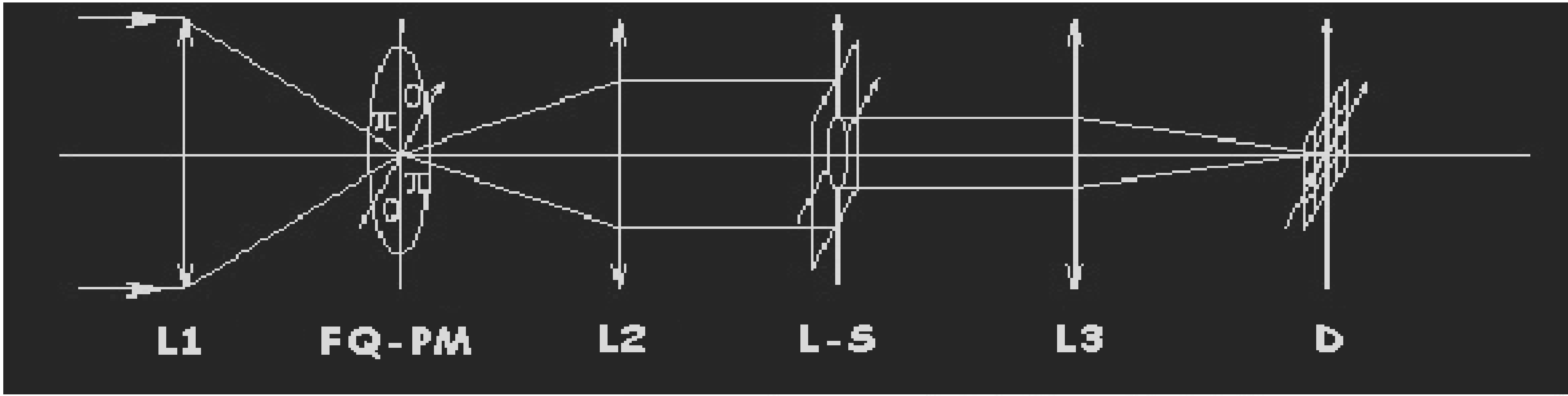
- 1 kg for 30 cm mirror
- 0.3 square meter sail

Metrology system

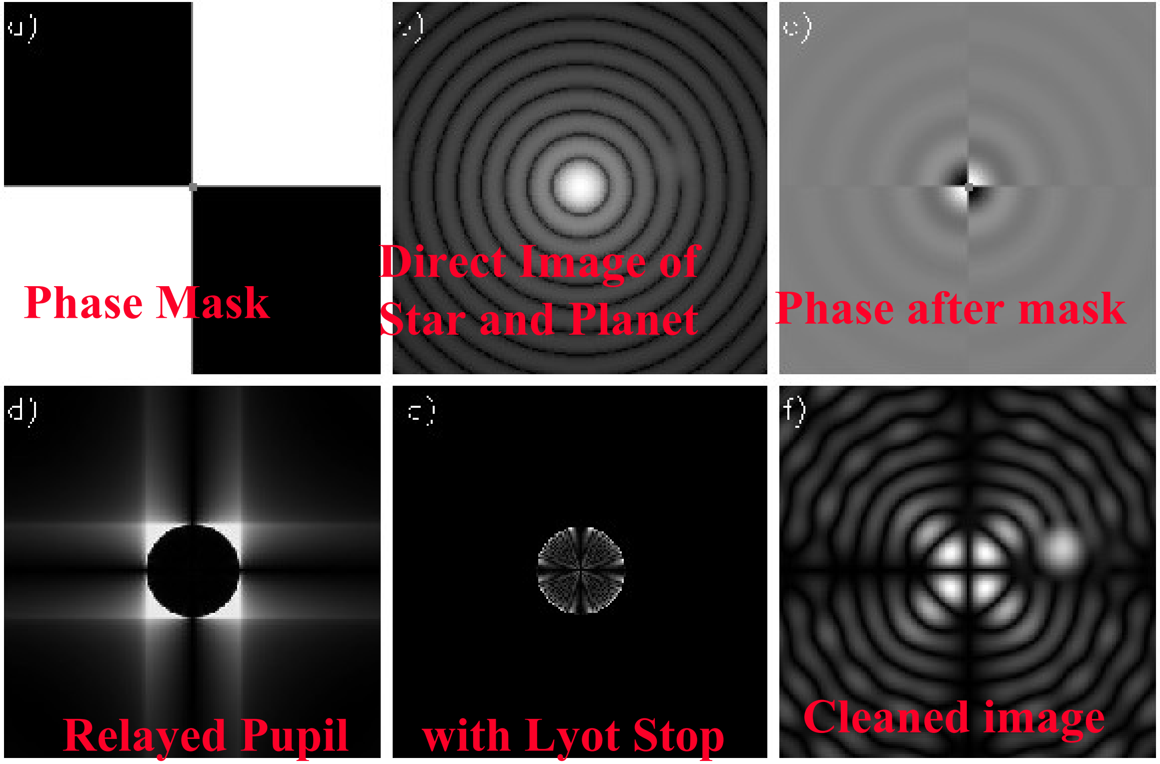
- GPS-like system considered for ST-3 requires multiple radio emitters , avoidable ?
- Instead: pulsed diode lasers give 1 mm accuracy
    - also allow alignment and internal data links
- Dedicated central satellite avoidable with two or more diode lasers



Densified Pupil Imaging w/ Coronagraphy



- Four-quadrant phase-mask in the focal plane (Rouan 2000)
- High dynamic range ⇒ 20 mag. with perfect optics
- Resolution unaffected
- Broad-band operation with achromated phase mask
- Exit pupil must be circularized
- Affected by guiding errors (null width $\propto \theta^2$)



Phase Mask

Direct Image of Star and Planet

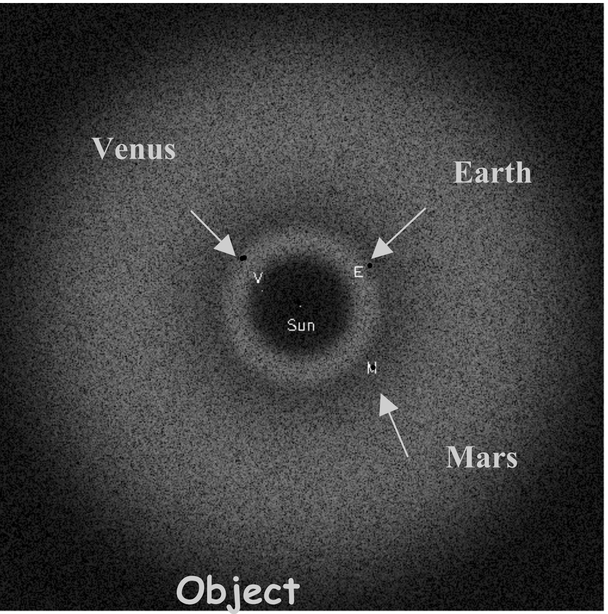
Phase after mask

Relayed Pupil

with Lyot Stop

Cleaned image

Coronagraphy simulations



Object

Image of a solar system (G2V star, Venus, Earth, Mars) at 20 pc for 100 m baseline

Lz = 12.7 mag/arcsec^2

Lez = 10 Lz

Wave error : $\lambda/170$ rms

Exposure : 10 h in N band (10.2 ± 2.6 μm) with 20 square meters of aperture , in 37 elements

Opposite quadrant subtracted

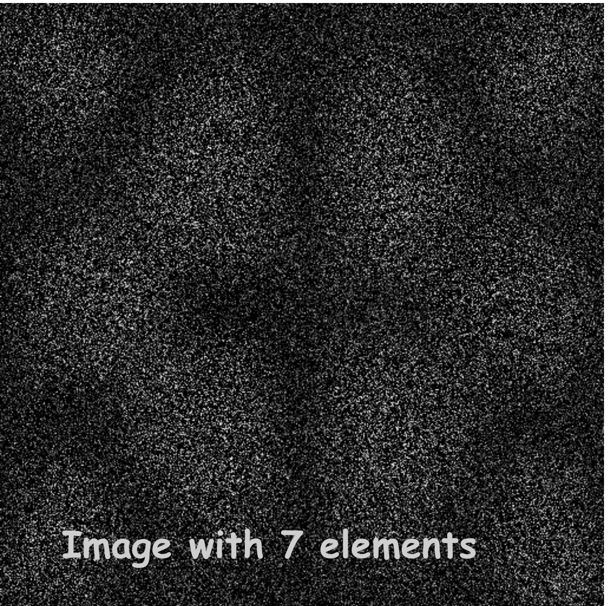


Image with 7 elements

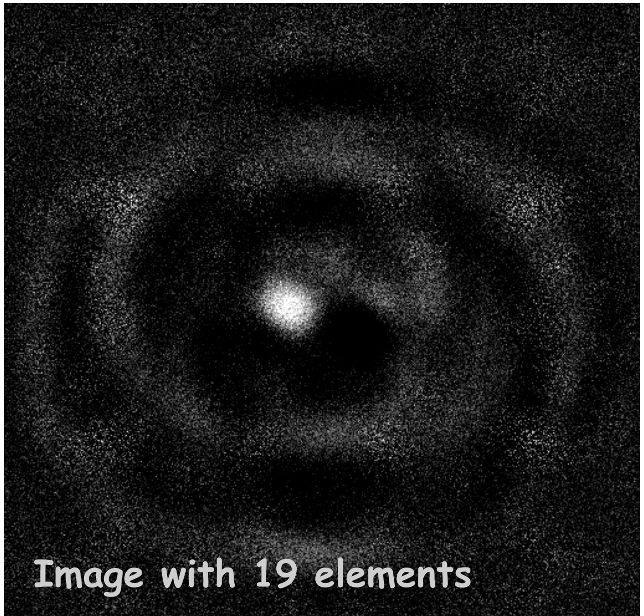


Image with 19 elements

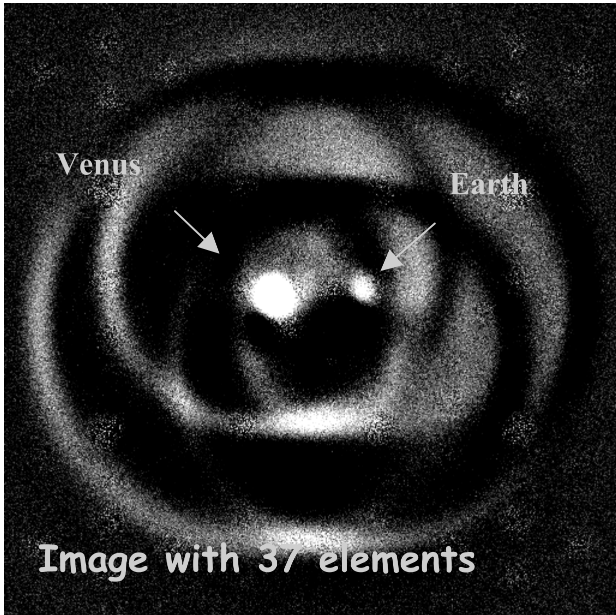
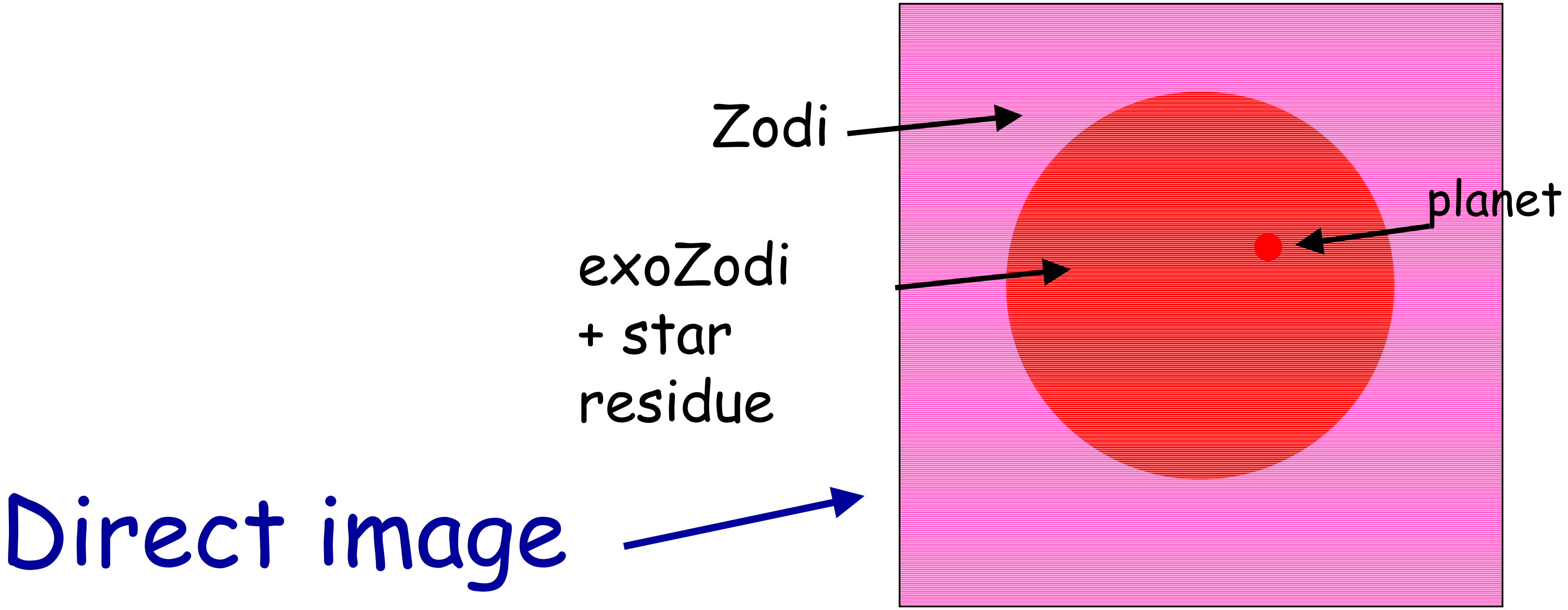


Image with 37 elements

The theoretical contrast advantage of hypertelescopes with respect to “Book Design”



- Image separates the planet’s peak from most zodi & exoZodi collected by the sub-apertures in a l/d sky patch.
- No such separation in Bracewell interferometry
- Planet contrast improves as N if star residue is negligible

So: large sensitivity gain

Hypertelescope detects planet faster than "Book Design" & DARWIN

- for same SNR, speed gain is: $(S_h / \tau_B S_B)^2 \ (F_B / F_h)$

where: $F_B = N_B L_z \lambda^2 \tau_B + N_B L_{ez} \phi^2 d_B^2 \ \tau_B + I_s G_B^{-1} N_B d_B^2$

and $F_h = L_z \lambda^2 /4 + L_{ez} \phi^2 d_h^2 \ /4 + I_s G_h^{-1} N_h d_h^2$

(Labeyrie et al. , in preparation)

- Example: 148 times faster detection for Sun & Earth-like system at 10 pc, with Zodi= ExoZodi (0.7 arc-sec. cloud); same aperture area = 20 m^2 ; $N_h = 37$ (d_h=0.73m) ; $N_B = 6$ (d_B=1.82m) ; λ= 10μ ; $\Delta\lambda$=4 μ ; $\text{nulling}_h = \text{nulling}_B = 10^5$ in 4 hours :

$SNR_h = 6.8$ and $SNR_B = 0.56$ planet contrast is 30 times better with hypertelescope

Possible trade-off

A hypertelescope TPF:

- having a smaller collecting area than "Book Design"
- but similar detection speed

- example: hypertelescope with 37 elements of 51 cm (S_h = 10 m^2) as fast as "Book Design" having 6 elements of 6.1m (S_B = 225 m ^{2})
- same SNR = 6 reached in 12 hours on Sun & Earth-like system at 10pc

"TPF lite" in Hypertelescope form

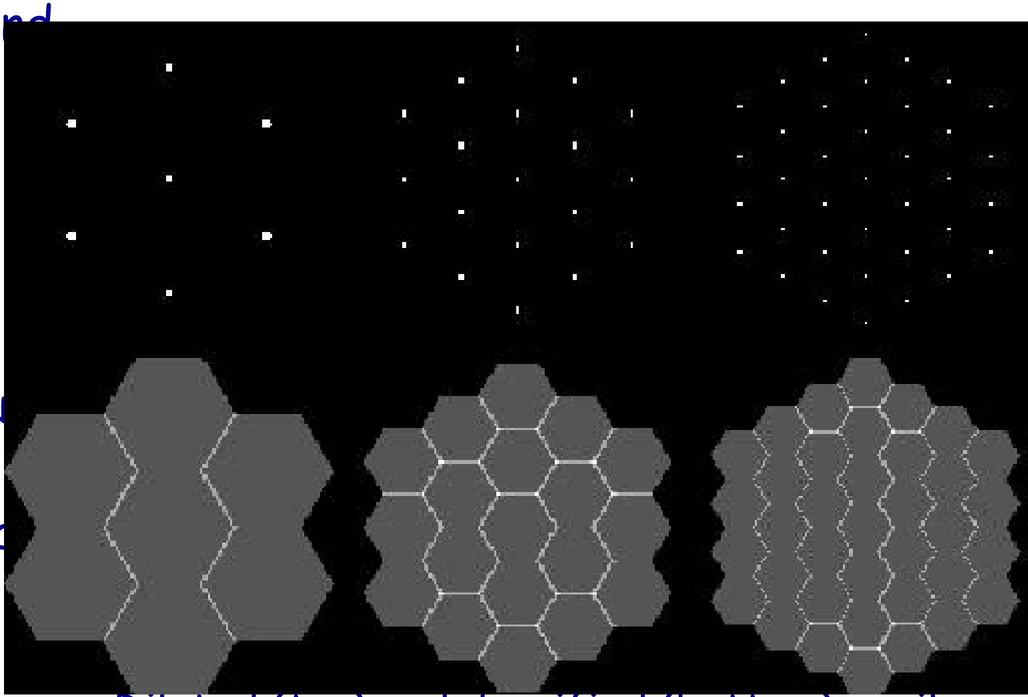
- Geostationary orbit , single launch
- Simplified thrusters: sails ?
- 18 or 36 apertures ?
  - At equal area , faster exoplanet detection with more apertures
  - Wider high-resolution field   8x8   vs. 12x12 resels

New technology needed

- Sails and small tiltable mirror or micro-mirror arrays
- Metrology:
  - GPS with local emitters, or
  - Pulsed diode laser for 1mm accuracy and data links
- Modified star trackers
- Offset guide star
- Coherence and phase analyzer: x,y, l algorithm ?

Spacecraft Configurations

- 3 possible configurations with 7, 19 an
  37 spacecraft
- central obscuration avoidable for coronagraph performance
- hexagonal shape : pupil can be fully densified
- located on a hexagonal pattern ⇒ fu
  densification
- spherical primary mirror to avoid del
  lines
- Direct FOV diameter 2 $N^{1/2}$ resels

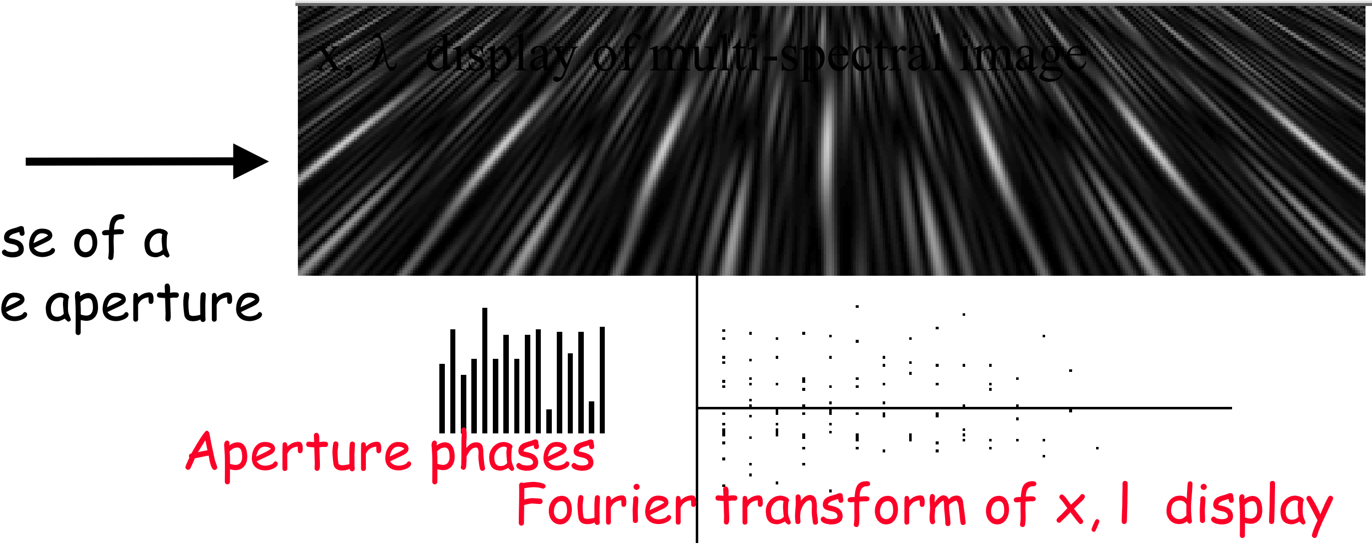


Diluted (top) and densified (bottom) pupils

Table 2. Spacecraft configurations			
Number of mirror elements	7	19	37
Element diameter (m)	1.39	0.84	0.60
Distance spacecraft-spacecraft (% size)	49.40	24.82	16.58
FOV (λ/D)	5.19	8.66	12.12

Simplifications considered for a bare-bone hypertelescope TPF

- Science : 10 micron + visible
- 150m size, small M1 elements , solar sailing
- Geo-stationary orbit , single launch
- Up-gradable with later launches
- Phasing: wave & coherence analysis from dispersed speckles in science image



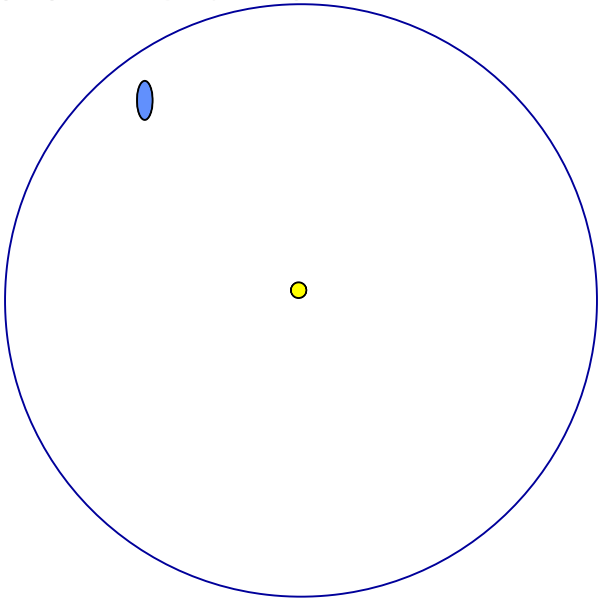
Case of a line aperture

Aperture phases

Fourier transform of x, l display

Guiding and Phasing with F/4 Mertz Corrector

Corrected Fizeau field with several imaging heads



- Guide star usable for general imaging
- Enough field for guide star mv= 16 ? **(± 38 μm of residual astigmatism on wave at 20 arc-sec off-axis)**
- Tolerable for software correction of observed star

Observing Sequence

- Free-flyers moved to assigned positions
- Positions verified with local GPS-type system (localization with local emitters: cm accuracy)
- (optional laser theodolite in focal station or laser ranging station at curvature center of M1: replacable by extended fringe finder)
- Adjustment of free-flyer attitudes (1 or 2 axes) with star trackers at M1 segments: aims star, optional center laser, focal beacon
- Acquisition of sub-images and fringes in focal station
- Cophasing on parent star (exo-planets) or guide star (general imaging)
- Snapshot imaging and coronagraphy

Number and Size of Apertures at Constant Collecting Area : Impact of More Apertures

Impact on Science

+ wider imaging field
+ less contamination from peripheral sources
+ effect of zodi and exozodi contamination decreases
+ more targets for general imaging

Technical implications

+ smaller mirrors
+ ultralight weight mirror driven by solar sails
+ figure tolerance relaxed (at expanse of more piston actuators in the form of solar sails)
+ failure of 1 element more tolarable if interchangeable
- cophasing
- metrology
- more drives
- cost

19 or 37 suitable, 7 problematic (longer exposures, Roddier et al processing)

Free-flyer vs. Monolithic

- Free flyer:
  - \+ small mirror elements
  - \+ higher resolution at given mirror area
  - \+ adjustable size, adaptable to scientific target
  - \- attitude control of many elements
  - \- position control, requires thrusters (mass ejection or solar sails)
- Monolithic telescope:
  - \+ pointable with torque wheels, no jets required = no pollution
  - \- high risk deployment
  - \- passive cooling
  - \- surface accuracy

Truss vs. free-flyers

- Advantage of truss: global pointing with torque wheels
- Drawbacks :
  - not so rigid ?
  - limited size (60 m ?)
  - Not a precursor of km and 100-km hypertelescopes

Solar Sails vs. Ion Thrusters

Solar sails for sky scanning *(see NASA FAME mission)* and phasing (*fine and permanent*) :

+ *infinite autonomy (good for orbit corrections)*
+ *light weight*
+ *micrometric translations and rotations*
+ *linear response*
+ *shields the payload from solar radiation*
- *strong tidal forces in low Earth Orbits (use Earth-trailing orbit or L_2 required)*
- *slow pointing and re-configuration*

Ion thrusters, intermittent preferred for focal optics *(coarse and non-permanent)* :

+ *stronger force, fast star acquisition*
- *limited autonomy*
- *gas condensation on cold mirror*
- *cost*

Operating Wavelengths

Ideally, 3 spectral channels for broad science (1 or several focal stations)

- 5-20μm IR: coronagraphic imager + spectrograph (CO_2, O_3, H_2O, CH_4)
  ⇒ detection and planetary atmosphere characterization

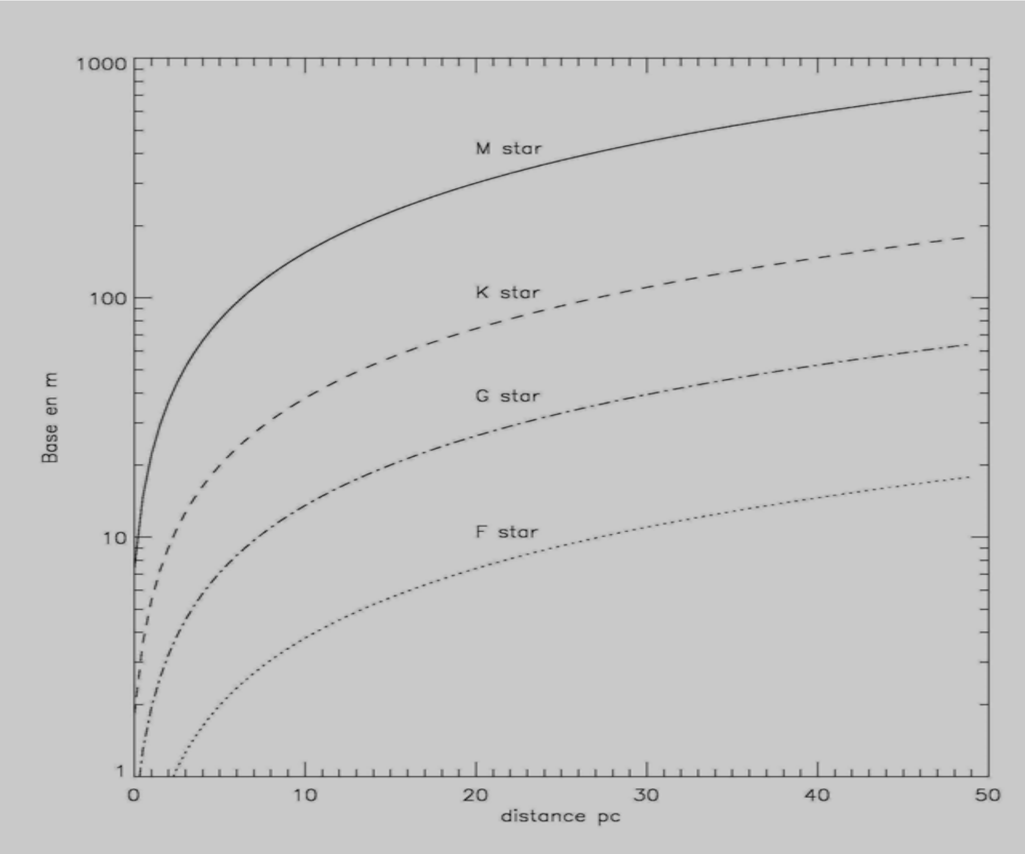
- 1-5μm IR: spectrograph ⇒ exo-planet characterization (H_2O, CO_2, CO, CH_4)
  coronagraphic imager ⇒ general astrophysics (circumstellar disks, EGPs)

- 0.6-0.9μm : angular resolution : 0.15 - 0.2 mas for 1 km baseline
  coronagraphic imager ⇒ high-angular resolution program
  dust torus in Seyfert and AGN (Hα)
  spectrograph ⇒ signs of biological activity (H_2O, O_2, O_2/ O_3)
  photosynthesis features in R band (for G stars)

option: ultra-violet general imager 0.1216 (Ly alpha) to 0.9 μm

↙ Minimal configuration : 5-20μm imager + spectrograph

Array size 1



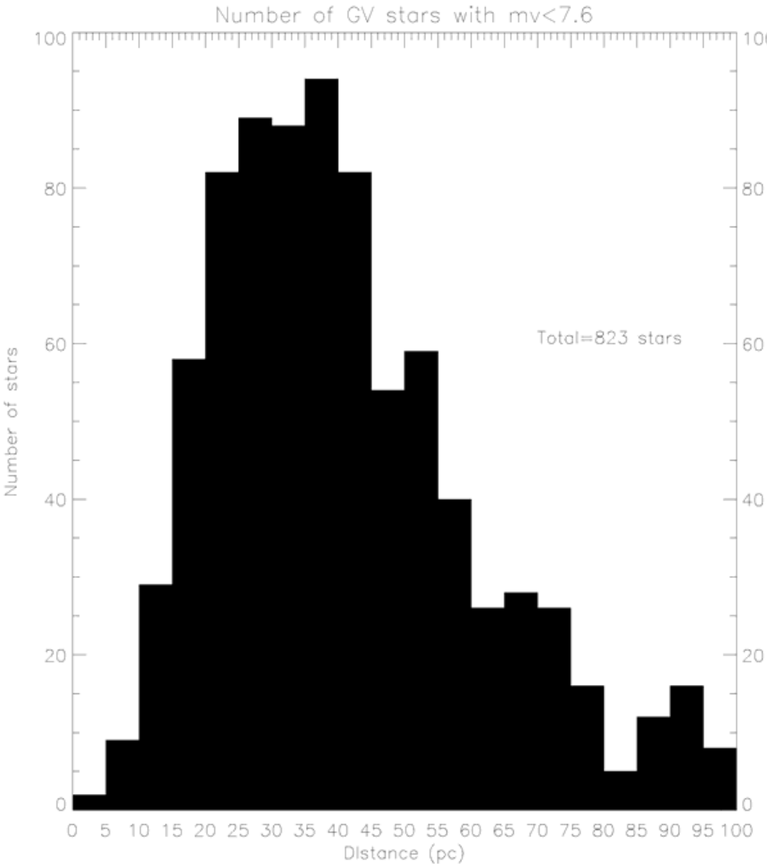
Optimal array size vs. distance for observing a planet at $3\lambda/B$

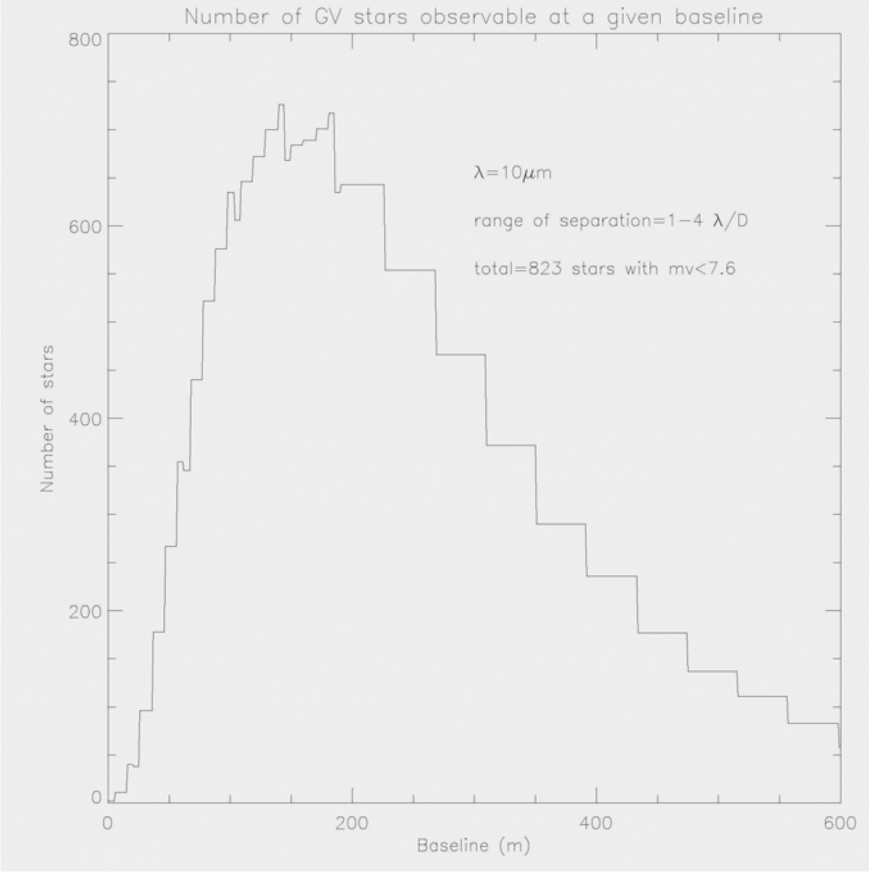
The radius of the habitable zone depends on the star temperature (spectral type)

→

Variable array size appears feasible at moderate extra cost

Array size 2





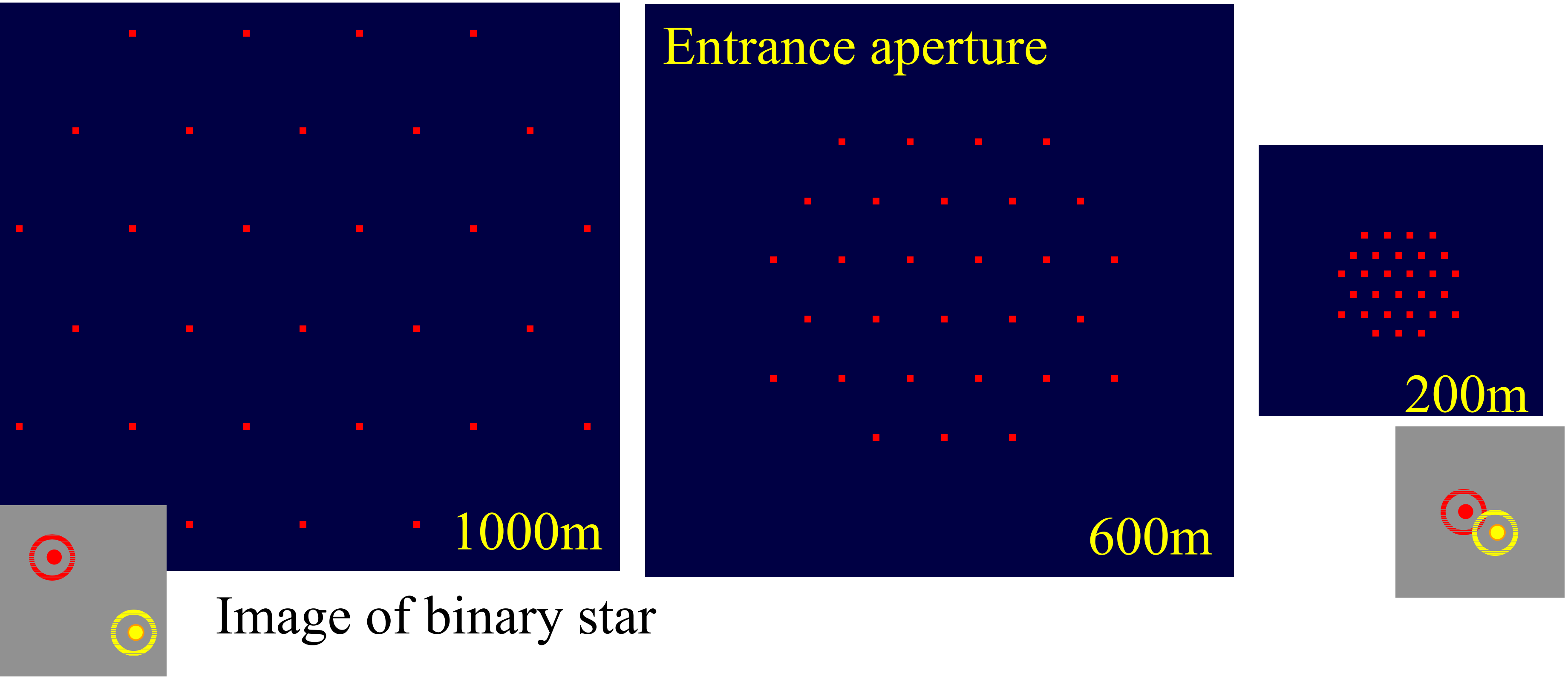
A 140m array can detect Earth-like planets around :

88% of GV stars (724)

- 53% of KV stars (188) ⇨ total : 934 main sequence G,K,M stars

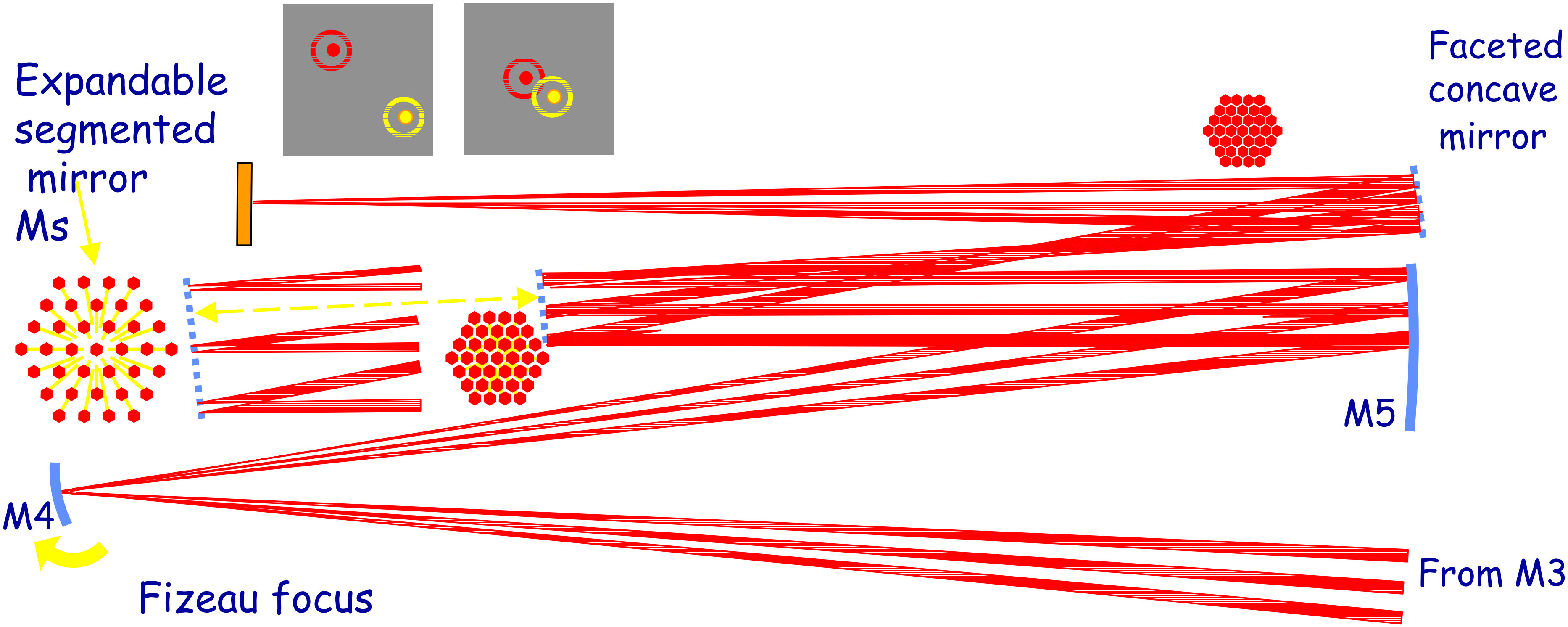
- 40% of MV stars (22)

Array expansion/contraction



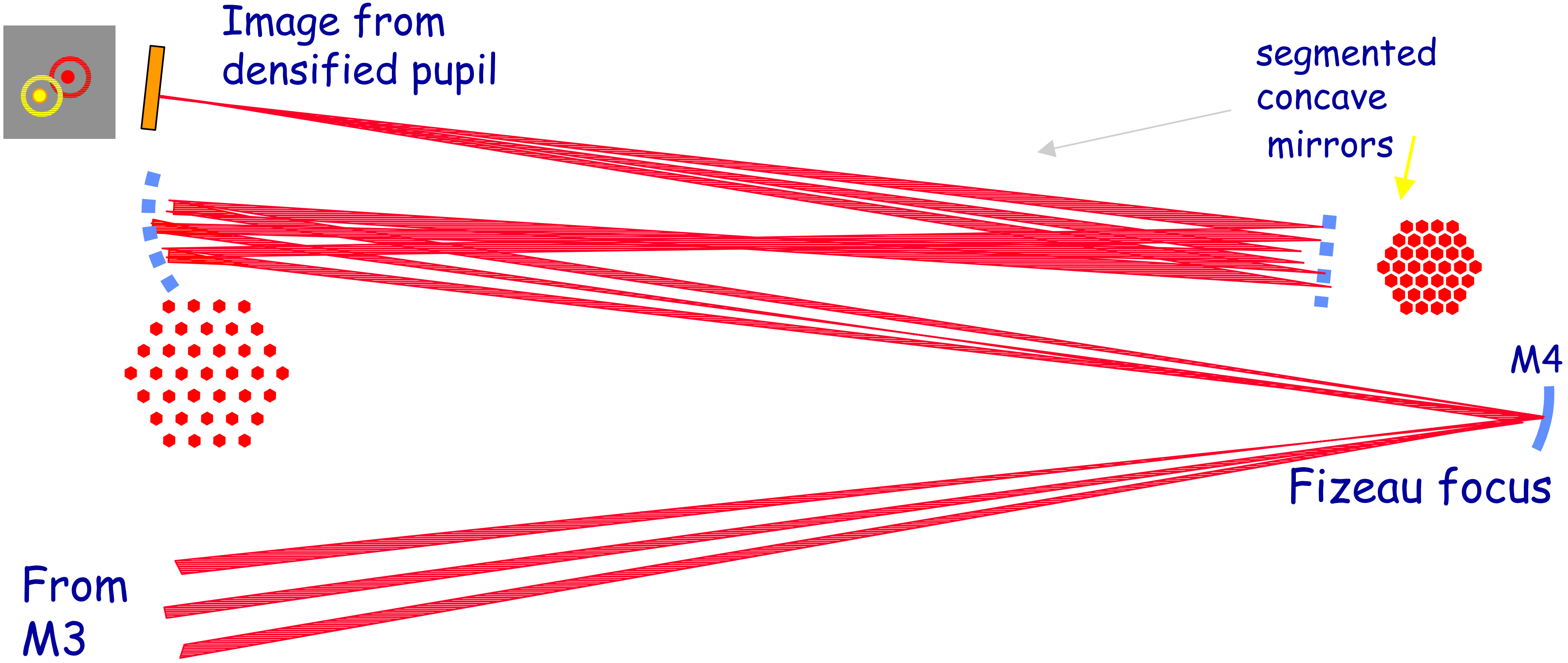
- Needed to match resolution to object ?
- Achieved by sliding elements on M1 spherical locus
- Requires simultaneous adjustment in the pupil densifier using expandable segmented mirror
- Achieves zooming in the direct image.
- Compatible with coronagraph, the exit pupil being invariant

Adjustable array size ?: Option of Zoomable Pupil densifier



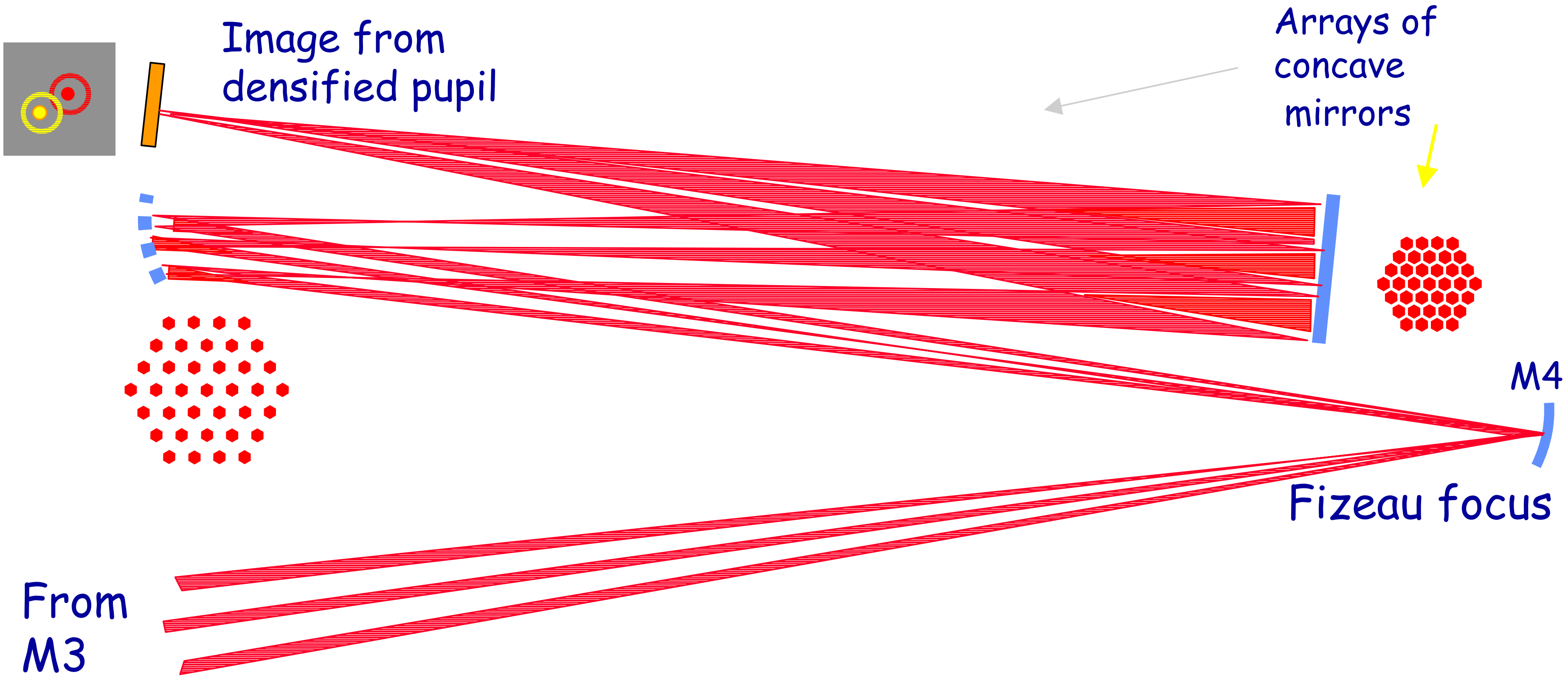
- Zoomable pupil densifier accommodates array expansion, achieved by sliding elements on M1 spherical locus
- Resolution proportional to aperture size
- Compatible with coronagraph, the exit pupil being invariant

Basic pupil densification at Fizeau focus



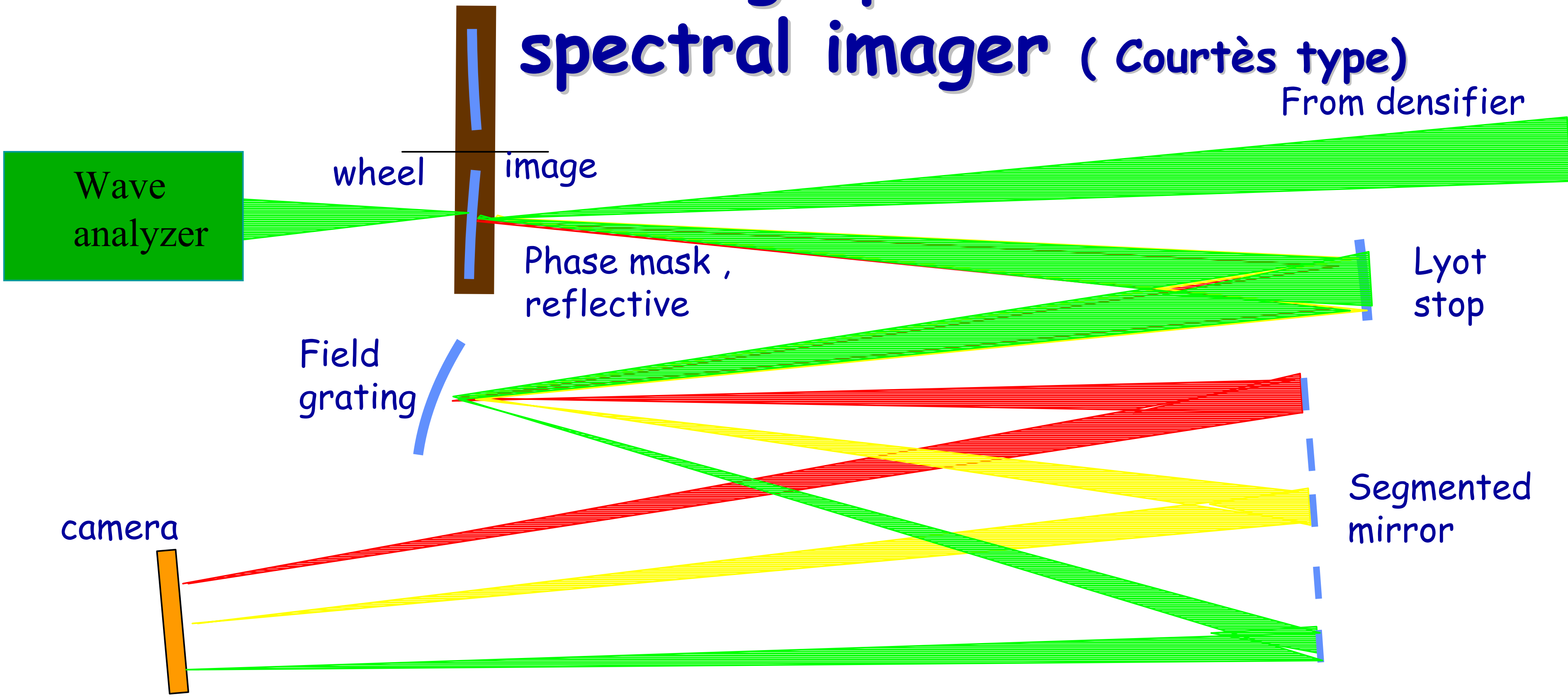
- Diversity of schemes possible

Basic pupil densification at Fizeau focus



- Diversity of schemes possible

Spectroscopy: Coronagraph with multi-spectral imager (Courtès type)



- Produces array of 10-100 monochromatic images
- Also white image on direct camera accessed by wheel
- design usable for visible and IR

Types of Mirrors

- **C/SiC mirror (IRIS technology)**
  Mirror areal density *<20 kg/m^2*
  a 17.6 kg/m^2 mirror was build by a German team with a roughness below 1 nm
  temperature < 6 K (Onaka et al., 1998)

- **CFRP mirror (NGST technology)**
  Mirror areal density (mirror, actuators, structure) *<5 kg/m^2*
  Membrane areal density *< 1.25 kg/m^2*
  Temperature < 77 K
  Experiment with a 0.5 cm diameter mirror under way (Hoffman et al., 1999)

- **Angel 's stretched membrane, replicated and ion-figured**
  Mirror areal density (mirror, actuators, structure) *< 1 kg/m^2*
  Membrane areal density *< 0.04 kg/m^2* *(rods and actuators dominate)*
  Temperature < 30 K

Optional ultra-violet imaging ?

- General imaging of stellar disks, galaxy nuclei, ...
- The accurate phasing needed for red coronagraphy (7 nm RMS) suffices for UV imaging
- Effect of intra-pupil bumpiness: envelope peaks lose energy to speckles around them , resolution unaffected
- Piston errors critical but OK if meeting red coronagraphy requirements
- Choice of:
  - dedicated UV station
  - or added camera in red coronagraphy station: moderate added cost

Sources of Noise and Tolerances

Sensitivity : photon noise	m < 24.5 @ 10 μm, 5 σ in 10 hr, R=10
Zodiacal light (solar)	Δm (Earth/zodi)= 0.65 @ 10 μm, B = 100
Exozodiacal light	< 15 zodi @ 10 μm, B = 100, 10 hr
Thermal emission of optics	< 70 K
Bumpiness of mirror element	λ/140 induced shadow pattern increases star 's halo (needs to be assessed)
Segments positioning (along the primary mirror surface)	5% of segment size
Co-phasing errors : piston	λ/110 for 15 mag. dynamic range with 37 elements

Major Issues

- General concept
  - full u,v plane coverage (number and size of mirror elements)
- Coronagraph
  - achromatic phase-mask in the mid IR
  - active correction of tip/tilt
- Spacecrafts
  - metrology between spacecrafts
  - set-up of the instrument (initial positioning of free-flyers)
  - mass and cooling of the spacecrafts
  - manage the light from solar sails
- Focal stations
  - aspheric mirrors for correcting spherical aberration
  - optical design of the pupil densifier
  - star tracking with focal station
  - relay of images

Comparison Against TPF Book Design

+ Hypertelescopes are more immune to background (zodiacal and exozodiacal)

+ SNR = 14.8 (hypertelescope with Rouan Phase-Mask, Lz = 12.7 mag/"^{2})

  = 5.8 (hypertelescope with Roddier Phase-Mask, Lz = 21mag/"^{2})

  = 0.5 (Bracewell, Lz = 21mag/"^{2}) *(Boccaletti et al., 2000)*

  G2V star at 20 pc, Lez = 10Lz, T = 10h, $\lambda/\Delta\lambda = 10$, 37 telescopes.

- Small field of view

Status

- ***Completed***
  - preliminary numerical simulations + theoretical SNR estimate
  - lab & sky experiments of a miniature hyper-telescope (single micro-lens array)
- ***On-going***
  - numerical simulations to assess all sources of noise ⇒ budget of errors
  - lab & sky experiments (2 micro-lens arrays)
- ***To be done***
  - lab & sky experiments of a four-quadrant phase-mask (single pupil)
  - lab experiments of corrector of spherical aberration
  - detailed study on solar sails
  - adaptive phasing
  - optical test at Arecibo site

Space testing a preliminary version

- Geostationary, free Ariane launch : 1% solar eclipse, 1.1hr duration
- Two free-flyers, monitored from transfer module ?

BOEING SVS

Planet Imager: a 150 km Hypertelescope

150 elements
of 3m
150 km
30 min exposure

Earth at 3pc

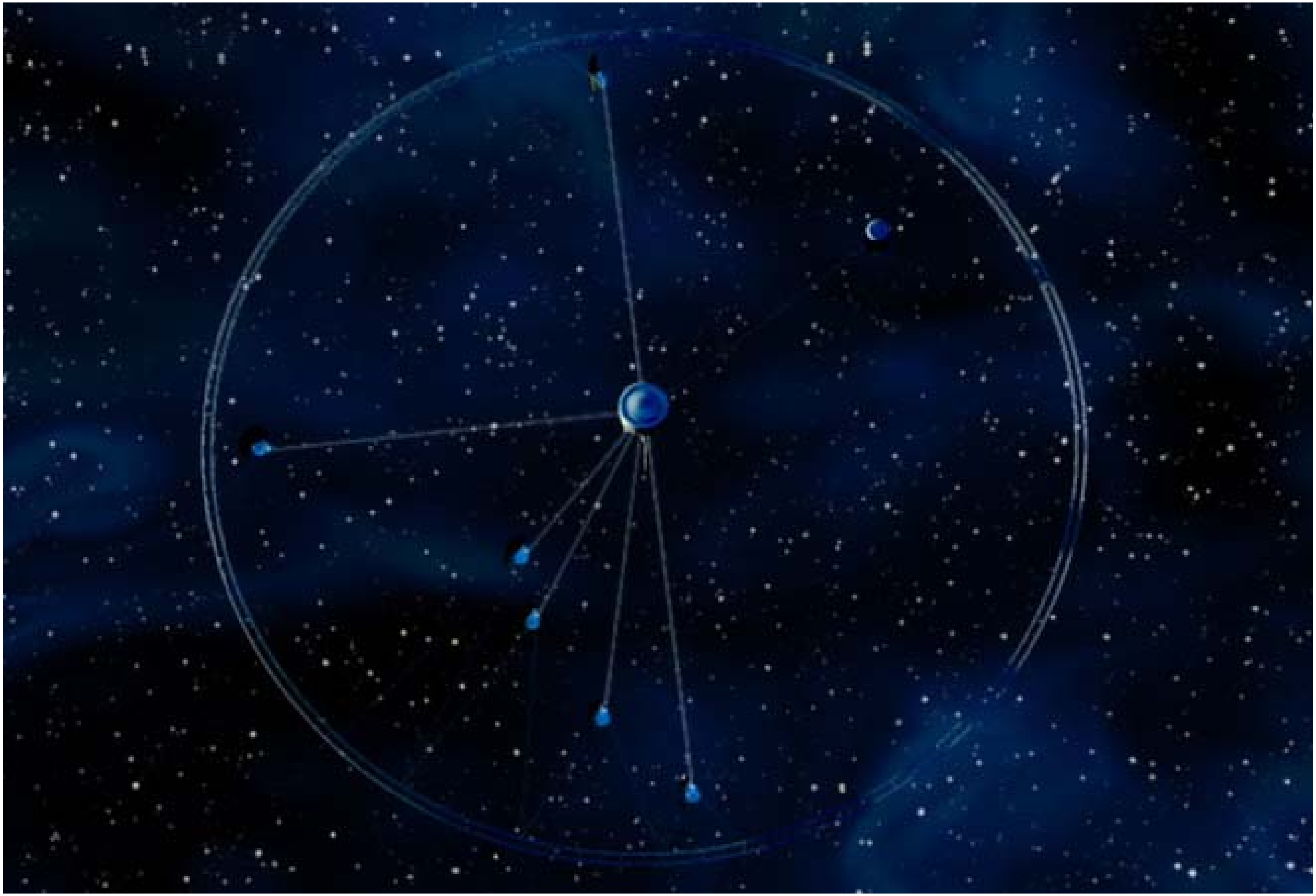
QuickTime™ et un décompresseur
Photo - JPEG sont requis pour visualiser
cette image.

Hypertelescope:
Rotational Imaging Array

Types of Rotational Synthesis Imagers

- Planar concept
- Parabolic concept

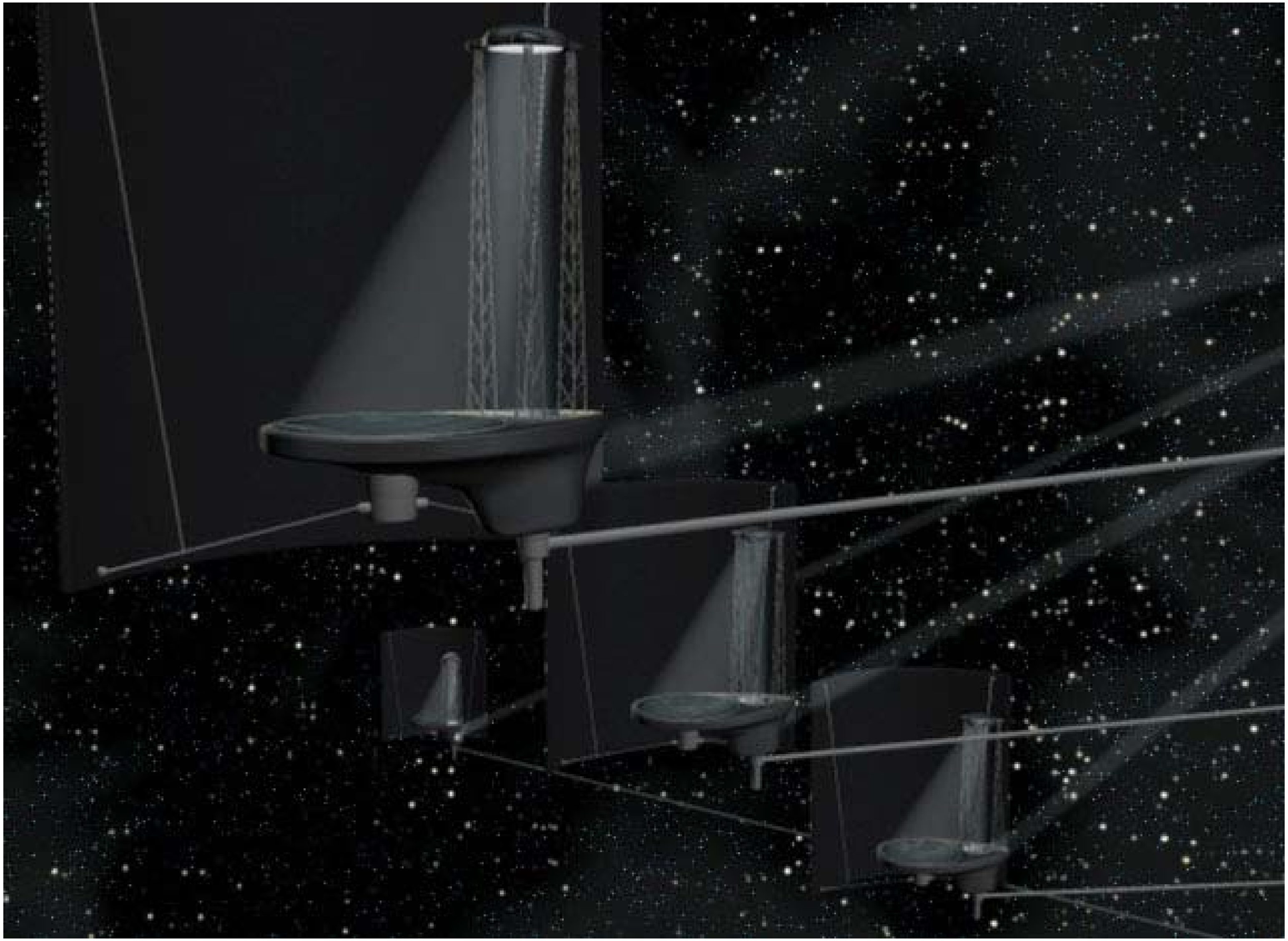
Artist's Rendition of Rotational Synthesis Imager: Parabolic



Animation of Rotational Synthesis Imager - Parabolic

QuickTime™ and a
Sorenson Video decompressor
are needed to see this picture.

Artist's Rendition of Rotational Synthesis Imager: Planar - Close-up



BOEING
SVS

Animation of Rotational Synthesis Imager - Planar

QuickTime™ and a
Sorenson Video decompressor
are needed to see this picture.

Rotational Synthesis Imager

Imaging using rotational aperture synthesis -> few apertures needed

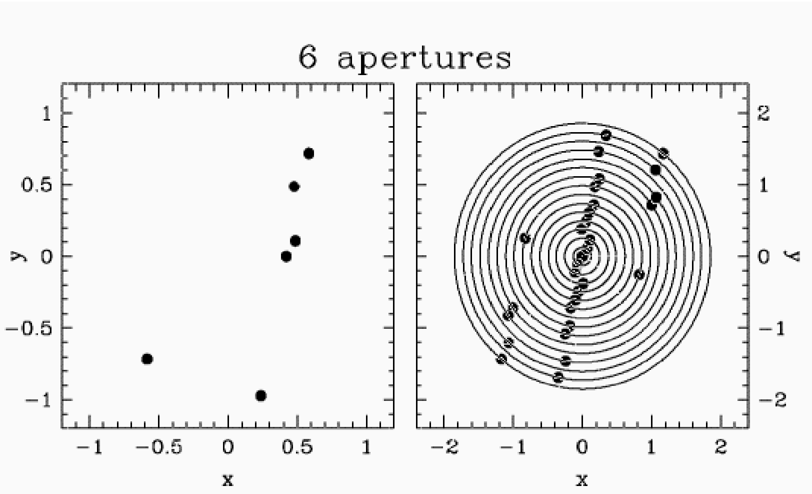
Overview

- 6 telescopes, 3m diameter each, on a 3D F/D = 1 parabola, total collecting surface is 42 sq m
- 10 mm wavelength, 5 to 15 mm for planet detection/spectroscopy
- 20 mas resolution at 10 mm
- 8 % snapshot (u,v) plane coverage. 100 % (u,v) plane coverage after half a rotation of the array.
- Nulling coronagraphy in densified pupil plane
- Use of rotational aperture synthesis to construct an image
- Wide field of view (3 arcsec): larger than the Airy spot of one individual telescope
- Full beam transport - no fiber optics
- 60 m baseline

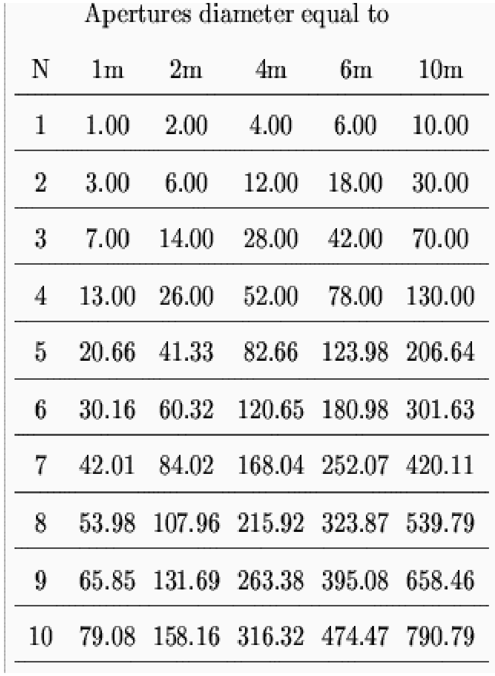
u,v Plane Coverage

Full (u,v) plane coverage up to 60m baseline with rotation.

- Reduces chances of confusion with background sources
- helps detection of planets in complex environments (exozodi clumps, multiple planets systems etc...)



6 telescopes configuration for optimum (u,v) plane coverage (left). Autocorrelation function of this array (right).

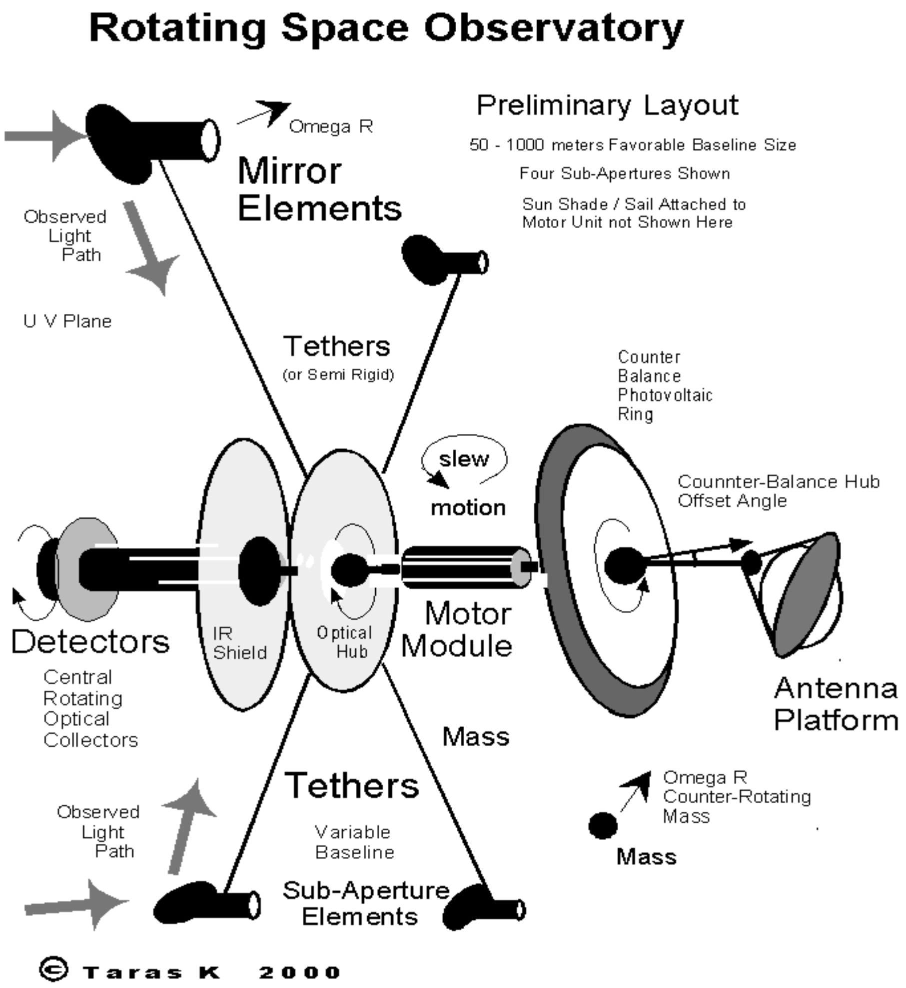


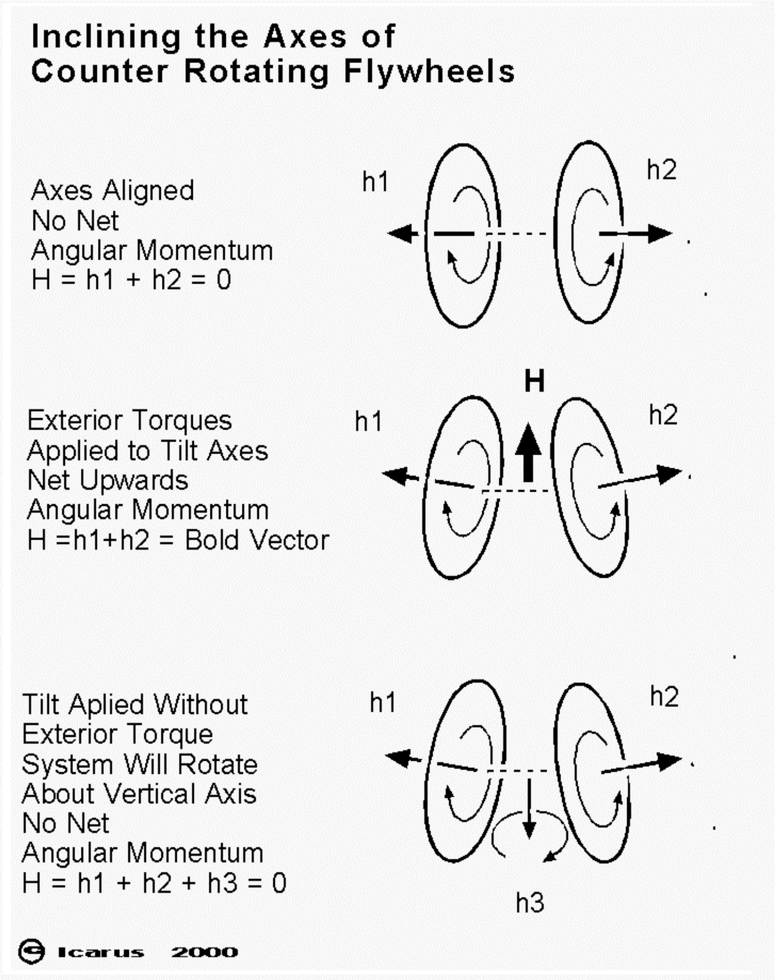
Apertures diameter equal to

N	1m	2m	4m	6m	10m
1	1.00	2.00	4.00	6.00	10.00
2	3.00	6.00	12.00	18.00	30.00
3	7.00	14.00	28.00	42.00	70.00
4	13.00	26.00	52.00	78.00	130.00
5	20.66	41.33	82.66	123.98	206.64
6	30.16	60.32	120.65	180.98	301.63
7	42.01	84.02	168.04	252.07	420.11
8	53.98	107.96	215.92	323.87	539.79
9	65.85	131.69	263.38	395.08	658.46
10	79.08	158.16	316.32	474.47	790.79

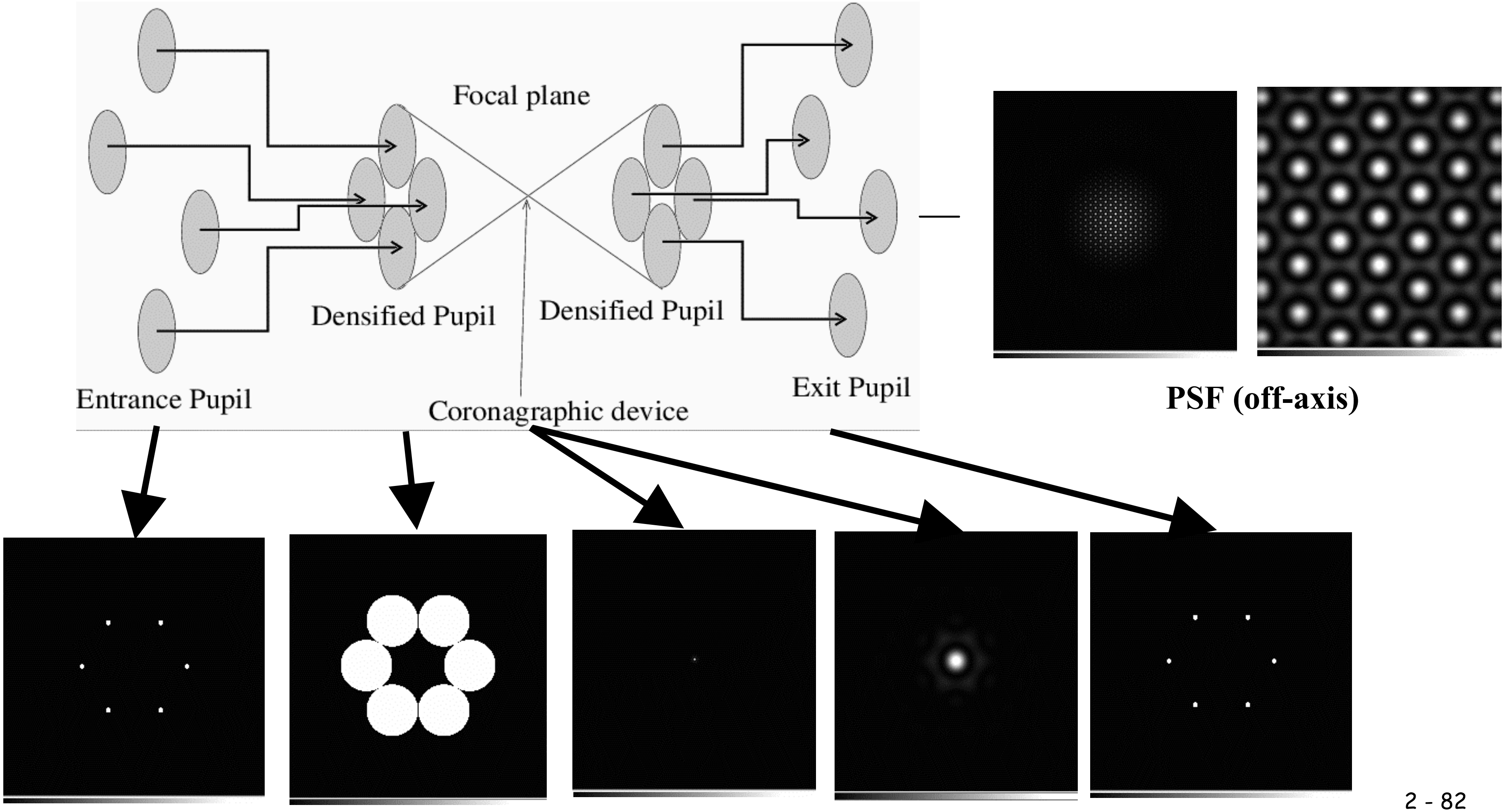
Rotation allows use of rigid, semi-rigid structure or tethers.

Array rotation - pointing





Pupil densification/dilution



Signal processing

I - Snapshots acquisition

- Array is continuously rotating
- each snapshot is a few minutes exposure time (saturation by star residual / background)
- One rotation of the array per 1 or 2 hours (or faster, but no faster than 5 rotation per hour)

II - Star residual subtraction

- Detector is rotating with the array
- Star residual component is obtained from statistical (median) filtering of the snapshots
- Star residual component is subtracted in each snapshot (photon noise still present)

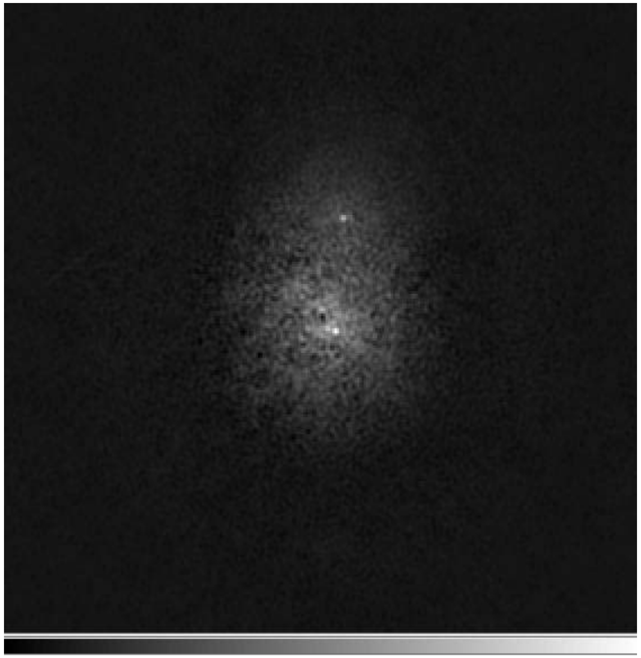
III - Image reconstruction

- Each snapshot is Fourier filtered (noise reduced)
- Each snapshot is Fourier Transformed
- After half a rotation, all spatial frequencies are known and the image is reconstructed

IV - Deconvolution

- The spatial frequencies have variable gain
- Fourier gain adjustment to maximize S/N
- Need for a deconvolution algorithm to suppress the effect of the coronagraphic device on off-axis sources

Detection limits



Earth-Sun system at 10pc

2.7h exposure time, 5 to 15 µm
No deconvolution, Fourier noise filtering
6 telescope, 3m diameter, 60m baseline
no zodi/exozodi light
extinction ratio for the star is 3500

Earth-Sun system at 10pc

S/N = 7 in 1.4h without deconvolution
With deconvolution and QE = 0.2 :
S/N = 7 in less than 2 h

Earth-Sun system at other distances

- If d < 4pc, S/N is better than the formula above (resolved by individual apertures)
- If 4pc < d < 20pc, the formula is valid
- If d > 20pc, the Earth is nulled too.

Spectroscopy

Use of STJ detectors if available

Full (x,y,l) image created
Photon-counting mode
Low spectral resolution

If STJs not available, 1D exit pupil with dispersive element

Small loss of (u,v) plane coverage efficiency
1D arrays can also solve some nulling chromaticity problems
Spectral resolution limited by number of pixels and spectral coverage

S/N = 7 x sqrt(T/2h/R)

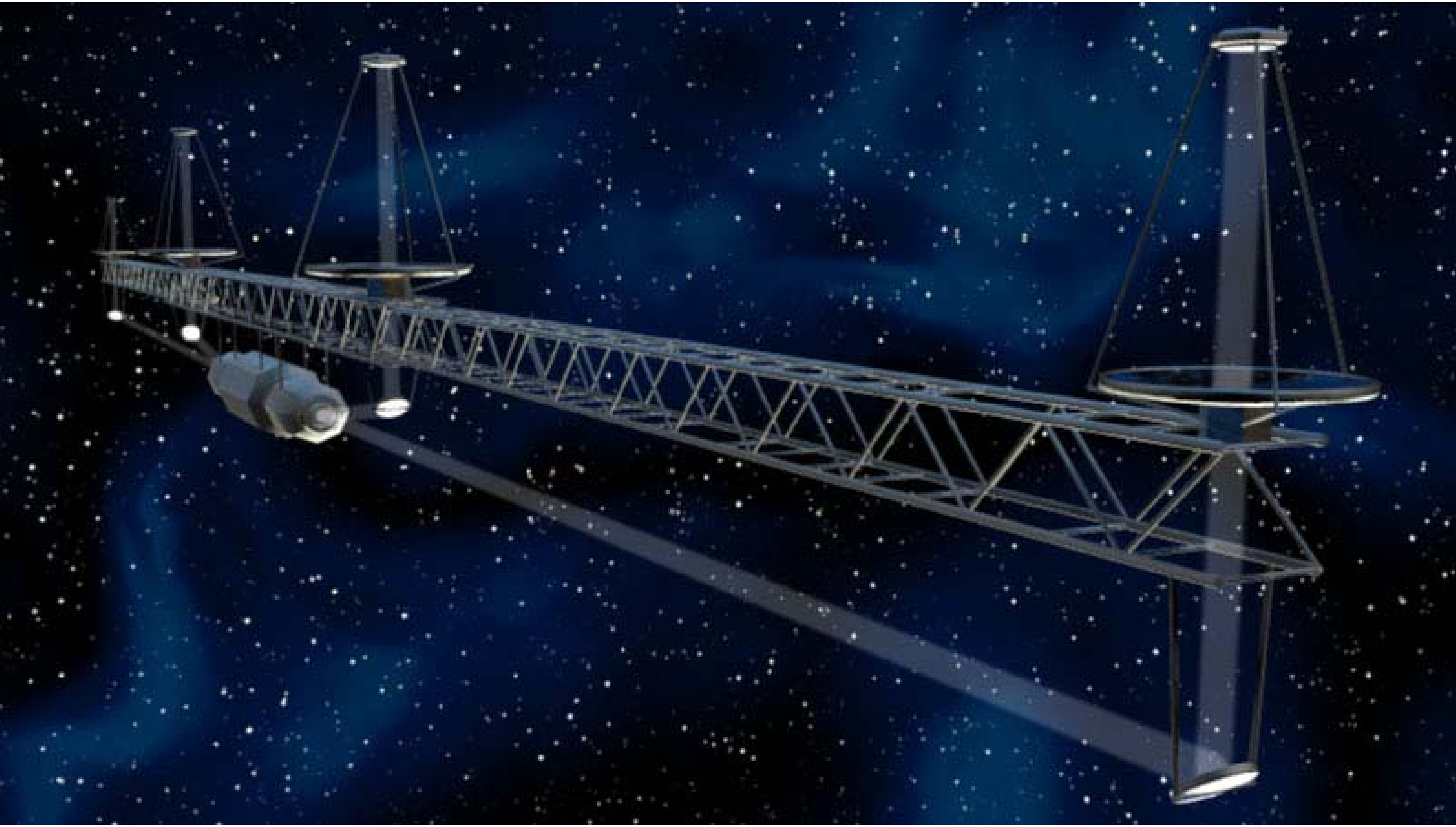
R = 10 -> T = 20h
R = 100 -> T = 200h

If planet previously detected, use of an optimized phase mask.

D = 10pc -> gain = 4x
D = 20pc -> gain = 16x

Redundant Linear Array

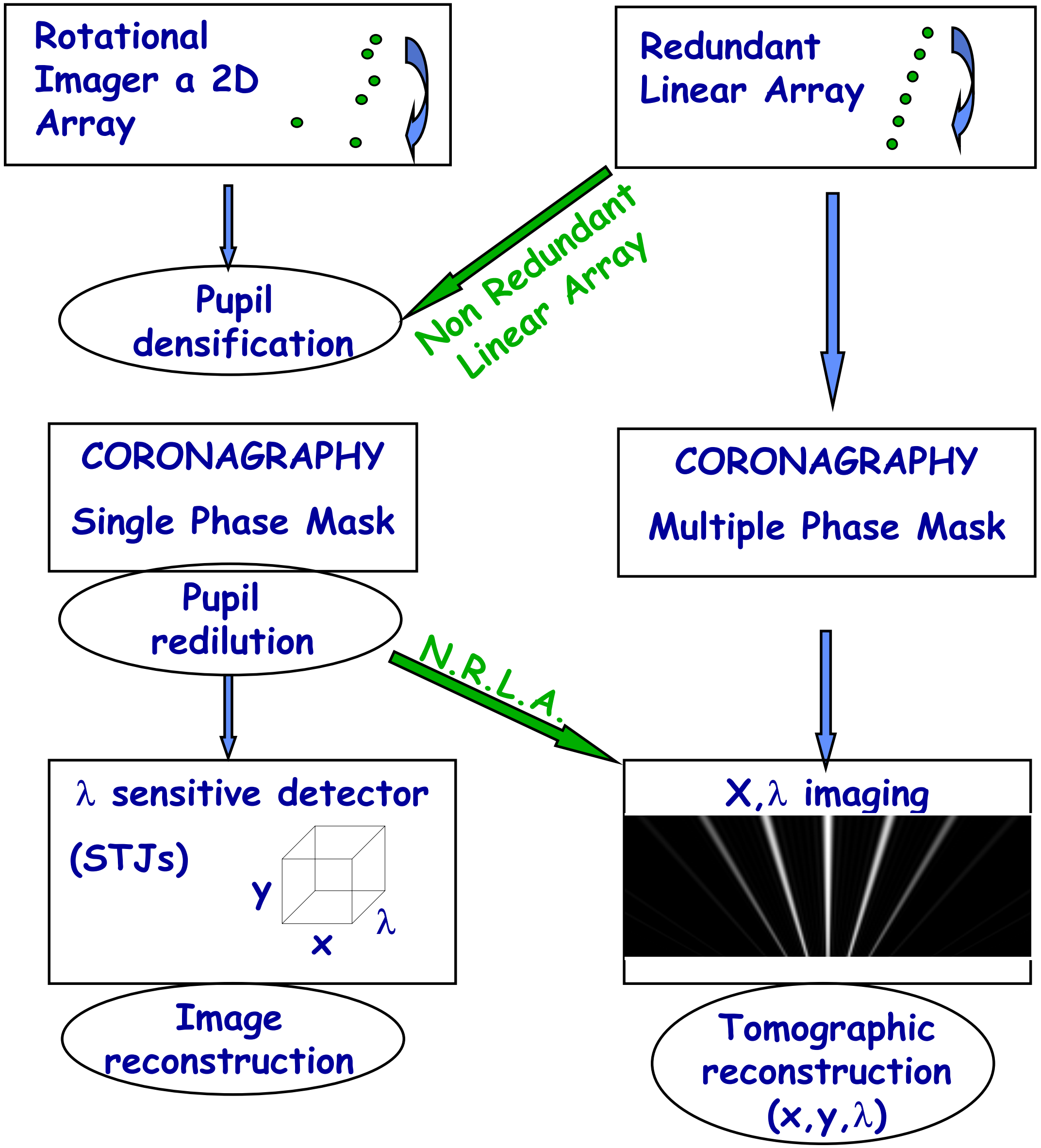
Artist's Conception of Redundant Linear Array



Animation of Redundant Linear Array

QuickTime™ and a
Sorenson Video decompressor
are needed to see this picture.

Comparison between Rotational Synthesis Imager and Redundant Linear Array



Rotational Imager a 2D Array

Redundant Linear Array

Pupil densification

Non Redundant Linear Array

CORONAGRAPHY

Single Phase Mask

CORONAGRAPHY

Multiple Phase Mask

Pupil redilution

N.R.L.A.

λ sensitive detector

(STJs)

X,λ imaging

Image reconstruction

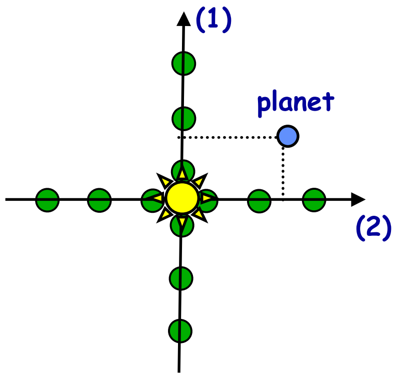
Tomographic reconstruction (x,y,λ)

- **Rotational Imager a 2D array**
  - Optimal u,v coverage
  - Needs pupil densification
  - Single Phase Mask
  - Needs STJs detectors
  - Image reconstruction by rotation
- **Redundant Linear Arrays**
  - Lower u,v coverage
  - Avoid pupil densification
  - Needs multiple masks
  - Use classical detector
  - Easier cophasing and calibration of the array
  - Tomographic image reconstruction
- **Possible concept merging : Non redundant Linear Array with pupil densification**

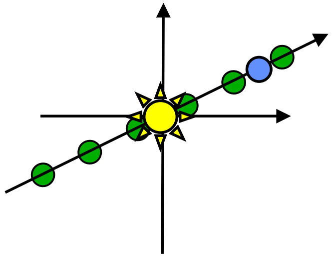
Why a linear array for TPF ?

- Optimal configuration for Spectroscopy and enabled astrophysics
- Optimized resolution in one direction for a given number of telescopes
- Very good multiwavelength tomographic image reconstruction by rotation of the array
- Simple Phase Mask achromatisation

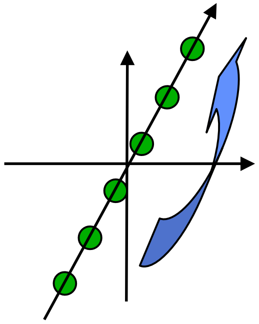
Linear Array Acquisition Modes



- Planet detection
  - 2 acquisitions in orthogonal directions sufficient for planet detection and positioning



- Spectroscopy :Atmosphere characterization
  - The Linear Array is fixed in the planet direction
  - Resolution optimized in this position
  - Spectroscopy by dispersion perpendicular to the PSF fringes

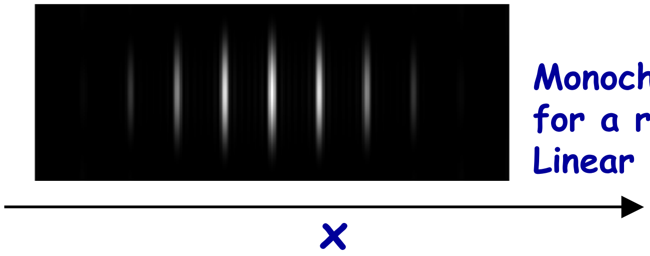


- Imagery of a planetary system or extended object
  - Full rotation of the interferometer
  - Reconstruction by mean of well known tomographic techniques

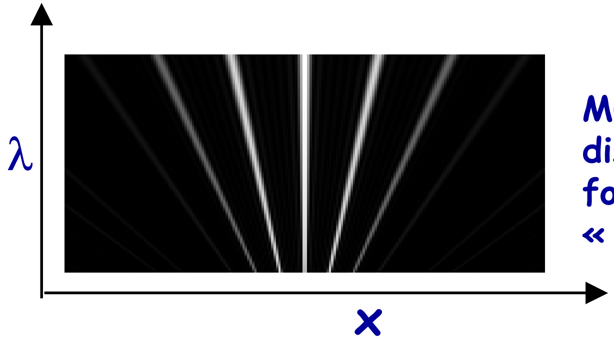
Spectroscopy & Coronagraphy

- Easy dispersion in the direction perpendicular to the PSF fringes
- High spectral resolution achievable
- X - λ recording using a classical 2D detector.
- Favorable for Phase Mask achromatisation

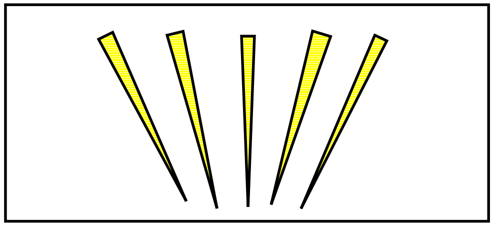
  (PM using mirror reflection under study)



Monochromatic PSF
for a redundant
Linear array

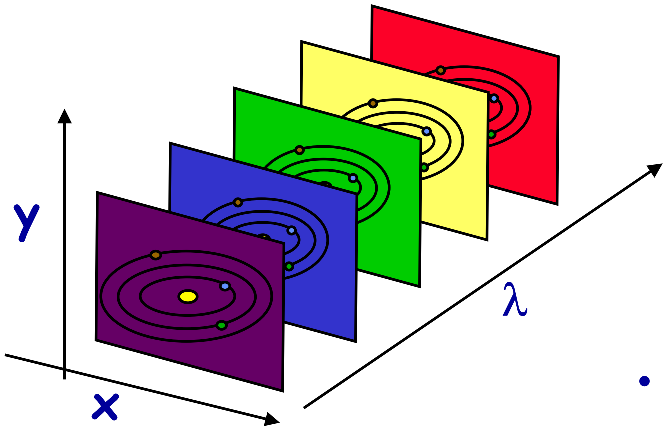


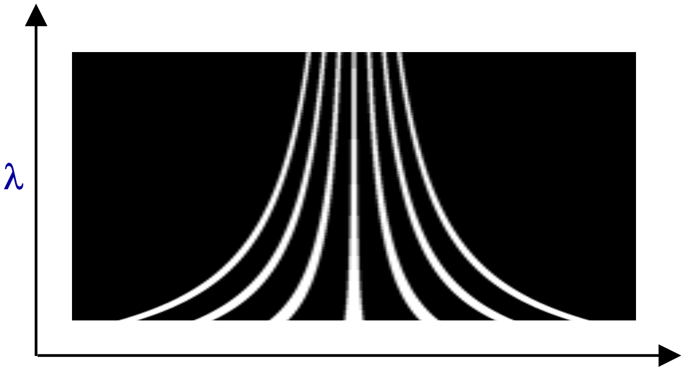
Multiwavelength
dispersed PSF
for a R.L.A. :
« (x, λ) PSF »



Phase Masks
adapted to
wavelength

Multiwavelength Tomagraphy





Wavelength dependence of the Array MTF support

- Image reconstruction by rotation
  - For a position of the array, the signal is a projection of the object
  - Very robust and well known method developed for medical imaging
  - Jitter effects already studied and overcome (Ref : Touma et al. Pure Appl. Opt. 1995 4,685)
- Multiwavelength image reconstruction
  - A tomagraphic reconstruction for each wavelength (spectral channel)
- Alternatively a single « white » image may be reconstructed for better SNR
  - Each λ contributes information to a different spatial frequency

Work in progress & planned

- Continuation of RLA study including numerical and laboratory simulations
  - Implementation of coronagraphic masks using mirrors.
  - Optimization of the apodization and coronagraphy
- Try to answer the question whether to use
  - Redundant Linear Array with Multiple Mask Coronagraphy
  - Rotational Hypertelescope Imager approach in a linear non redundant configuration.

Note : These two techniques are very similar because they both use rotating super-synthesis for image reconstruction

- Study of the image reconstruction for the densified pupil inverse problem
  - Inverse Fredholm integral for a non stationary kernel
- Linear configuration for TPF lite
  - 12m x 1.5m rotating filled aperture

The Book Design and Related Architectures

Sparse Interferometers Operated as Nulling Arrays

TPF "Book Design" Architectural-level Trades

- Previous study appears to concentrate on single structure vs. free-flyer
- Alternative instrumental (aperture) configurations have evolved but not necessarily compared as systems; null depth primary (only) discriminator
- Single structure vs. free-flyer trade appears heavily dependent on a specific deployment system mass; more detailed evaluation needed here
- Quantitative comparison of single structure vs free-flyer aperture alignment, phasing, and disturbance-rejection performance is needed
- No serious consideration of on-orbit assembly/servicing options
- Insufficient consideration of tethered options

Some possible nulling interferometer concepts

No. Tele.	Array Configuration	Null Width	Chopping Feasible?	Comments
4	Linear 1:2:2:1 or 1:3:3:1	q^6	NO	
4	2 each 3-element interferometers	q^4	YES	Baseline 75 – 135 m, aperture 3.5m [nominal "book" design]
4	Double Bracewell	q^2	YES	
4	Angel Cross	q^4	NO	
6	2 fixed, 3-element interferometers	q^4	YES	Each 3-el I/f a separate s/s ~40m nominal baseline each
6	ESA "Mariotti" configuration	q^4	YES	"3DAC" array
5	Mennesson/Mariotti elliptical array	q^4	NO	5 each 1.5m at 5AU geometry 50 x 25 m

Note: Analysis to date of the above concepts has assumed working in IR only, e.g., > 6 microns.

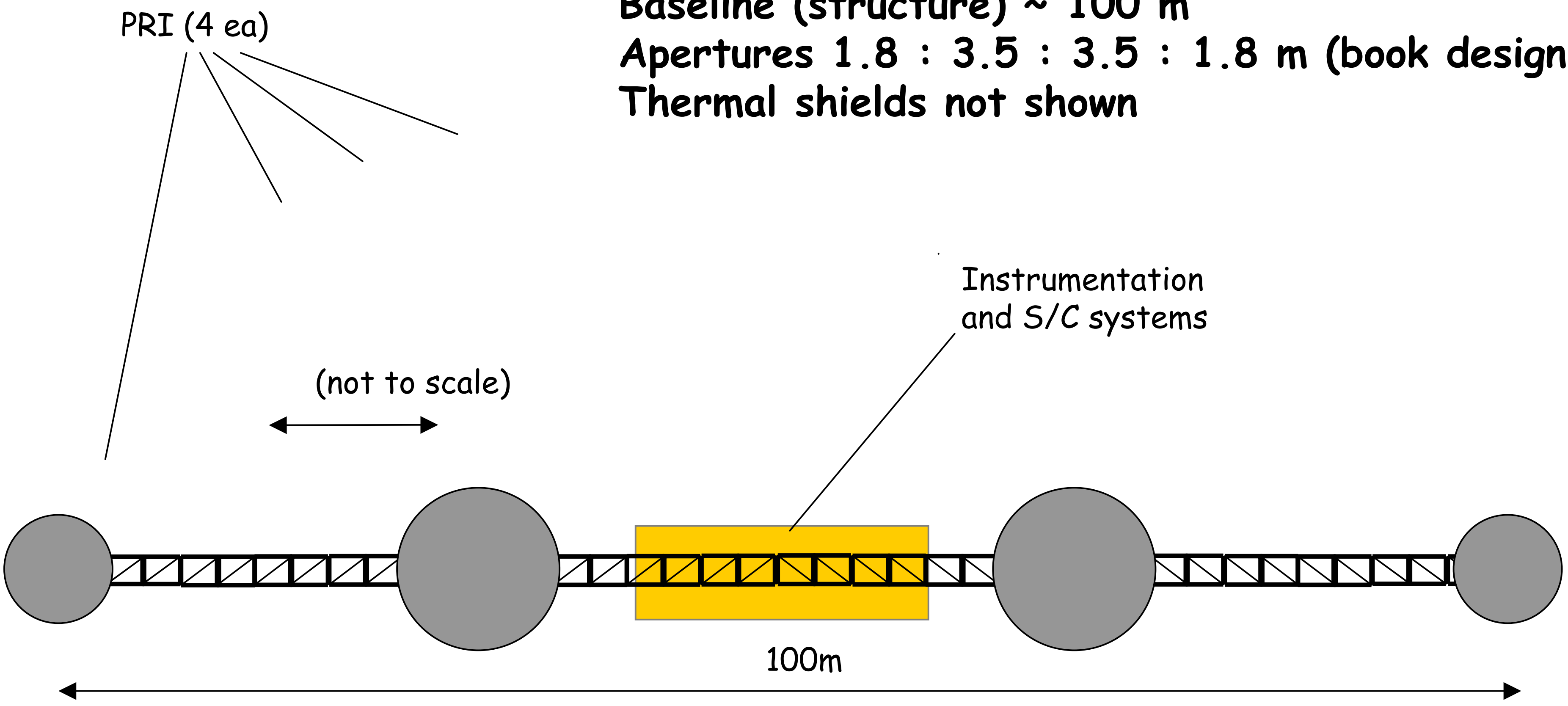
Ref. (1) TPF Book
(2) Mennesson & Mariotti, Icarus 128, 202-212

Performance and Design Issues

- Not clear from TPF book whether polygonal circle path approximation has been factored into nulling performance and SNR
- Astrophysics time allocations need an initial quantitative estimate to check against mission allocations; could be a lot worse (?)
- L_2 nonlinear dynamics modeling tools still in development

Concept – IR nuller on deployable structure

Example dimensions shown
4-element linear array on deployable truss
Baseline (structure) ~ 100 m
Apertures 1.8 : 3.5 : 3.5 : 1.8 m (book design)
Thermal shields not shown



Status

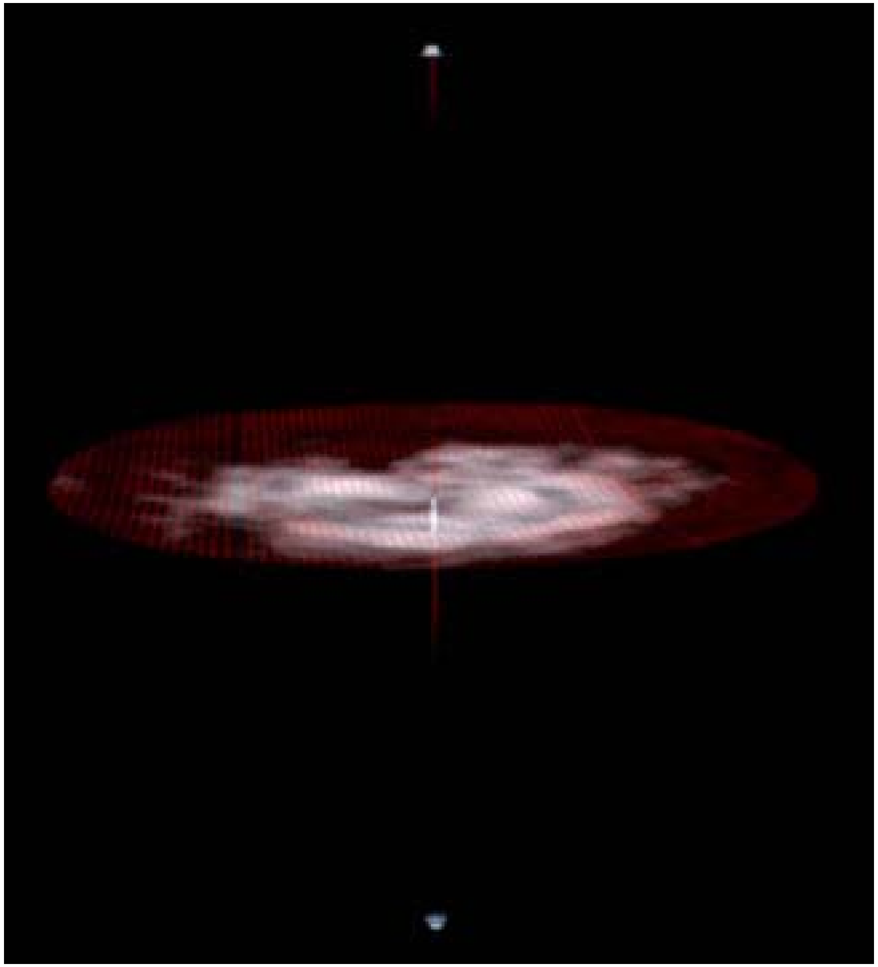
- Architectural-level trades
  - Previous study appears to concentrate on monolithic vs. free-flyer
  - Alternative instrumental (aperture) configurations have evolved but not necessarily compared as systems; null depth primary (only) discriminator
  - Monolithic vs. free-flyer trade appears heavily dependent on a specific deployment system mass; more detailed evaluation needed here
  - Quantitative comparison of monolithic vs free-flyer aperture alignment, phasing, and disturbance-rejection performance is needed
  - No serious consideration of on-orbit assembly/servicing options
  - Insufficient consideration of tethered options

- Performance and design issues
  - Not clear from TPF book whether polygonal circle path approximation has been factored into nulling performance and SNR
  - Astrophysics time allocations need an initial quantitative estimate to check against mission allocations; could be a lot worse (?)
  - L_2 nonlinear dynamics poorly understood and modeling tools still in development; level of impact on free-flyers TBD

The Laser Trapped Mirror

A Technology for the Future

Artist's Conception of Laser Trapped Mirror



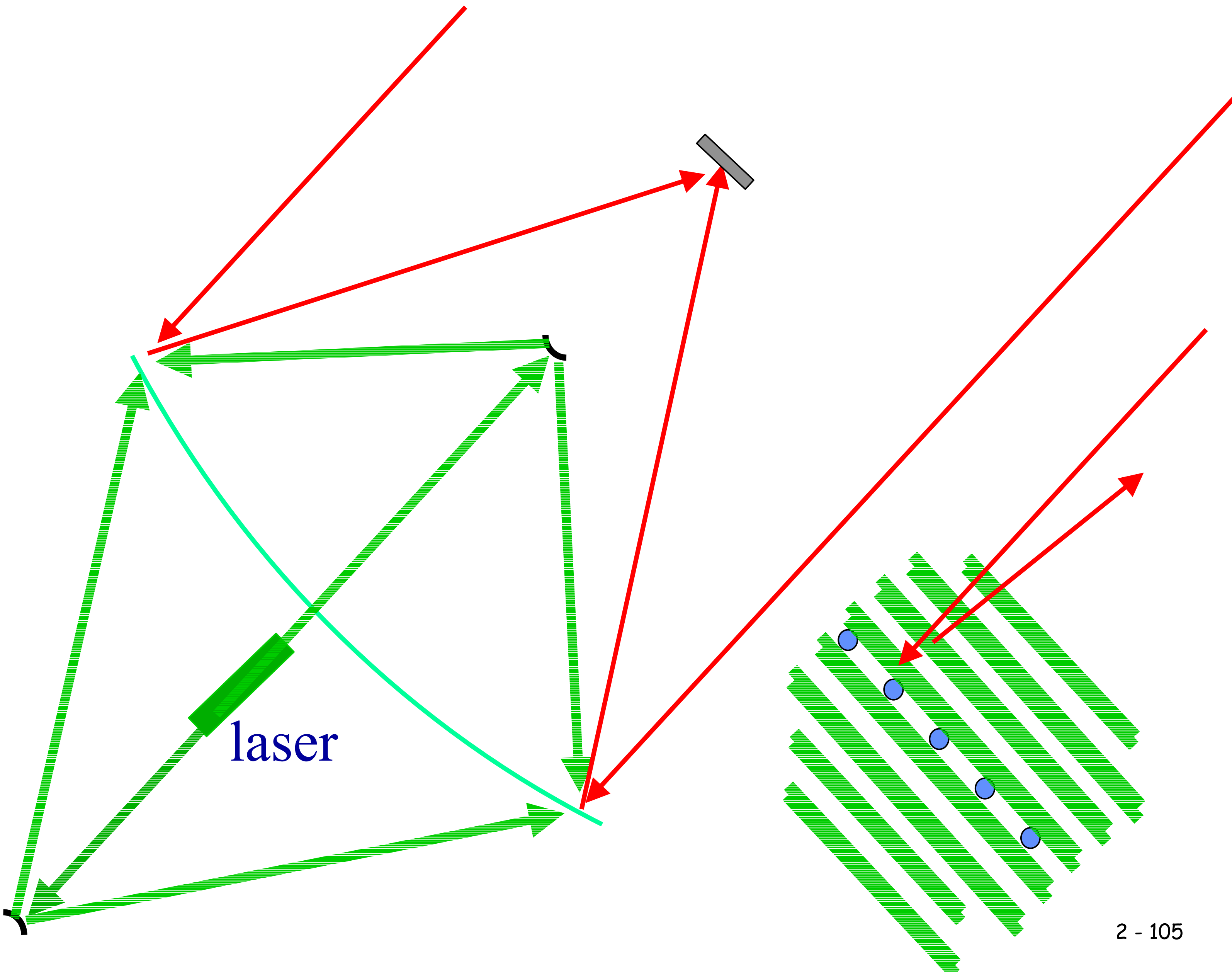
Animation of Laser Trapped Mirror

QuickTime™ and a
Sorenson Video decompressor
are needed to see this picture.

Laser-Trapped Mirror

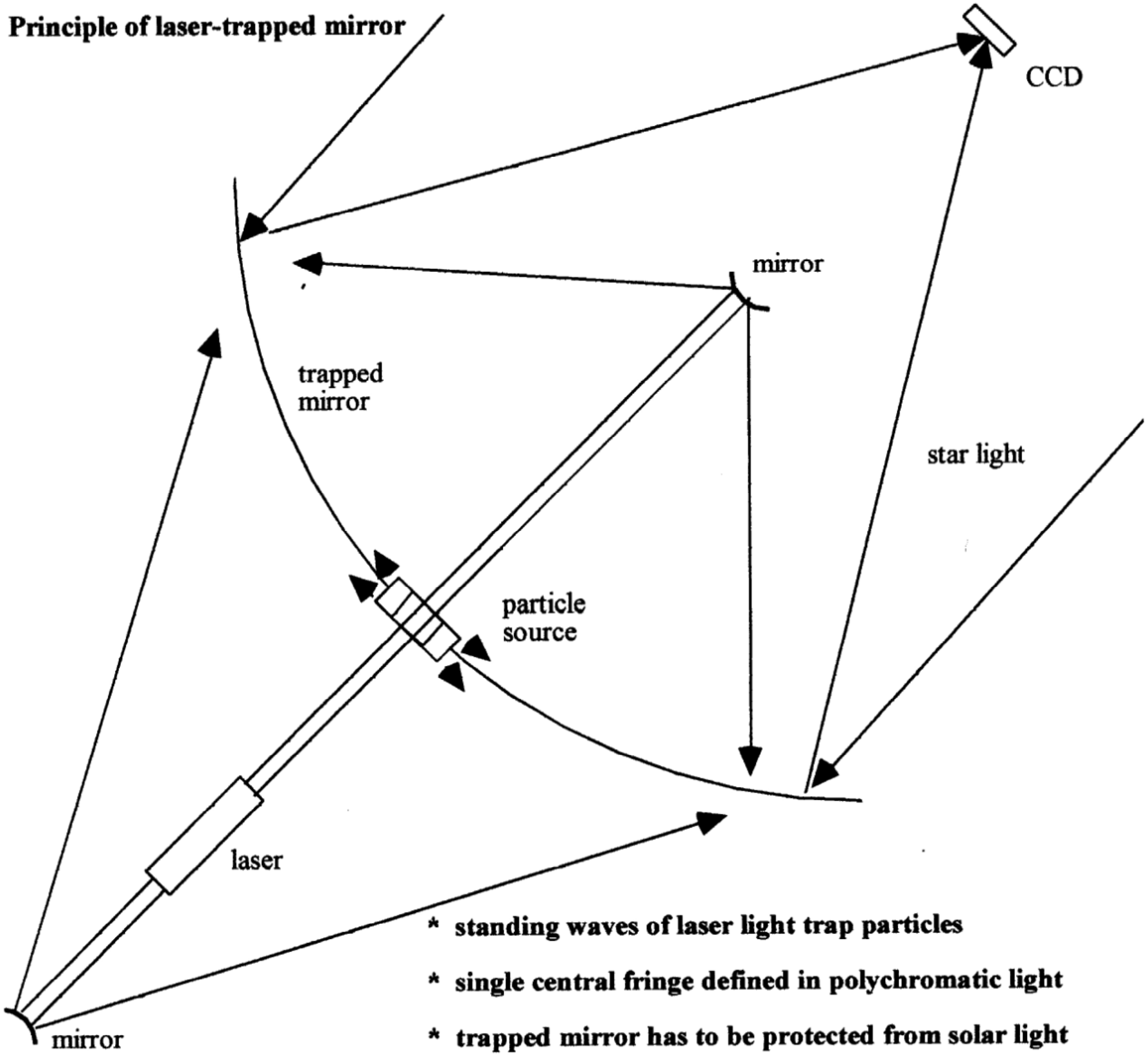
- A pair of coherent point sources of light naturally produce standing wave sheets having hyperboloidal shapes. A correcting lens can be used to convert this to a paraboloidal shape -- which is what we need.
- Nano-spheres are trapped in the area of destructive interference forming a paraboloidal mirror.
- Nano-spheres may be metal atoms or dielectric spheres smaller than the wavelength -- more research needed here.

Laser-trapped mirror



Laser Trapped Mirror

Principle of laser-trapped mirror



- * **standing waves of laser light trap particles**
- * **single central fringe defined in polychromatic light**
- * **trapped mirror has to be protected from solar light**

The Laser Trapped Mirror

- Concept proposed by Antoine Labeyrie in 1979
- Beams emitted in opposite directions by a multi-wavelength tunable laser strike two beamlaunchers
- For appropriately shaped beamlaunchers, reflected laser light produces a system of paraboloidal fringe surfaces
- Phenomenon similar to that employed by (commercial) "optical tweezers" to manipulate single cells allows trapping of reflective particles along bright fringes
- Sawtooth laser wavelength tuning permits collapse of particles to the zero fringe
- Result is a reflective paraboloidal surface of almost arbitrary size

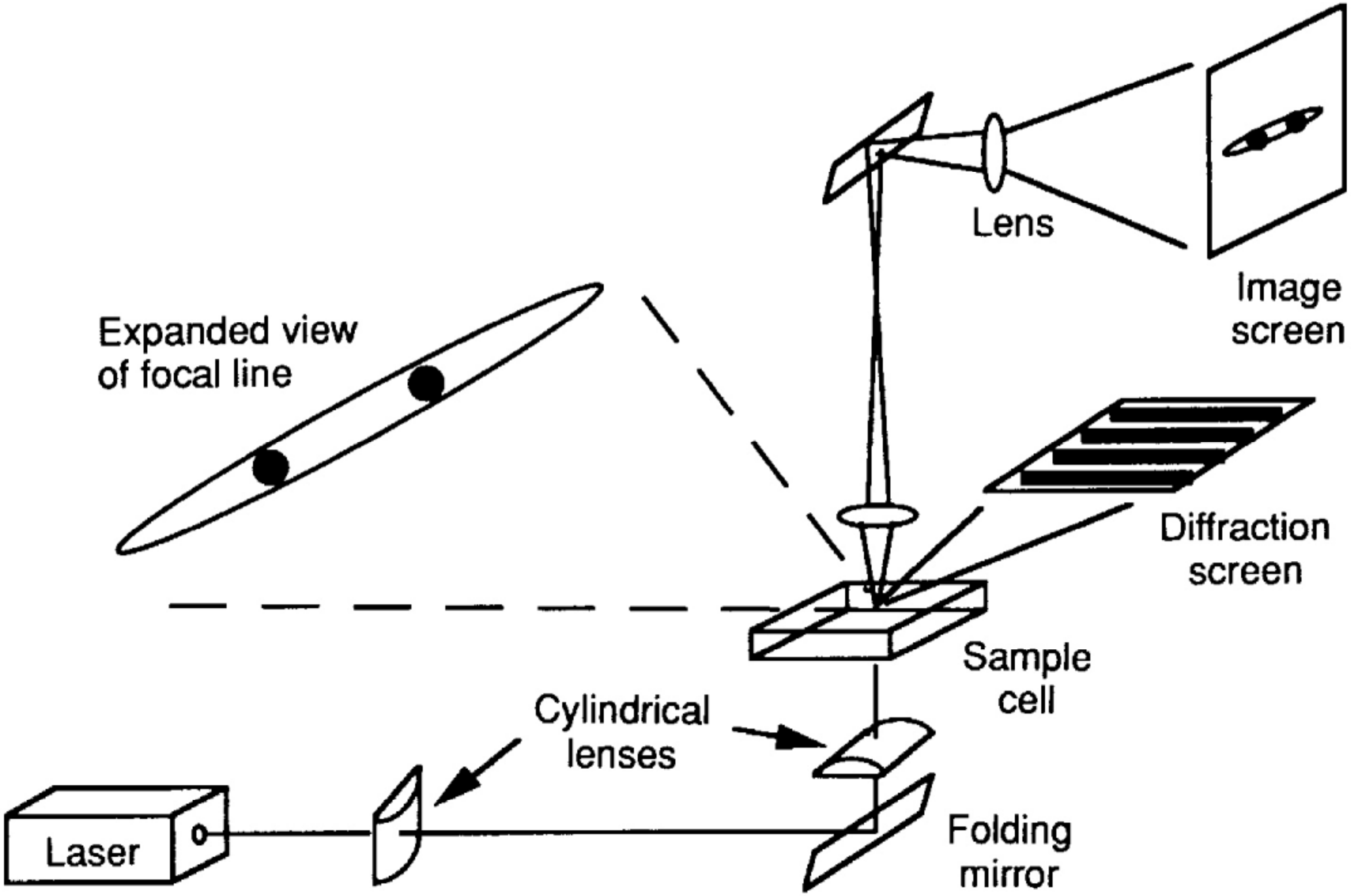
Laser Trapped Mirror

Current Status

- Experiments by Fournier et al in the early 1990s demonstrated laser trapping of macroscopic particles
- Fournier et al further discovered that laser trapped “optical matter” self-organizes due to photon scattering, in contrast to ordinary electronic matter, which is self-organized by electron interactions
- Understanding the properties of “optical matter” is crucial to understanding the behavior of a Laser Trapped Mirror

Laser Trapping of Particles

Experimental Arrangement



Laser Trapped Mirror

Application to TPF

- Potential for very large apertures with low areal mass (35 m => 100 g)
- Low moment loading on pointing system
- Deployment without large moving parts
- Extremely high packaging efficiency (35 m => 5 cm cube)
- Resilience against meteoroid damage
  - Potential for active control of the primary's figure
  - Potential for use with coronagraph
- Flexibility to effectively change "mirror coatings" on orbit
- Potential for fabricating "naturally" co-phased arrays

Laser Trapped Mirror

Concept Maturity and Proposed Plan for Development

- Even the most fundamental attribute of an optical matter mirror, ability to form an image, remains to be demonstrated
- A subgroup of the Boeing TPF team has submitted a proposal for 2+ year study of the Laser Trapped Mirror concept in response to the Gossamer Spacecraft (and Optics) NRA. Emphasis is on fundamental physics of an optical matter mirror
- PI on proposal is Prof. Elizabeth McCormack/Bryn Mawr, an optical physicist.
- Plan is to demonstrate basic concepts and to devise a strategy for space feasibility demonstration
- If we are successful in obtaining support for a Laser Trapped Mirror study, we will keep JPL apprised of progress and will orient the study toward TPF needs.

Laser Trapped Mirror

Technical Approach for Gossamer Study

Heavy emphasis on experimental demonstration of particle trapping and binding

- Heavy emphasis on fundamental theoretical understanding of the properties of optical matter
- Commitment to devise substantive, if preliminary, answers to the "28 (initial) questions" about the Laser Trapped Mirror concept

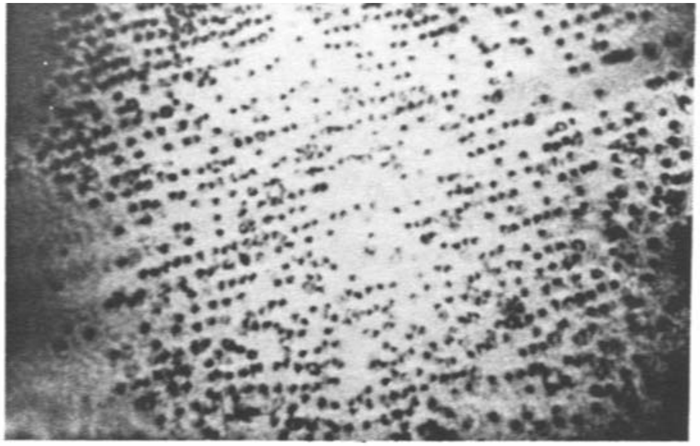


Figure 6. 2.9 μm polystyrene spheres in a polyacrylamide hydrogel.

Laser-Trapped Mirror Assessment

- Advantages
  - Extremely thin "mirror", potentially low mass, potentially easy deployment
- Disadvantages/issues
  - Concept needs extensive development. Even the fundamental physics of "optical matter" is poorly understood

Laser Trapped Mirror

Technology Development Tasks

1) demonstrate optical crystallization for a range (size, shape, composition) of particles in liquid
2) assess confinement of optical matter to a plane in liquid
3) demonstrate reflection imaging off optical matter in liquid
4) demonstrate optical crystallization for a range of materials in vacuum
5) assess confinement of optical matter to a plane in vacuum
6) evaluate reflection imaging off optical matter in vacuum
7) rigorous numerical modeling of trajectories of spherical particles influenced by a system of interference fringes
8) assess influence of space particles and fields on the LTM and ensemble response of mirror to realistic perturbations
9) assess effect of charging on the LTM
10) assess mechanisms for discharging the LTM
11) model accuracy and roughness of laser trapping along a parabolic sheet
12) model scheme to collapse particles to the central fringe
13) evaluate sunshade placement and support (use an asteroid?)
14) evaluate particle dissipation (meteoroids, loss at edges, etc.) with and without mirror repointing
15) evaluate variations in reflectivity across mirror (due to variation in filling factor)

Laser Trapped Mirror

Technology Development Tasks

16) determine space laser power, wavelength, stability, etc. requirements
17) determine space laser/mirror alignment requirements and implications for control structure
18) determine spacecraft power, pointing, etc., requirements
19) devise particle injection plan for use on-orbit
20) develop complete LTM optical design to assess system technical drivers
21) devise plan(s) for assuring that laser light used for LTM support does not contaminate the telescope's focal plane.
22) evaluate differences between IR and visible imaging mirrors
23) evaluate implications of LTM for coronagraph design
24) model a system meeting TPF requirements, including 10e-6 to 10e-9 coronagraphy for planet detection
25) evaluate multi-layer trapping for enhanced reflectivity or single wavelength observations
26) devise a phased plan for demonstrating progressively larger optical matter mirrors in liquid and, eventually, in vacuum
27) devise a plan for building an optical matter mirror in vacuum in zero-g on either the Space Shuttle or International Space Station
28) devise a plan for flying a small engineering version of a Laser Trapped Mirror Telescope as a free flying satellite

Occulters

Occulters: Overview

- BOSS: Big Occulting Steerable Satellite
  - ~ 35 m thin-film occulter, positioned ~10^5 km anti-sunward of NGST
  - Light blockage of central star to about 10^{-5}
  - Integration times > 3000 s
  - Proposed orbit: L2
  - Add-on occulter concepts exist for both NGST and HST
  - Planet detection by direct imaging; occultation outside of telescope
  - Occulter built around and spacecraft bus w/ion engines along outer truss structure for maneuvering

Occulter Status

- BOSS Proposers argue occulters up to 100 x 100 m possible with present-day/near-term technology
- Very little analysis devoted (yet) to astrophysical targets
- BOSS: appears to work best for $\lambda < 2\ \mu m$
- Some design features, mass scaling, have been developed
- References
  - Preprint: CWRU-P17-99, Copi & Starkman, submitted *Ap. J.*
  - UMBRAS paper: Al Schultz (STSCI) et. al. *Proc. SPIE 3759*

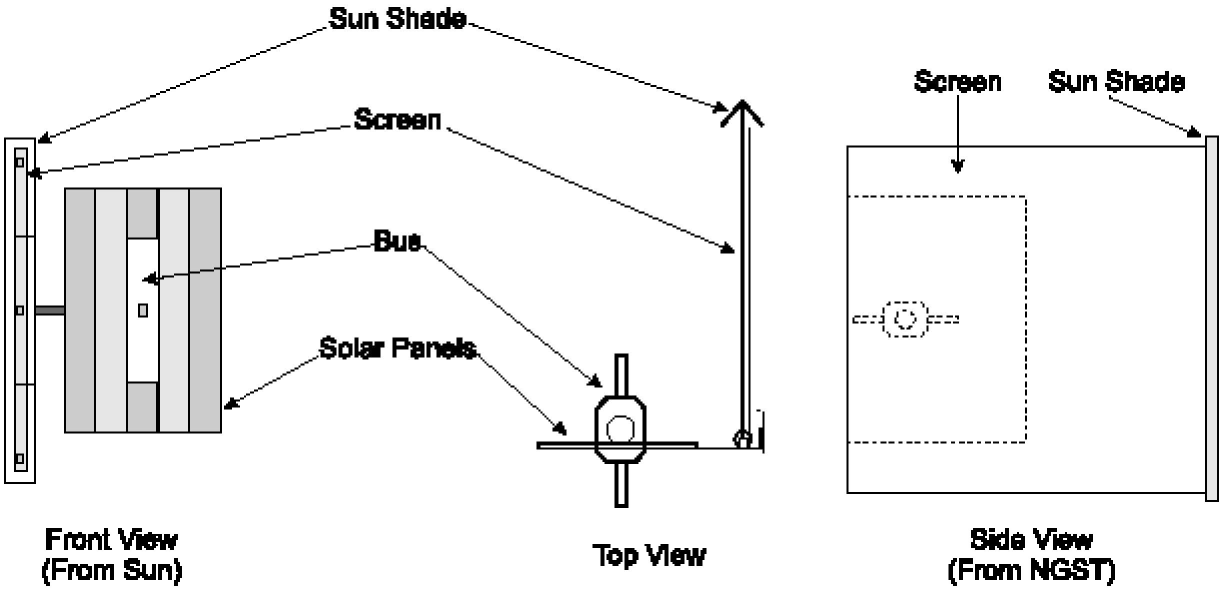
Occulter Issues

- Technology Challenges
- Demonstration of ultra-light film technology
- Long-duration occultations and slow transits require position uncertainties 0.1 – 1 m, $\Delta v \sim 0.005$ m/s
- Minimization of scattered light needs further development
- Solar radiation pressure as a significant disturbance (proposers argue for solar sail maneuvering, no analysis shown)
- Design trades: mask geometry and transmission profile could be varied to optimize for either high-resolution image reconstruction OR high-dynamic range source separation (i.e., planet-finding)
- Square structure has been assumed as a given

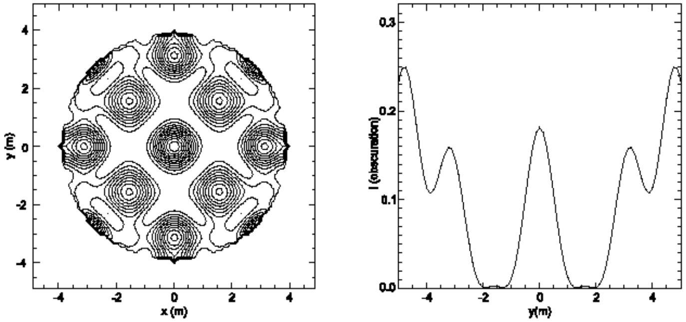
Occulter – Evaluation Needs

- Starkman et. al. have proposed follow-on analysis/study efforts [funding status: unknown]
  - Characterization of high-resolution imaging capabilities for binary, compound, & extended sources
  - Improved characterization of planet-detection capabilities
  - Further analysis of low-thrust maneuvering and stationkeeping
  - Analysis of attitude control requirements
  - Identification and characterization of candidate occulter materials
- Other occulter concepts exist:
  - UMBRAS: also proposed for NGST (different group)
    - 16 x 16 m square occulting screen (no apodization)
    - option: rectangular screen; rotate to change effective width
    - distances 1000 – 15000 km, tangentially displaced in orbit
      may require 2nd satellite for metrology (stationkeeping)

UMBRAS “Spider” (occulting screen)



- 3 yr mission, 70 targets/year
- Direct imaging at 0.15 arc-sec from target stars



UMBRAS diffraction pattern at NGST (8m) aperture

UMBRAS/Occulters (1 of 2)

- Received additional info on UMBRAS from Ian Jordan (CSC)

- Fairly detailed design info current on UMBRAS concept
  - 3 size/cost/mission life design levels
  - For use with 1m (vis), 2m (vis), 10m (vis, MWIR) telescopes
  - Engineering level detail is at "preliminary study" level yet fairly complete (equal to or better than TPF book)
  - No additional info on science targets/modeling & sim of imagery
  - ref. AIAA paper 2000-5230

- Jordan's comments:
  - BOSS design does not adequately deal with scattered sunlight (from occulting film); UMBRAS has a separate shade to keep the occulting shield dark
  - Ball team has been looking into BOSS (and presumably other occulters)

UMBRAS/Occulters (2 of 2)

- Additional concept reviewed: SCODOTEP, J. Schneider
  - Less mature than either UMBRAS/BOSS
  - Considers both artificial disks & Moon as a possible occulters
- Feasibility issues with all concepts
  - Relative position (telescope-occulter) severely limits flexibility in selecting targets (or else requires frequent repositioning)
  - Good metrology required to maintain occultation (solvable)
  - The occulter is a complete spacecraft, requiring development, launch, and operations, yet only half an instrument
  - Null depth only to 10^{-4} with 100m dia. occulter
    - → BUT, Could be used with other methods
- Questions
  - Could L_2 dynamics help with occulter trajectory management?

Orbit Trades for TPF Architectures

Recommendation - L_2 for all options

Major Concept Trades: Orbit Options

	Advantages	Disadvantages
1 AU	Large amounts of available solar power	Passive cooling harder
	Multiple passes over each part of sky	Increased zodiacal dust
	Easier communications	Larger apertures required
	Larger launch capacity	
5 AU	Smaller collectors needed	Long delay between launch and arrival on station
	Less zodiacal dust	Less power available
	Passive cooling easier	More difficult communications
		11-year orbit period
		More autonomy required

BOEING SVS

Major Concept Trades: Separated Spacecraft

	Advantages	**Disadvantages**
Separated Spacecraft	Tunable baseline for planet finding	Multiple spacecraft buses and avionics systems
	Astrophysics imaging capability	Requires development of formation flying systems
	Provides heritage for future separated missions	Potential for neighboring spacecraft to cause contamination
	Less structural mass	More propellant mass
	Multiple launch is possible	
Single Spacecraft	Single set of spacecraft subsystems	Complex, high-risk deployment
	Less propellant mass	More structural mass
		Attitude and jitter control for large structures

Orbit Trades

- Orbit options examined as part of engineering assessment
  - -- Orbits considered: L_2, Earth-trailing drift-away (SIRTF), 1x5 AU ecliptic elliptic
  - -- Others possible (e.g., 1AU inclined) but discarded
- Factors considered included zodiacal background vs. aperture, LV requirements, orbit insertion, system power needs and communications impact
- OSC and B-SVS assessed independently
- Conclusions (same for both assessments):
  - -- <u>L_2 has least overall impact on system concept</u>