Apodized Square Aperture

A Visible Direct Imaging Solution for TPF

BOEING-SVS, Inc.

Apodized Square Aperture Telescopes for TPF

- An ASA telescope is one of our candidate architectures for the TPF planet detection and characterization mission
- Direct imaging of planets requires a system designed for very high contrast imaging.
- ASA telescopes manage diffracted light enabling direct planet imaging
- The size of ASA solutions for the TPF mission are comparable to NGST

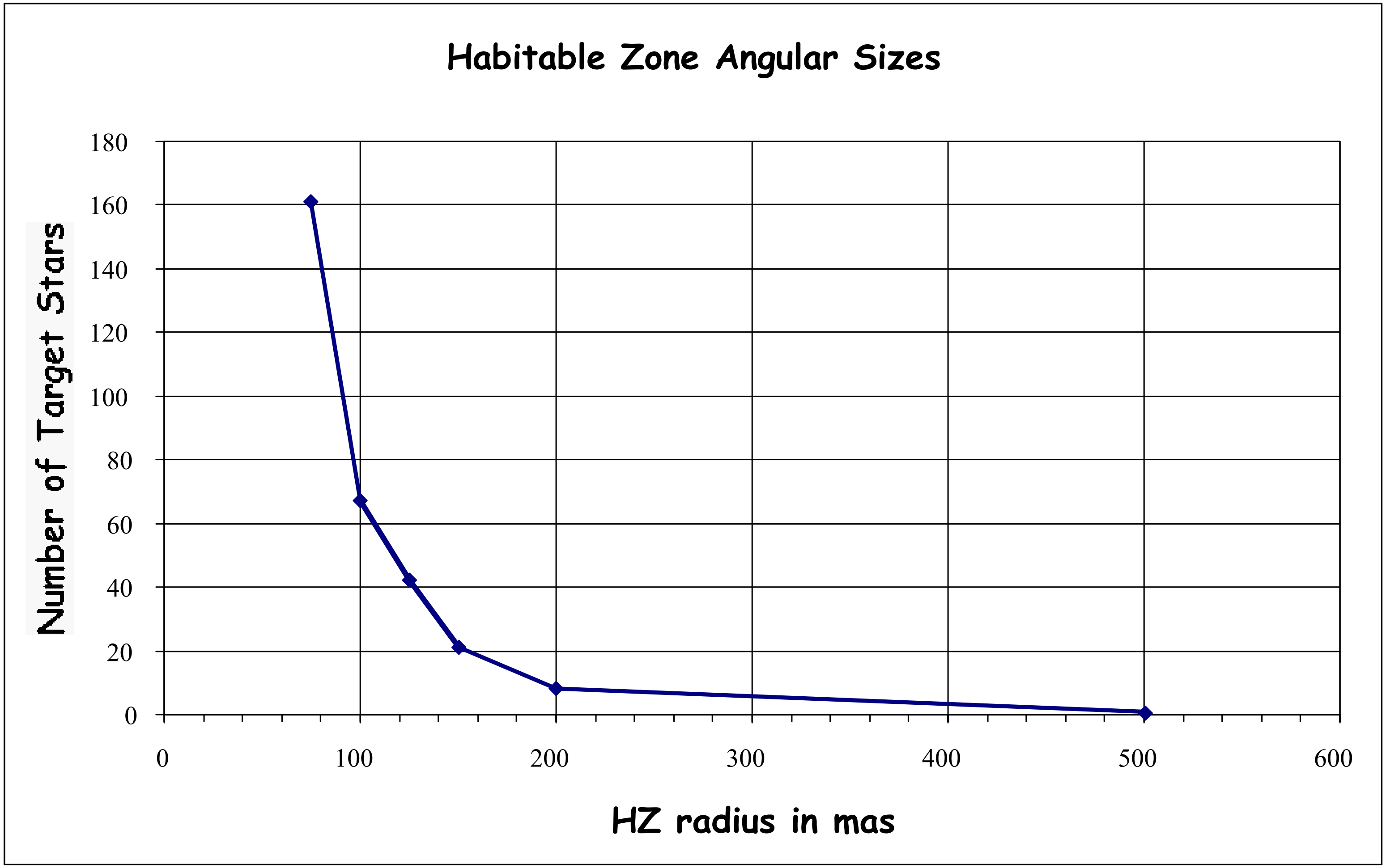
Our Methodology for ASA Architecture Development

- The science objectives were described
  - TPF science team defined the objectives and success criteria
- We quantified the observables that would allow the science team to meet the mission objectives
- We developed an ASA architecture to provide these observables
- We evaluated the concept
  - Calculated SNRs and mission life for the TPF mission
- We defined technology needs and developed roadmaps

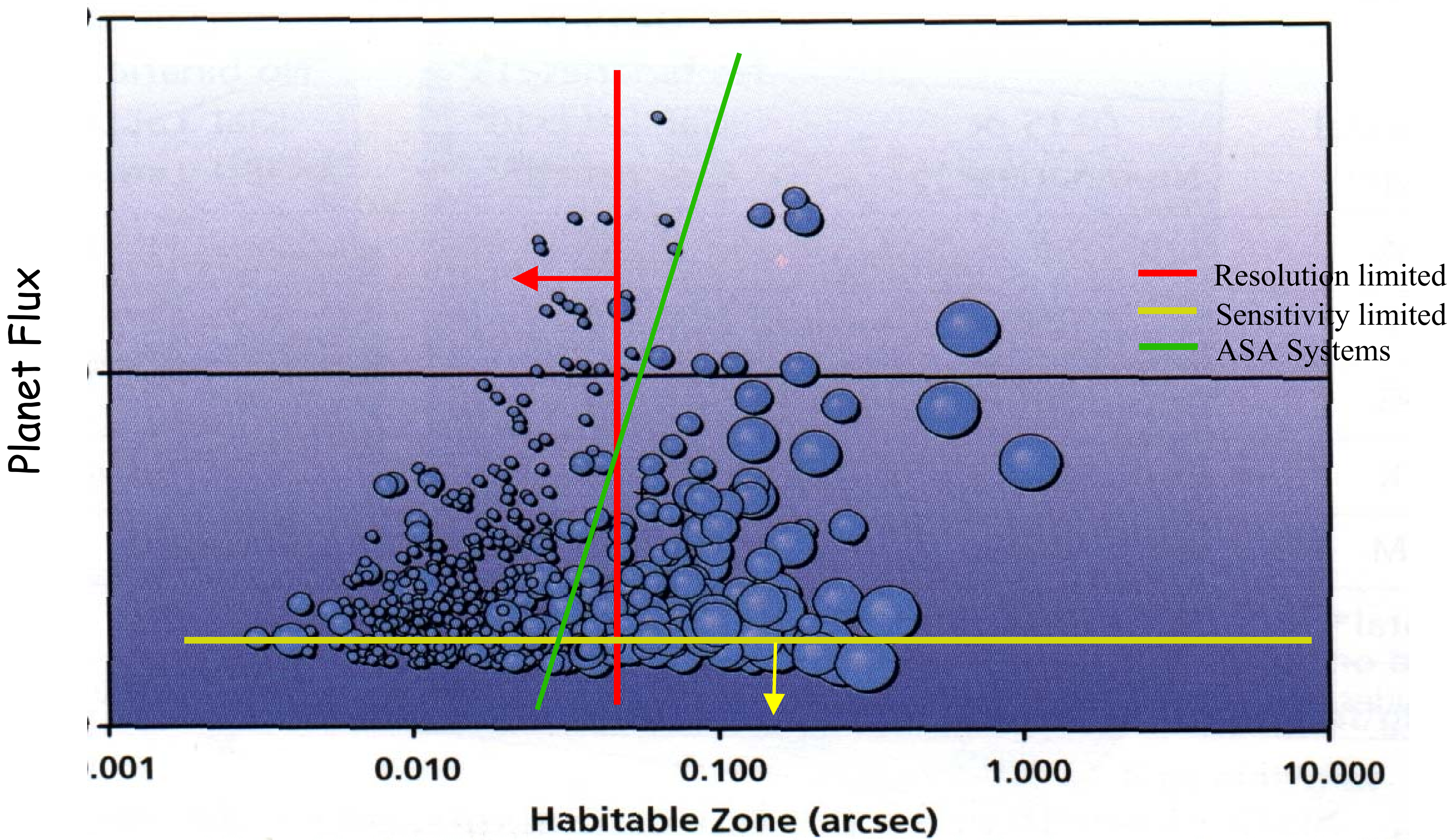
Quantifying the Observables - Target Star Selection for an ASA TPF Mission

- For the TPF mission we want the 150 easiest F-K target stars
  - For resolution limited systems easy means large HZ radii
  - For sensitivity limited systems easy means bright HZ planets
- The TPF book (5/99) target star selection criteria excluded:
  - Visual binaries within 15" - a cut sample by a factor of 2
  - Distances beyond 15 pc; for resolution limited systems HZ angular extent is the driver not distance
  - Galactic latitudes $\leq$ 10 deg & ecliptic latitudes $\geq$ 45 deg
- Simon & Vogt (AAS 1/01) started with 7,058 stars within 50 pc
  - Excluded the visual binaries within 10"
  - Excluded A-type and younger stars
  - The ASA target star characteristics are based on this study
- For an ASA-based TPF, a Sun-Earth analog at 10 pc is representative of the target star ensemble average

For 150 Target Stars - Resolution Limited Systems Like ASA Need to Study HZs with Radii as Small as 75 mas

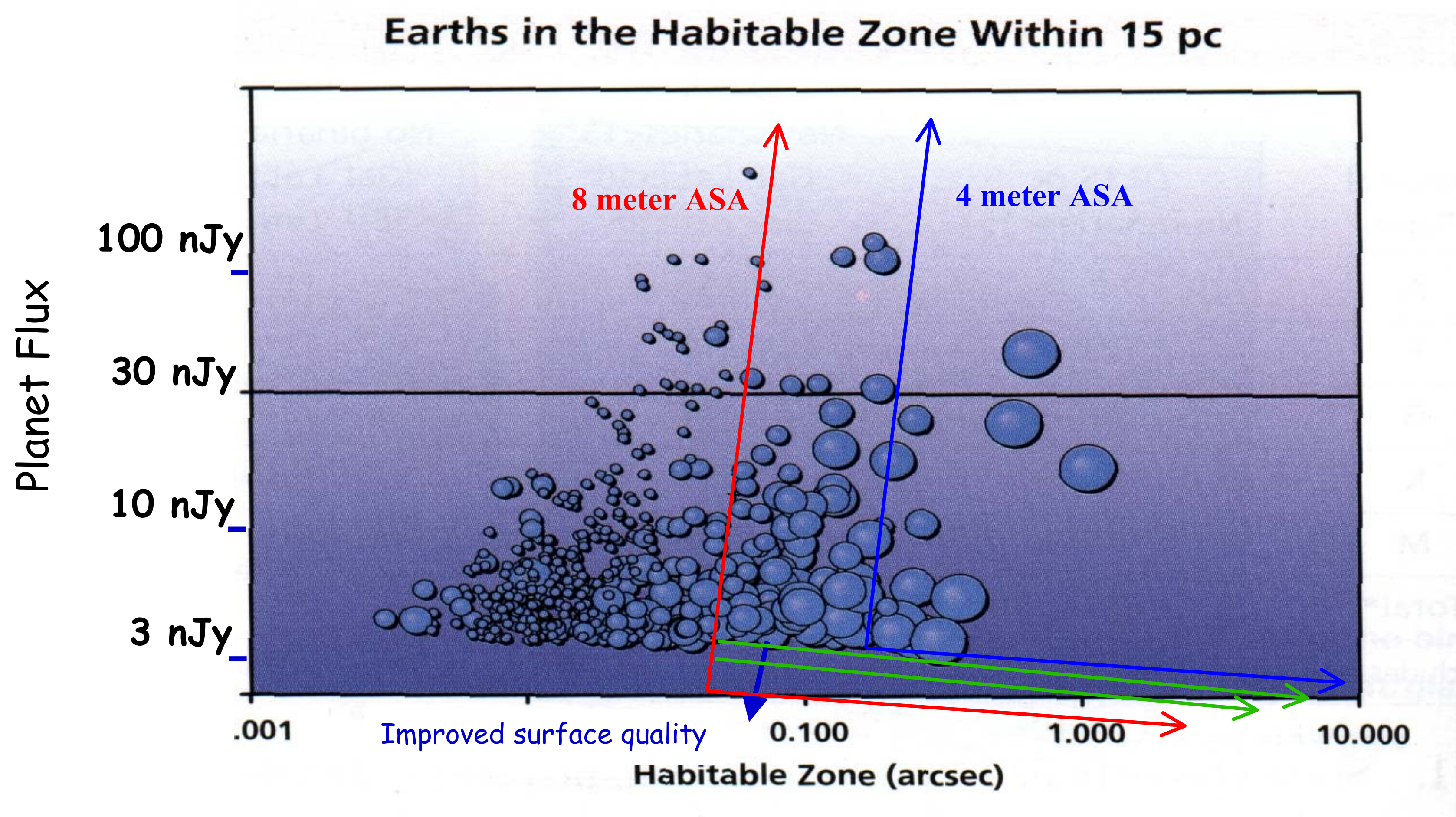


ASA Systems Are Not Strictly Sensitivity or Resolution Limited



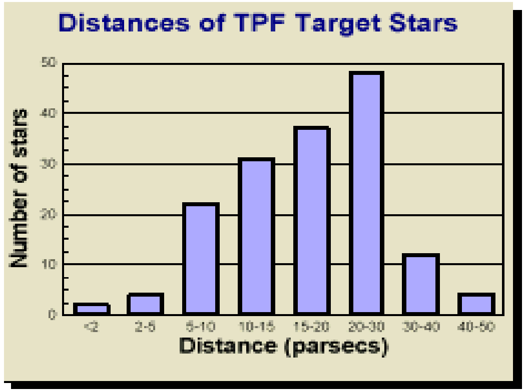
(After TPF Book p 68)

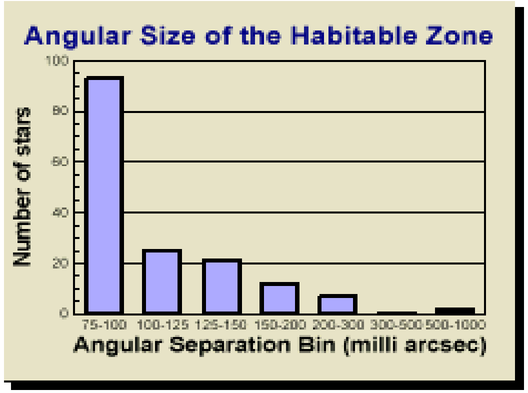
The ASA Detection Space is Extended by Aperture Size and Surface Quality

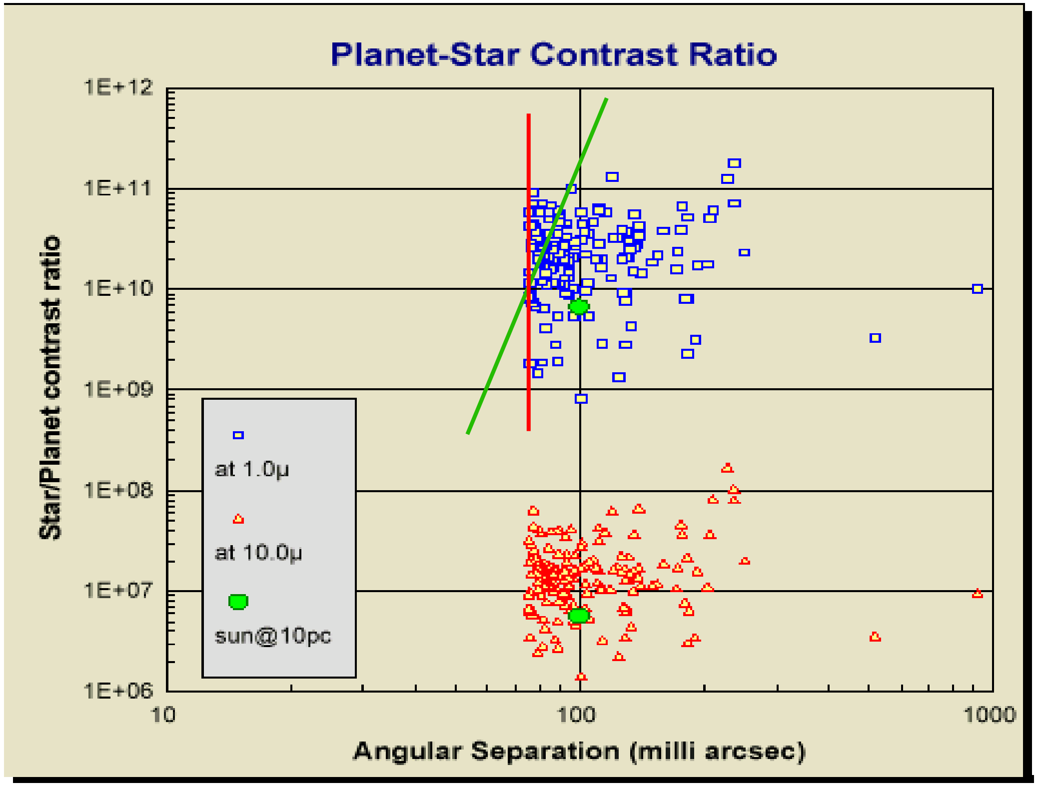


TPF Target Star Analysis for Earth-like Planets by Simon & Vogt

For an ASA the minimum detectable separation angle is a function of contrast ratio







Target Star Selection:
- HIP Stars with "Habitable Zone" > 75 mas
- Suspected binary stars <10" or Spec Bin. < 5yrs excluded
- Stars with Spectral type A or earlier excluded
- Giants (Lum Class III, II, or I) excluded
- Known RS CVn's, W Uma's, Algols, roAp's, or A2CVn's excluded

Planet Characteristics:
- "Planet" is an Earth-Analogue:
- Equilibrium Temp. = 293K
- Earth-like albedo and radius

The Largest 150 F-K HZs Determine ASA Performance Requirements

	Toughest Case of Easiest 150 targets	Typical Case to determine survey time	Easiest 20% to determine characterization times
Resolution (mas)	63 mas	80 mas	105 mas
Planet flux at 600 nm	3 nJy or 54 $ph/m^2/hr$ at R=3	10 nJy or 27 $ph/m^2/hr$ at R=20	30 nJy or 82 $ph/m^2/hr$ at R=20
Star-Planet flux contrast ratio	10^{11}	$3x10^{10}$	10^{10}

1.5.1 Overall observatory geometry and array configuration

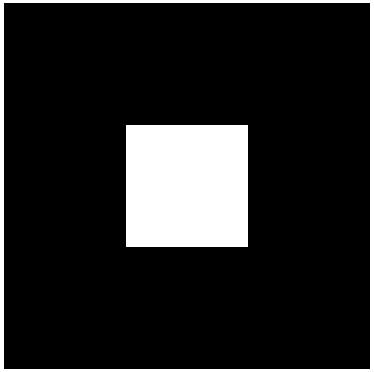
A Square Aperture Apodized Coronagraph (ASA)

Summary

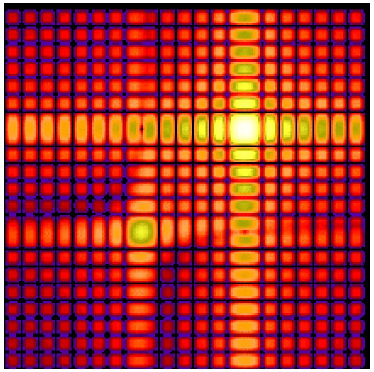
- ASA provides extremely high dynamic range with conventional technology
- ASA uses monolithic apertures operating in the visible
- The technology is relatively low risk, requiring minimal development
- ASA can perform all of the TPF requirements in the visible

Apodized Square Apertures Manage Diffracted Light

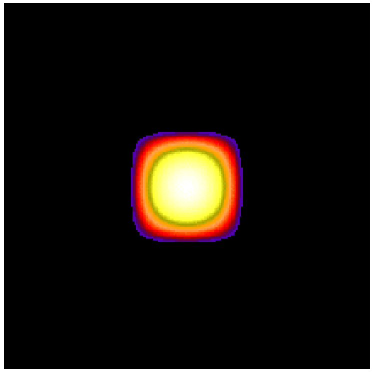
- Square aperture diffracts mostly along axes perpendicular to aperture edges (4√ display)
- Apodization reduces diffraction but broadens PSF
- Diffraction in diagonal regions greatly suppressed
- Nisenson P. and Papaliolios, C. 2001, ApJ, V 548, L201.



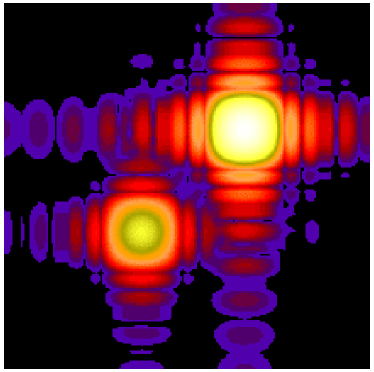
Square Aperture, No Apodization



100:1 Star to Planet Ratio
No Apodization



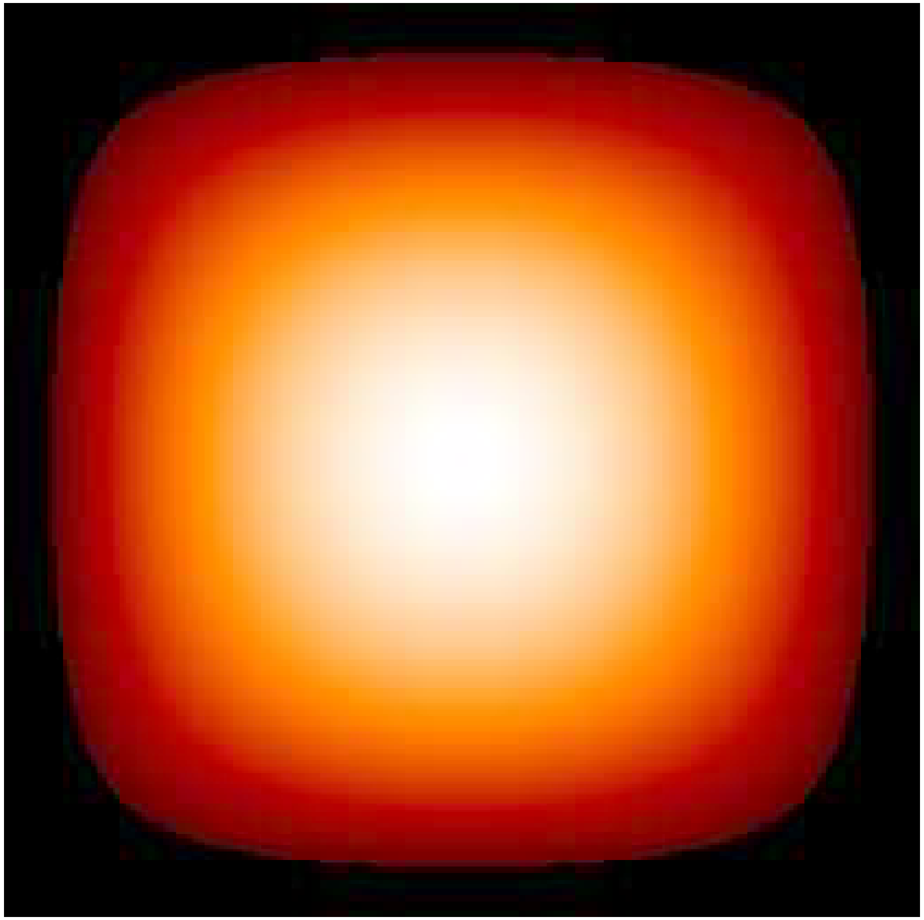
Apodized Square Aperture



100:1 Star to Planet Ratio
Apodization

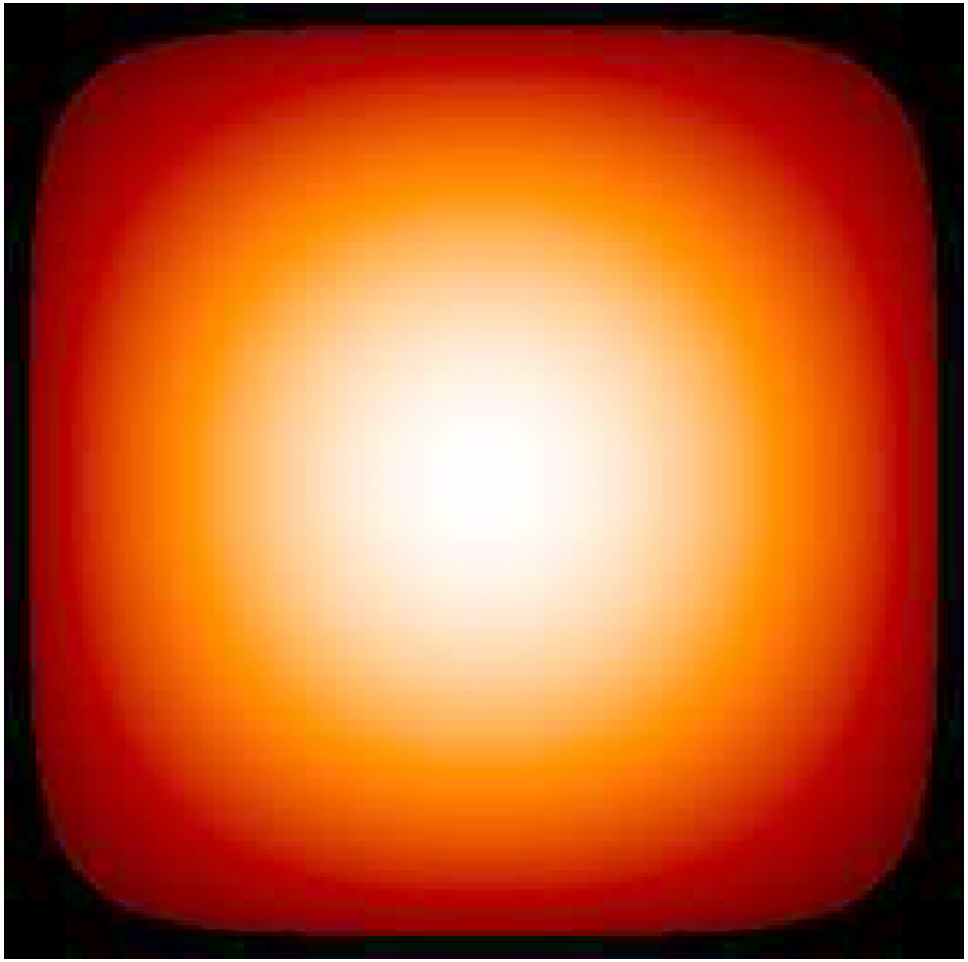
The Sonine apodized square aperture

- Most of the energy is transmitted by the central third of the apodized aperture



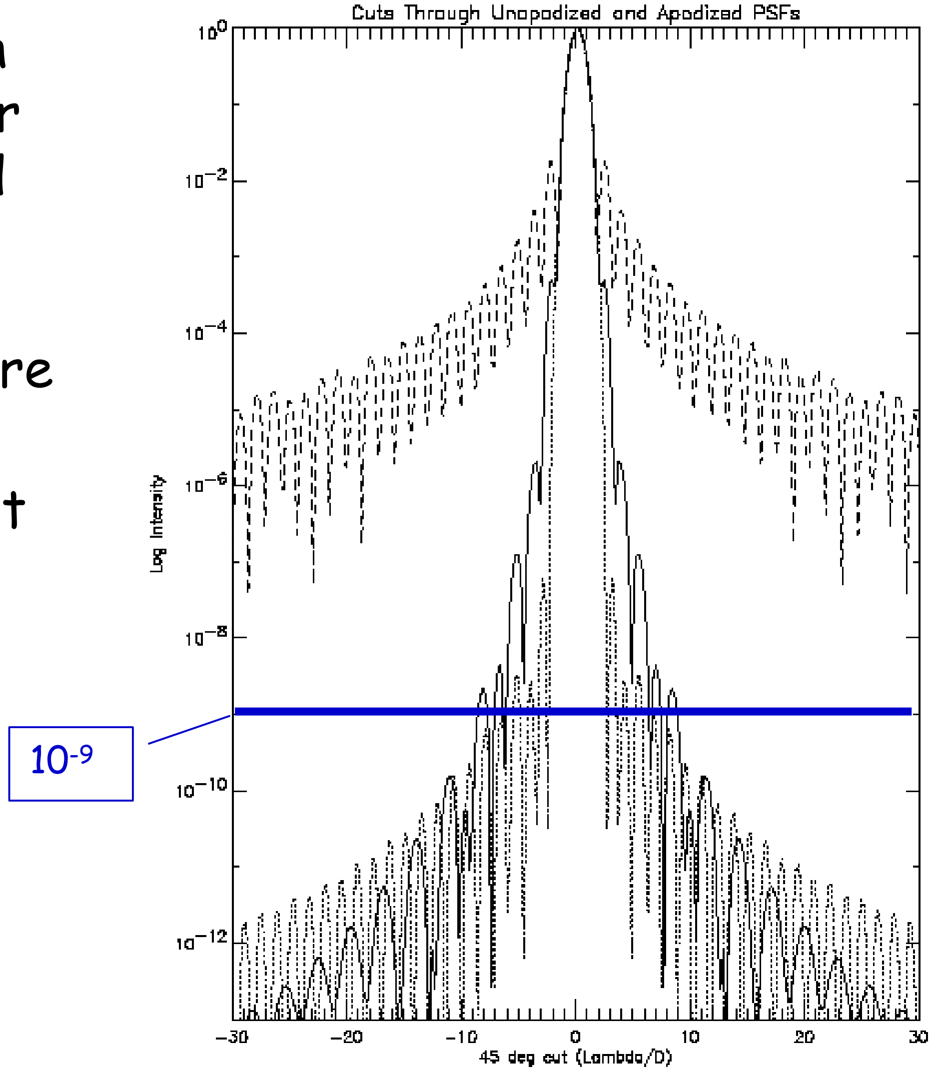
Square aperture with Jacquinot apodization

- Broader, flatter transmission function
- More throughput than Sonine (30%) and a narrower central peak of the PSF



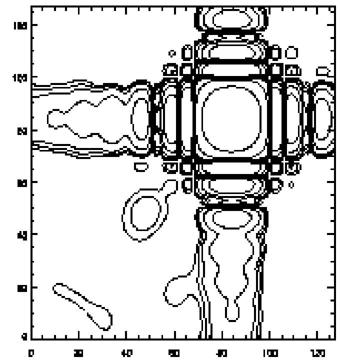
Apodization of a Square Aperture Greatly Suppresses Side Lobes

- 45 degree cuts through circular aperture (upper curve), Sonine apodized square aperture (solid curve) and Jacquinot apodized square aperture (dotted curve)
- Note that the Jacquinot PSF has narrower core but higher wings

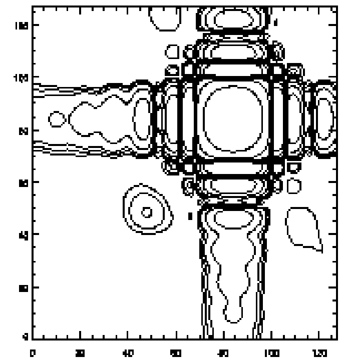


Illustrations of Planet Detection

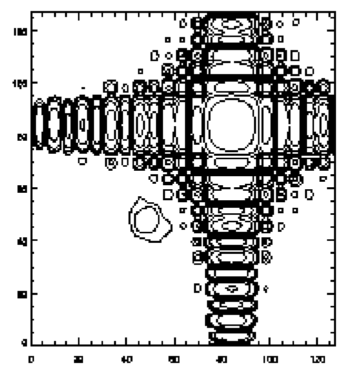
- Contour plots for different apodizations for star plus planet with planet 10^9 fainter than star. Lowest contour is 10^{-10}
- Note that diffraction is suppressed in all four quadrants over most of the field



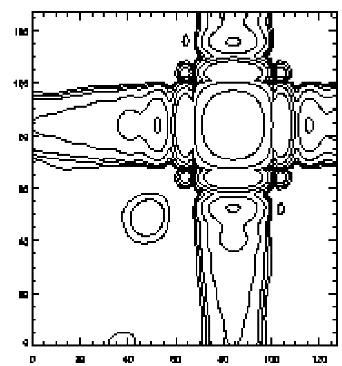
Sonine nu = 4, Transmission = 17.2%



Sonine nu = 5, Transmission = 15.9%



Cos^2, Transmission = 19.4%

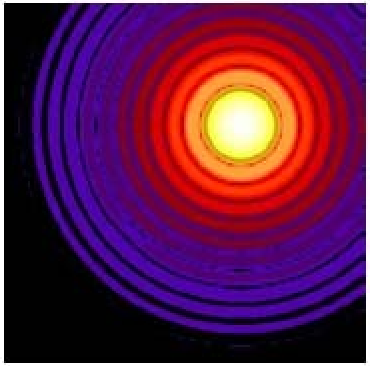


Cos^4, Transmission = 14.6 %

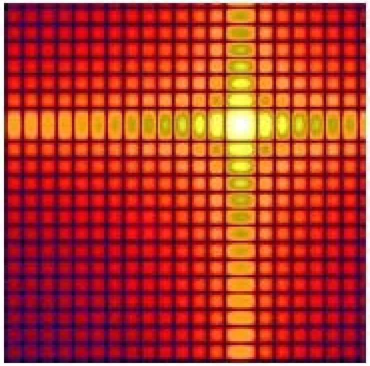
ASA systems Enable Planet Detection by Direct Imaging

- Planet Detection with Circular and Square Apertures demonstrating the gain from apodization. Note that the planet is all four figures, but unobservable except in the lower right.
- Upper Left – Circular Aperture with no apodization.
- Upper Right – Circular aperture with Sonine apodization.
- Lower Left – Square aperture with no apodization.
- Lower Right – Square aperture with Sonine apodization.

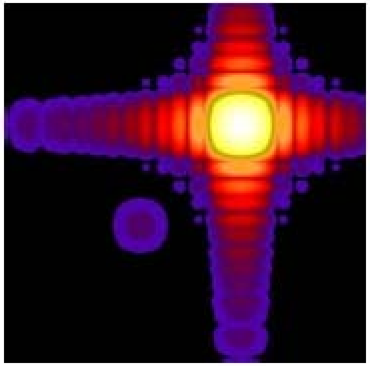
Circular Aperture Telescope
10^8:1 Star to Planet Ratio
No Apodization



Circular Aperture Telescope
10^8:1 Star to Planet Ratio
Sonine Apodization



Square Aperture Telescope
10^8:1 Star to Planet Ratio
No Apodization



Square Aperture Telescope
10^8:1 Star to Planet Ratio
Sonine Apodization

ASA Telescope Performance Principles

- Square aperture diffracts most of the power perpendicular to the edges
- Diffraction along diagonals falls off as R^{-4}
- Transmission weight with crossed apodizing functions perpendicular to aperture edges
- Diffraction in regions around diagonals down by more than 10^9 @ 3 Lambda/D from central peak

Aperture Size & Resolution

- Aperture size determines the minimum detectable angular separation
- Smallest dimension in aperture sets widest diffraction in PSF
- Rectangle, cross or separated squares about same diffraction level along PSF diagonal as diffraction from smallest square
- Filled square aperture optimal
- Segmented OK as long as gaps small (0.1 %) and edges in outer parts of apodized aperture

Description of the Sonine function

- Apodization of a square aperture uses the product of two transmission functions, each perpendicular to the vertical or horizontal edges of the aperture
- Crossed Sonine functions have a transmission function of the form

$$T(x,y) = (1-x^2)^{\upsilon-1}(1-y^2)^{\upsilon-1} \text{ if } -1 \le x \le 1; -1 \le y \le 1$$
$$0 \text{ otherwise}$$

- ν is a small integer such as 3, 4 or 5
- Apodization with Sonine functions was suggested by Oliver (1975)
- The maximum throughput for the Sonine mask with ν =4 is less than 18%
- Reference: Oliver, B.M. 1975 in Tech. Dig. For AAS/OSA Topical Meeting on Imaging in Astronomy, Cambridge MA p. WB7-1

Jacquinot Apodization

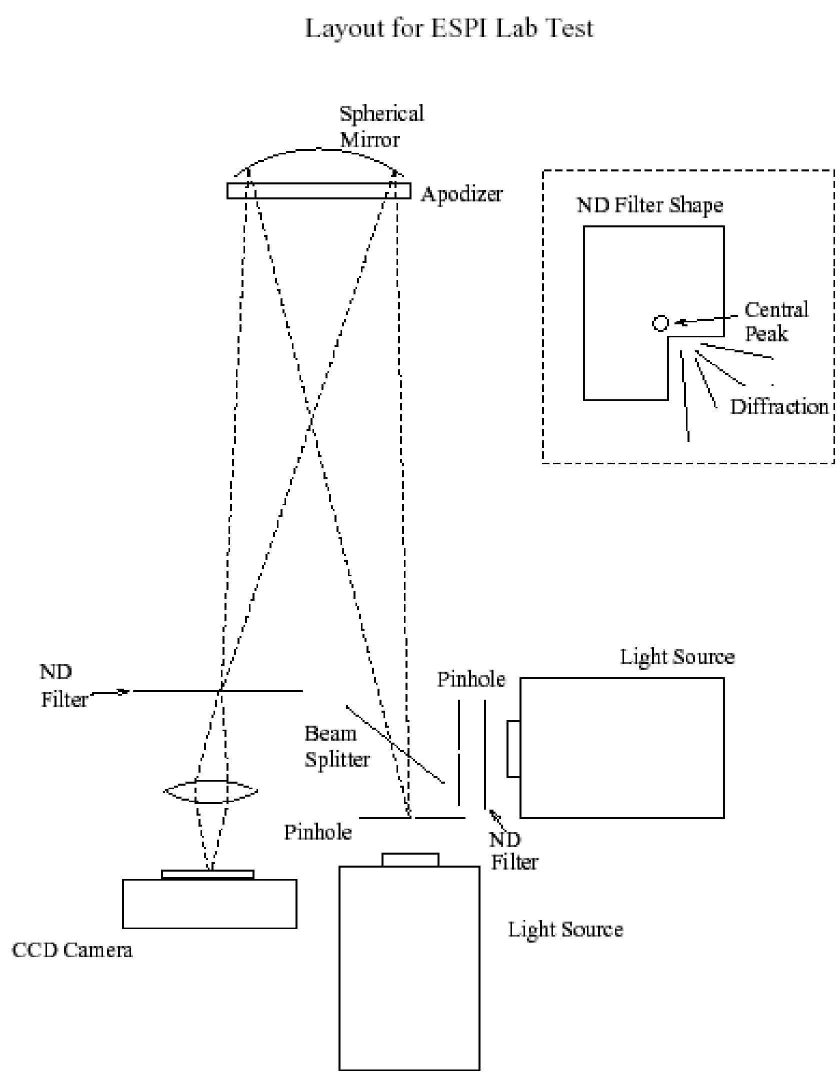
- Another apodization function was suggested by Jacquinot
- The Jacquinot apodization has better than 30% throughput
- It also has a narrower central peak
- The function has the form of a power series

$$t(\rho) = c_0 + c_1\rho + c_2\rho^2 + c_3\rho^3$$

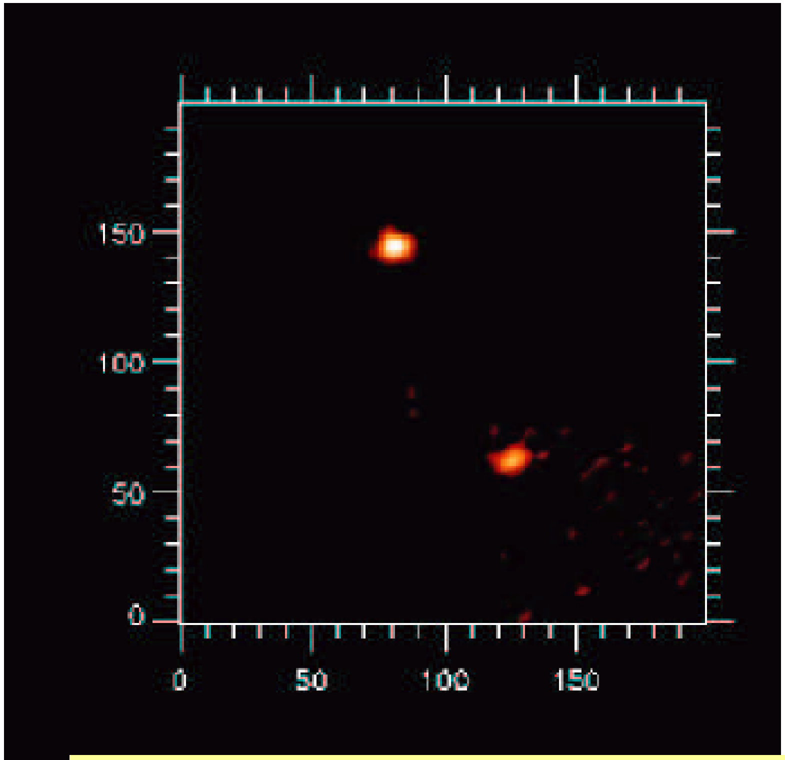
- Where c_0 =0.074, c_1=0.302, c_2=0.233, c_3=0.390
- r=1-r^2 and r is the radial distance
- The two-dimensional apodization function is then
- T(x,y)=t(r)x* t(r)y
- The maximum transmission of this function is greater than 30%
- Coefficients can be chosen to optimize properties such as throughput or narrowness of the central peak
- Reference: Jacquinot, P. and Roizen-Dossier, B. 1964, Progress in Optics 3, p. 29

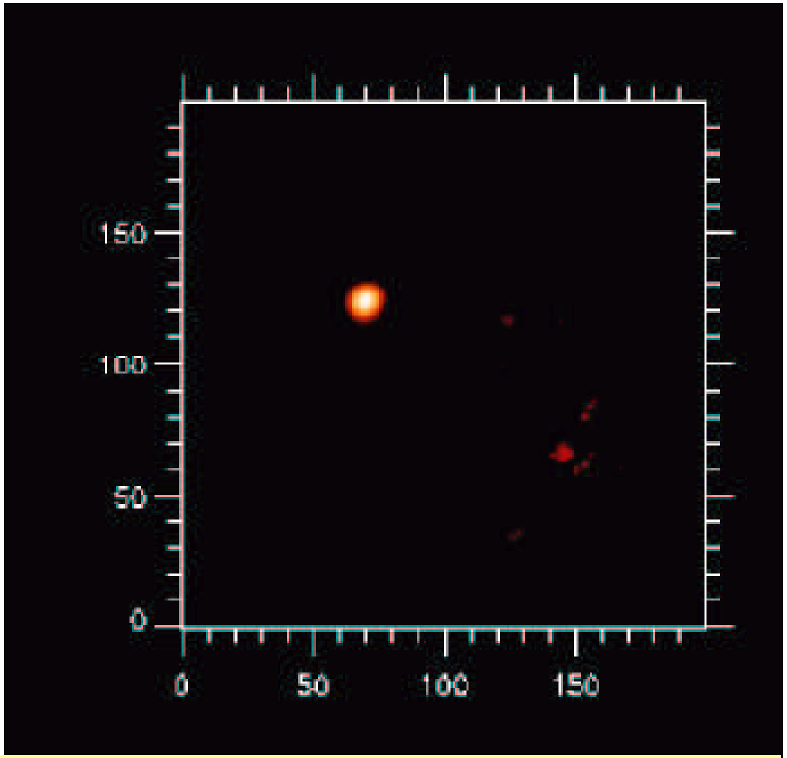
Lab Experimental Layout for SAO tests of ASA

- 1" spherical super-polished mirror from General Optics
- Cos^2 apodizer made by Canyon Materials
- ND filter with corner cut out for suppressing central peak and cross (see inset)
- CCD window and apodizer not super polished



Images from Lab Tests of ASA





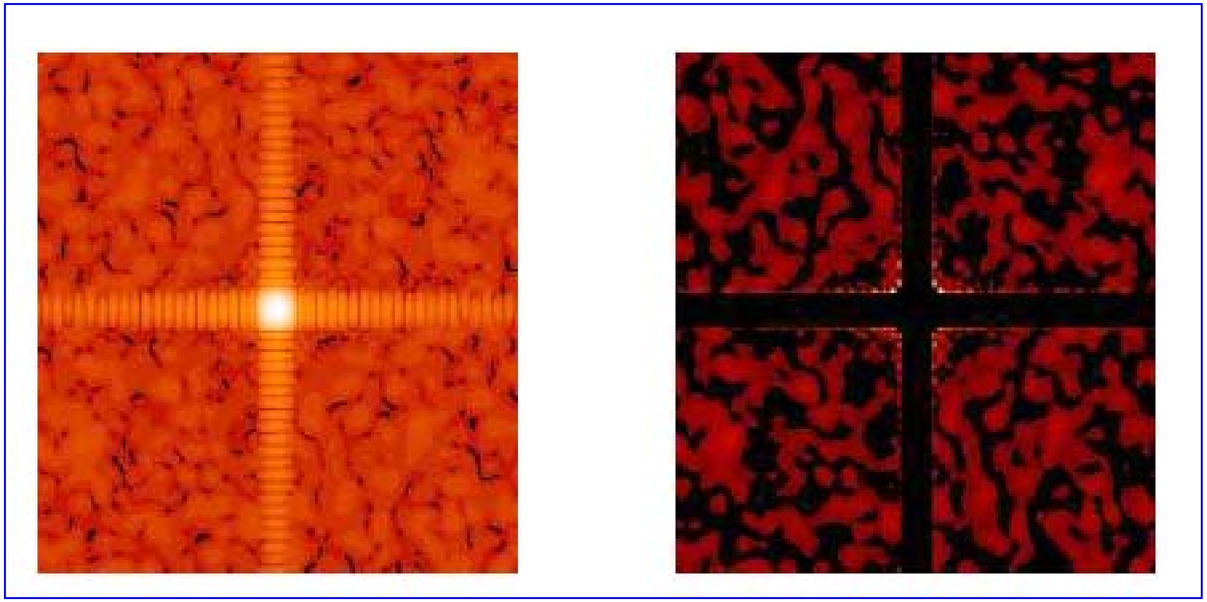
- Left image direct image with $5*10^7$ Source Ratio
- Right Image Calibrated Background subtracted from raw image allowing detection with $3*10^9$ Source Ratio

Lab image - 5 x 10^7 Ratio

Lab image - 3 x 10^9 Ratio

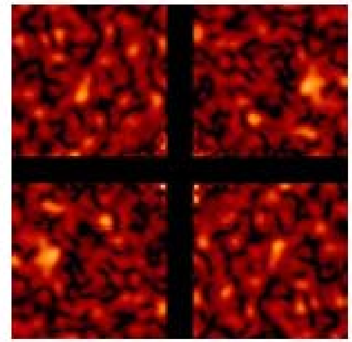
Point Spread Function for ASA including Scattered Light

- Mid-spatial frequencies (3-30 cycles/mirror) 1/1000 wave.
- Higher frequencies fall off as $1/f^2$.
- Left image $\sqrt[4]{}$ display with no blocker.
- Right image linear display with coronagraphic blocker.

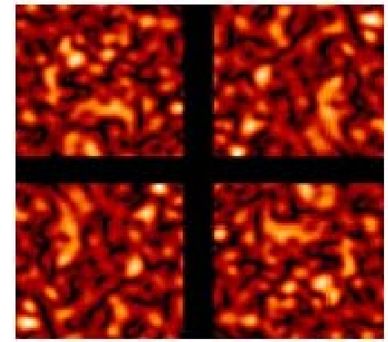


Four Realizations of Scattered Light Background Around PSF for Four Different Mid-frequency RMS Values

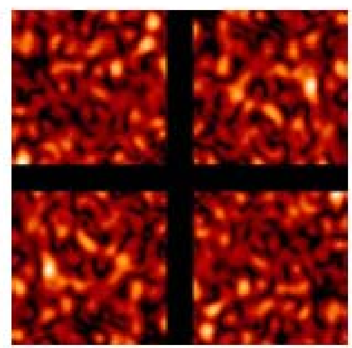
- Upper left – 1/1000 wave (600 nm)
- Upper Right – 2/1000 wave
- Lower Left – 3/1000 wave
- Lower Right – 4/1000 wave



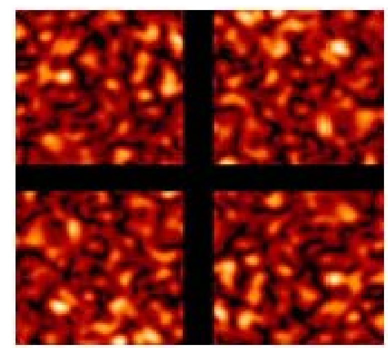
.001 RMS Wave Surface Quality



.002 RMS Wave Surface Quality



.003 RMS Wave Surface Quality

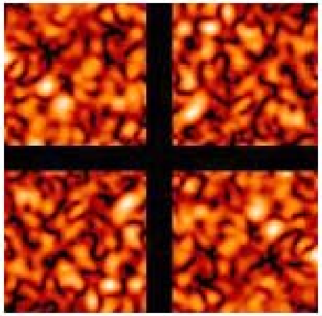


.004 RMS Wave Surface Quality

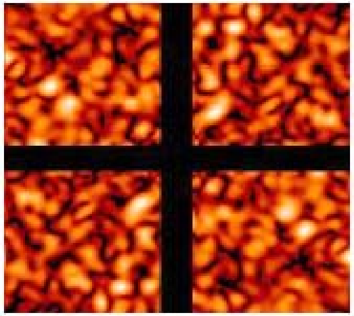
ASA Focal Plane for Different Primary Mirror Surface Quality, all with 1000 Angstrom Bandpass. The Darkest Speckles are Fainter than 10^(-10) and Cover Successively more of the Focal Plane Area with lower RMS. The Central Cross Blocks the Diffraction from the ASA Mask.

Scattered Light Around PSF for Four Different Bandpasses Around 600 nm

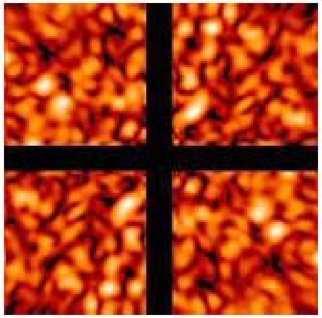
- All have 3/1000 wave rms surface quality
- Upper left – 10 nm bandpass
- Upper Right – 50 nm bandpass
- Lower Left - 100 nm bandpass
- Lower Right – 200 nm bandpass
- Note increased spectral smearing with bandpass at large radii



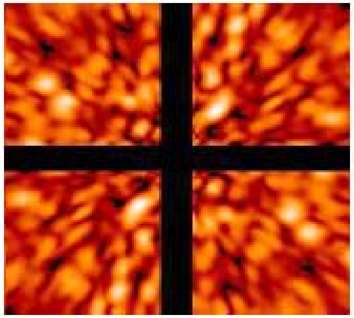
100 Angstrom BP



500 Angstrom BP



1000 Angstrom BP



2000 Angstrom BP

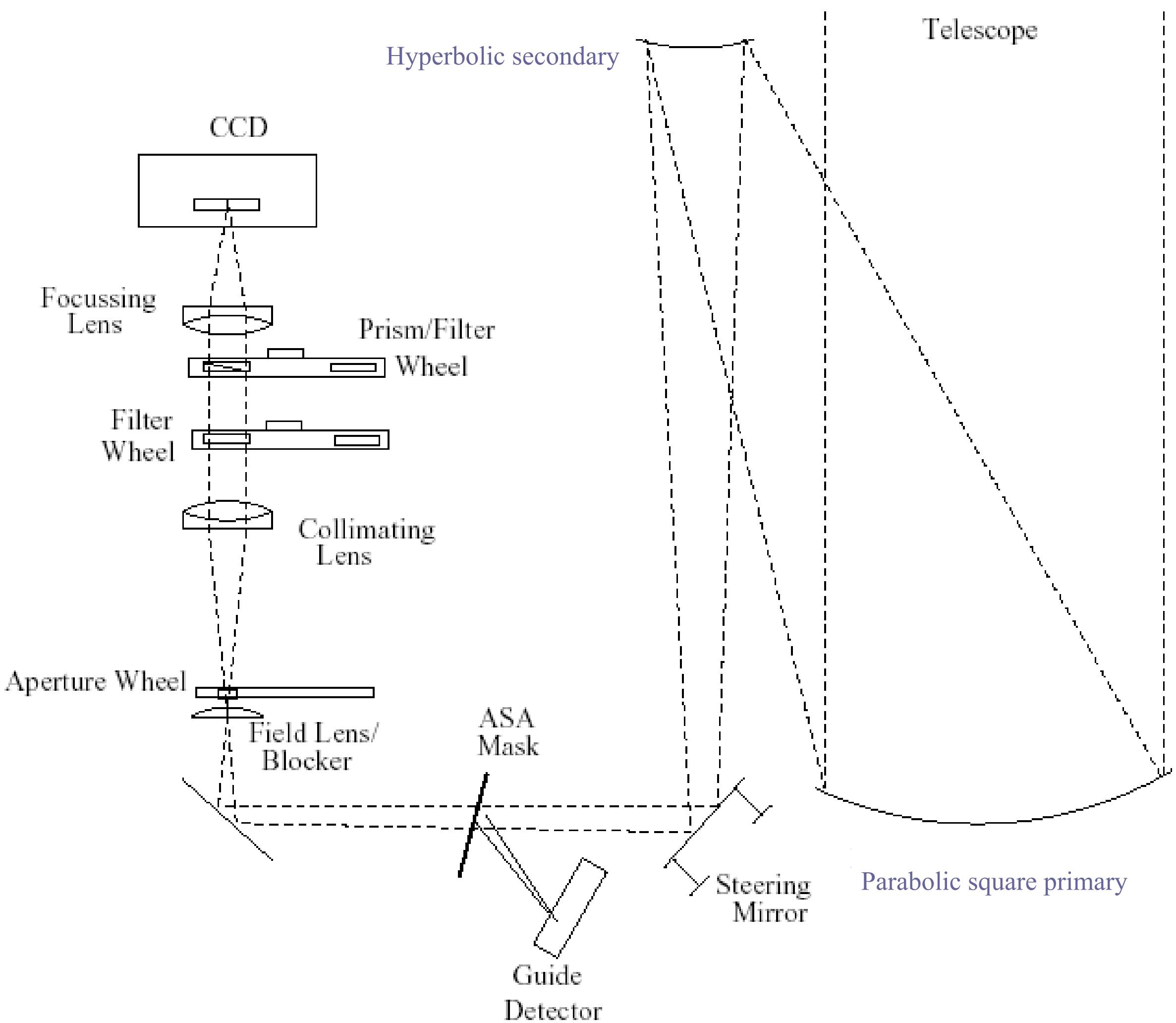
ASA Focal Plane for a Primary Mirror with .003 Wave RMS Surface Quality and Four Different Spectral Bandpasses all around 6000 Angstroms. The Darkest Speckles are Fainter than 10^(-10) of the Central Peak. The Central Cross blocks the Diffraction from the ASA Mask.

Future Demonstrations Will Continue to Mature the Architecture

- Lab demonstration with larger optics
- Possible demonstrations at ground telescopes equipped with adaptive optics and appropriate optical configurations and atmospheric conditions
- Telescope testing requires
  - Surface roughness, spatial frequency and figure error content
  - Configurations that allow apodization masks to be placed in the pupil plane
  - Characterize the system with spatial frequency information on the primary mirror and interferograms of the secondary
- Systems that might be considered include AEOS on Maui, Apache Point, the 1 meter telescope at WSMR, and Keck

1.5.2 Complete end-to-end optical layout

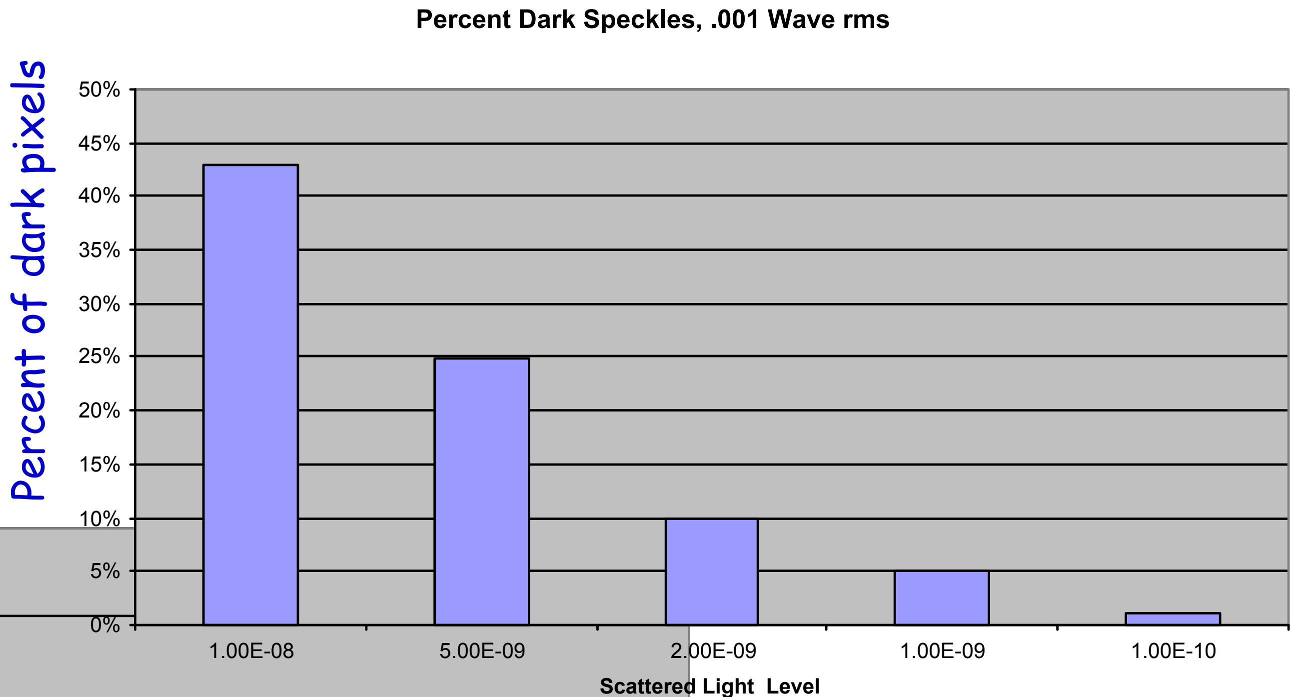
Note that apodizer can be in converging beam since it needs to precisely operate only on central star

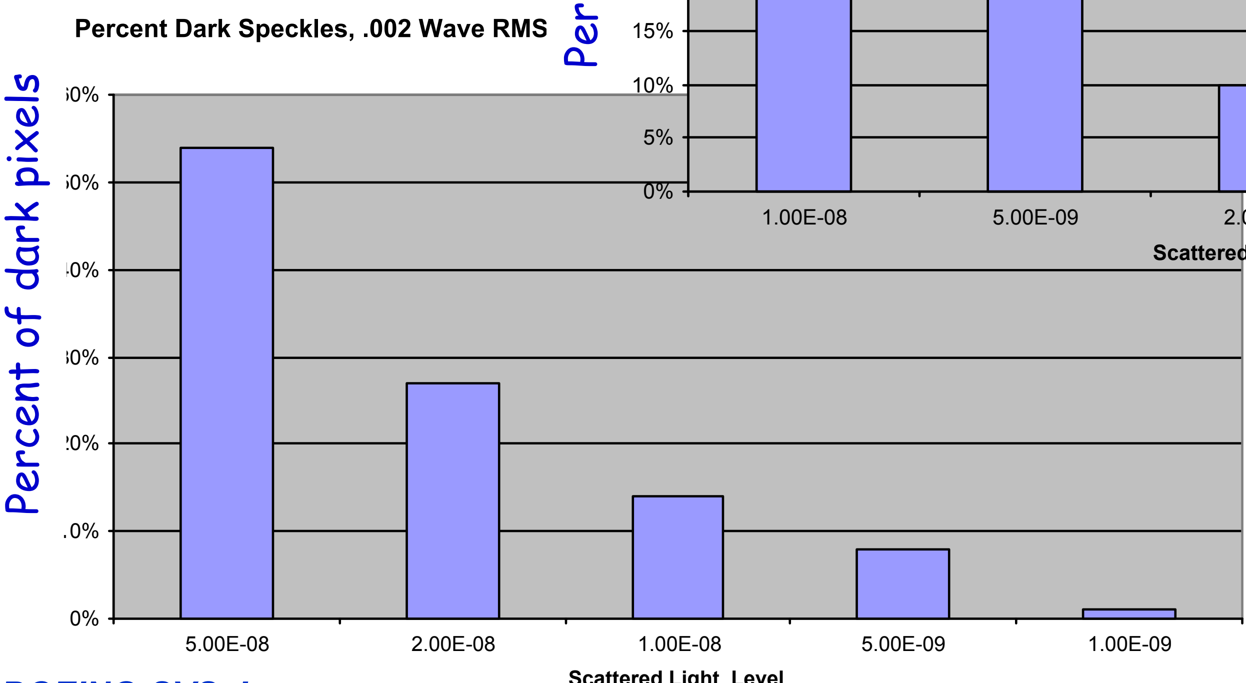


Key Features of ASA Apodization

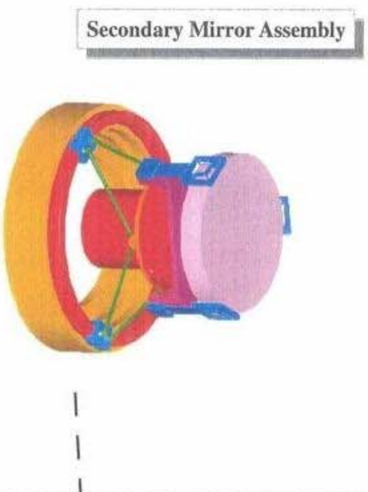
- ASA maximizes area with suppressed diffraction
- Jacquinot apodization gives narrowest central peak and 30% throughput
- Apodization reduces specifications on off-center mirror and edges
- Apodization reduces specifications on segmented mirror control when segments are in the outer parts of the primary
- Speckle pattern from mid-frequency roughness is centro-symmetric, allowing calibration
- Speckle pattern invariant with low-order aberrations
- Speckle pattern invariant to thermal instability

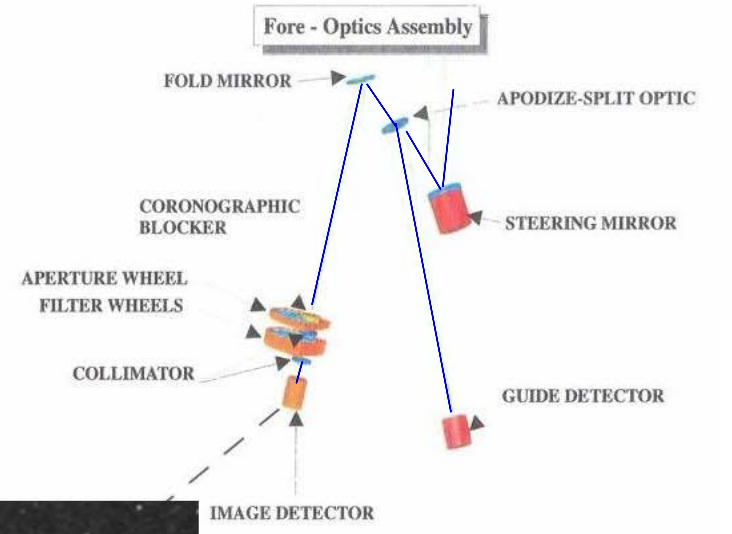
A large fraction of pixels are dark enhancing planet characterization

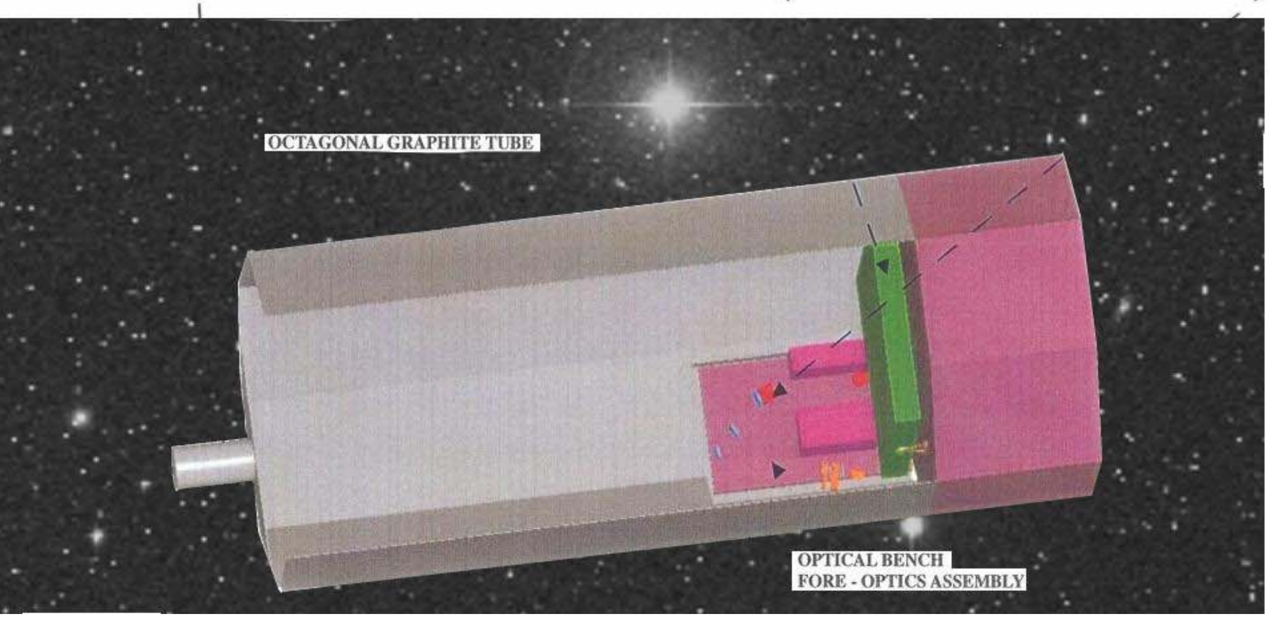




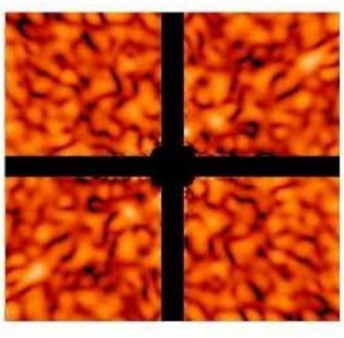
Conceptual Layout for an ASA Telescope with Off-axis Cassegrain Design







ASA Focal Plane



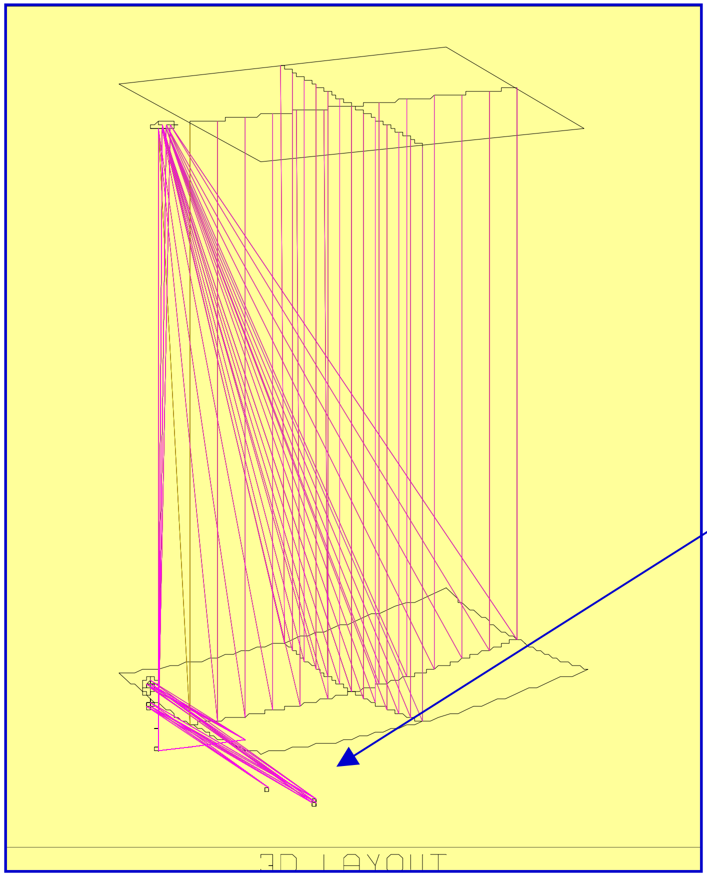
Preliminary ASA System Design Issues

- Manufacture of 8 meter segmented mirror
- Optical surface mid-frequency RMS errors in large segmented mirrors
- Pointing jitter
- Segment edge finish and edge matching
- Full and sub-aperture testing
- Scattered light control
- Thermal environment

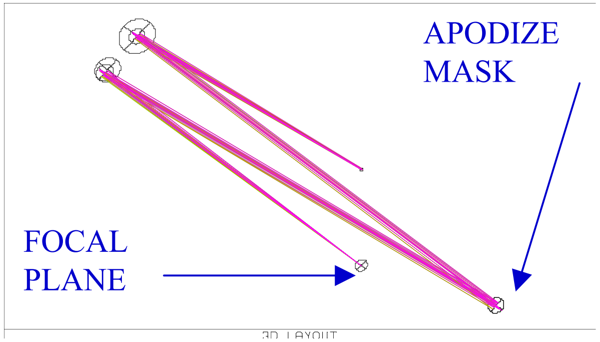
1.5.3 Optical beam transport concepts

- Optical design layout has been created
- No detected unwanted optical radiation (DUOR) analysis was performed for ASA but we have addressed surface quality requirements elsewhere in this presentation

Off-Axis Non-Obscured 8x8 meter Cassegrain Telescope



- Off Axis Cassegrain configuration fully baffled to control scattered light
- Parent Primary is f/1 parabola
- FSM located after pupil relay
- Powered optics relays pupil to reflective apodization mask of 3"
- Access to intermediate focus for possible spatial filter



Three Monolithic Telescope Designs

Critical design parameters	3 or 4 mirror system With spherical primary	Fast aspheric off axis primary Cassegrain or Ritchey-Chrétien
Surface roughness structure function< 5 nm	Superior if primary scatter is driver	Most aspheric
Figure control WFE < lambda/200 rms	Fabrication more difficult with 3 aspheric mirrors	Fabrication to meet WFE may require ion polishing
Compactness, Weight	Secondary and tertiary 1/2 wt of primary.	Longest system if f/no is held constant
Baffle design and spiders Baffled FFOV<50 microrads	Most difficult to baffle with internal focus	Limit FFOV to reduce zodiacal contribution
Apodization	Relayed pupil	Place on primary or secondary or relayed pupil

Some Design & Fabrication Issues for ASA Mirrors

	Benefits	Penalty
Round vs square primary blank	• Better figure control during polishing • Improved thermal control Improved metrology mount performance	• Tertiary placed above mirror surface • Weight difference may exceed 50%
Finish with ion polishing versus conventional polishing	• Zero surface loading so one can remove print thru of lightweighted inner struts • Predictable control of surface figure • Polishing mount not so critical • Not so sensitive to % of light weighting • Figure less dependent on mirror shape and f #	• Increase in high spatial frequency surface roughness • Removal rate slower • Few manufacturers with capability
Apodize primary versus exit pupil	• Optical path is simplified with 2-4 mirrors and no pupil relay • Surface roughness spec per optic approaches demonstrated roughness	• No capability to change mask to optimize for planet detection • Requires spacecraft to rotate,not mask • Extensive tooling and risk to coat zonine masks on large primary optic

1.5.5 Detector requirements

- ASA enjoys the benefits of operating in the visible wavelength regime
- We can exploit mature Si CCD technology
  - High quantum efficiency
  - Cooling by TEC
- We expect additional options in the epoch of the mission
  - Potential application of CMOS active pixel sensors
    - On-chip amplification of each detector element as well as improved radiation tolerance when compared with today's CCDs
    - On-chip timing, control and drive electronics, reducing system cost and complexity
    - Today, the cost of fabricating a CMOS wafer is one-third the cost of a similar wafer using a specialized CCD process
    - Electronic shuttering, readout windowing, variable integration time
    - Pixels in the array can be addressed randomly supporting dual use of the focal plane for both science and guiding
    - Enhanced UV/blue response
  - Possible application of the Lawrence Berkeley National Laboratory fully depleted architecture which provides improved near IR capability
  - Even larger formats than are possible today

1.5.6 Molecular and particulate contamination

- See details in NRLA section

1.5.7 Requirements on cryogenic components

- Science does not demand 'cold' optics, baffling
- Other factors (such as ground testing) define the appropriate operating temperature of the optics and structure
- Detector array may need cooling

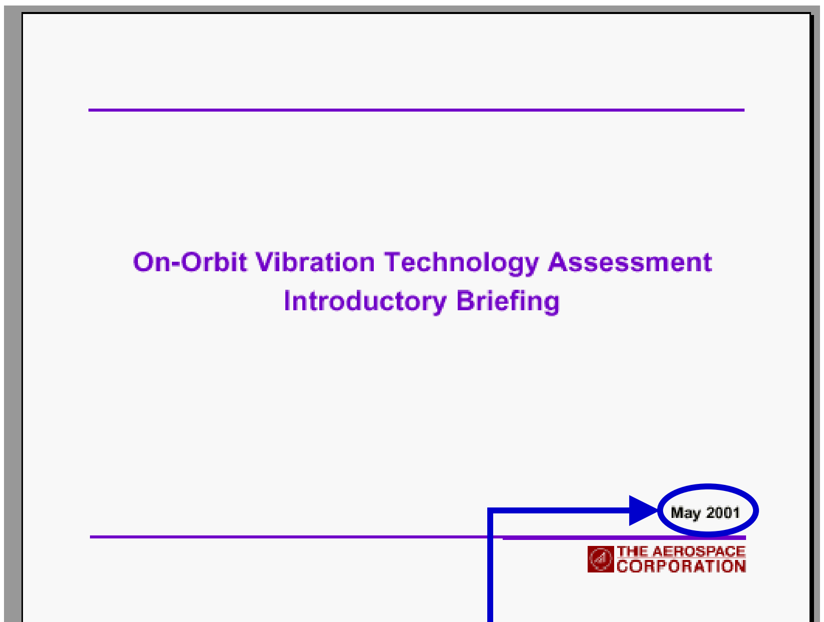
1.5.8 Thermal design concepts

- By operating in visible, ASA avoids many of the thermal requirements of IR systems
- Although sunshades could be used, an MLI design can be employed
- No sunlight is allowed to enter the telescope aperture
- The solar exclusion angle has not yet been allocated but may be as large as 135°

1.5.9 Approaches for integration-and-test

- We have considered on-orbit testing for large versions of ASA but the solution can exploit the I/T process used for NGST
- The potential exists for more efficient use of launch vehicle mass and volume capabilities by exploiting on-orbit assembly
  - More structural stiffness per unit mass on orbit
  - Smaller deformations of the optical surface at relevant frequencies
  - Higher packaging efficiency

The industry is beginning to address the 'on orbit' testing approach

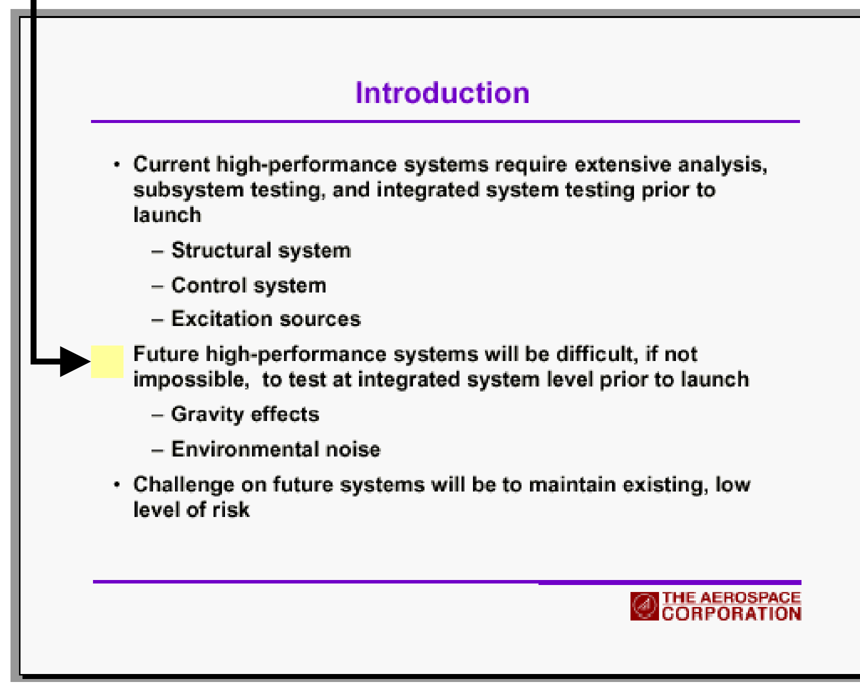

On-Orbit Vibration Technology Assessment
Introductory Briefing

May 2001

THE AEROSPACE CORPORATION

Very recent activity

Critical to optics as well


Introduction

- Current high-performance systems require extensive analysis, subsystem testing, and integrated system testing prior to launch
  - Structural system
  - Control system
  - Excitation sources
- Future high-performance systems will be difficult, if not impossible, to test at integrated system level prior to launch
  - Gravity effects
  - Environmental noise
- Challenge on future systems will be to maintain existing, low level of risk

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1.5.10 Orbit and sky coverage

- Orbit baseline is L2
- A conservative solar avoidance angle of 135 degrees satisfies the requirements in Exhibit II
  - Smaller solar avoidance angles will be explored
- Instantaneous sky availability is 15%
- Annual sky coverage is 69%
- Since target stars are uniformly distributed typical slews are 17 degrees.

1.5.11 Launch strategy

- ASA will exploit the launch experience of NGST
  - Solutions with mirrors larger than 4 meters will use deployment
- Larger systems will use deployed mirrors but can safely ride on existing launch vehicles

1.5.12 Deployment strategy

- The system will exploit the NGST heritage, as well as work under way for defense applications that use segmented mirrors
- Technology exists for manufacturing fast optical components that will allow relatively short secondary mirror structures

1.5.13 Operations Scenario

- For each target star the survey requires two bore-sight orientations rotated 45 degrees
- Each target star is surveyed once per year for 3 years
  - Confirms common proper motion and begins orbit characterization
  - Planets too close to their parent will have moved
  - Helps distinguish planets from background sources
  - Minimum (near 11 months) and maximum (near 13 months) time delays between revisits improve detection probability of planets with 12 month periods.
- Planet spectroscopy can be improved by placing the planet in a 'dark speckle', reducing the background stray light by about 10x. This has NOT been assumed for our mission life estimates.

ASA System Performance Basis

- Assumed star-planet flux contrast ratio is 3×10^{10}
- Minimum detectable planet-star separation is $4*\lambda/D$ or 62 mas
  - for D= 8 m, λ = 600 nm and a 45 degree azimuth focal plane detection zone
- Minimum detectable planet flux density is 0.6 nJy for SNR = 5, R = 3 and t = 100 hrs
- Minimum detectable flux density is a function of surface accuracy
  - rms surface error is assumed to be $\lambda/1800$
- Greater sensitivity at larger separation angles is due to reduced diffracted/scattered light

1.6.1 Optical, structural, thermal and control system computer models of the proposed architectures

- Our modeling work has concentrated on performance predictions (already shown) and estimates of the sensitivity of the system performance to optical surface quality (to follow)

1.6.2 Integrated end-to-end performance computer models demonstrating that the scientific goals, as defined in Exhibit II, will be met

- Sky coverage is 69%
- The habitable zones of 150 F5-K5 stars are surveyed (SNR ≥ 5, R = 3) for planets in 5,760 observation hours
- Planet characterization at R = 20 and SNR ≥ 10 (30 planets) and SNR ≥ 25 (5 planets) in 7,243 observation hours
- Survey and characterization time is about 1.5 years

ASA Mission Life Estimates

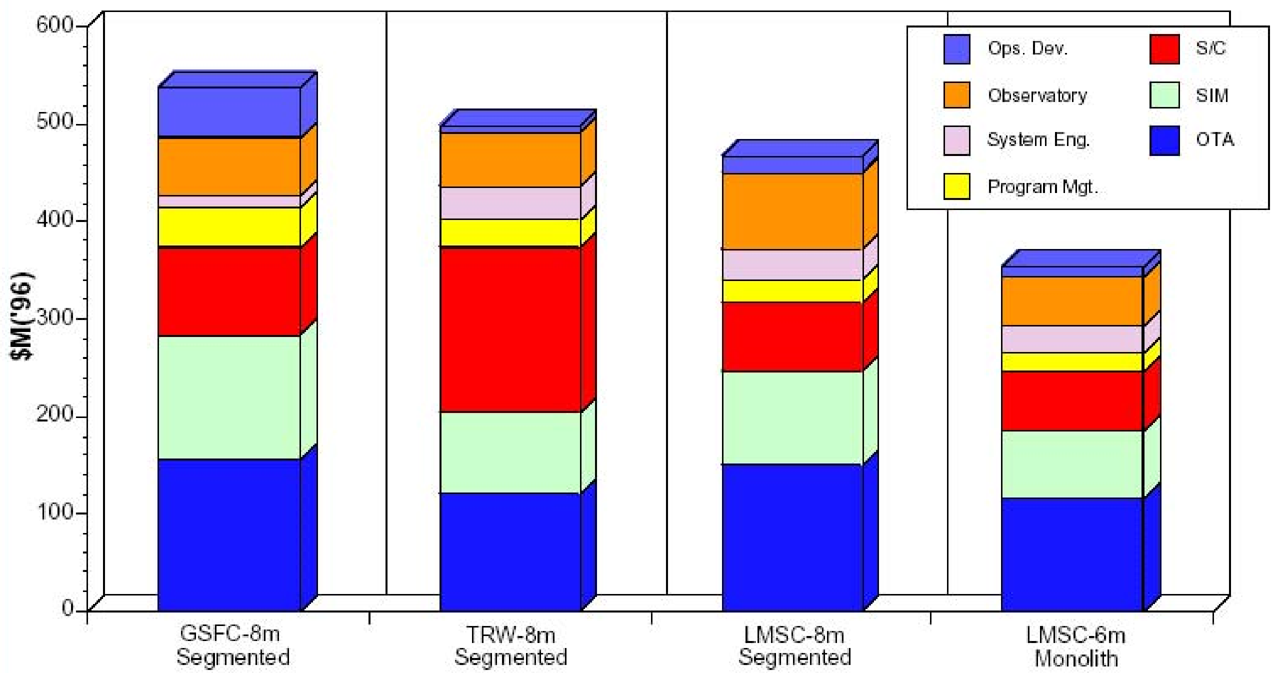
- System sensitivity determines integration time
  - For SNR=5, R=3, 10 nJy at 80 mas the on target time is 4.8 hours
  - Assumes 8-meter ASA, $\Delta\lambda$ = 200nm, λ = 600 nm, mirror rms surface error = $\lambda/1800$, flux contrast ratio = 10^{10}, and 30% transmission
- Survey mission integration time is:
  - 150 stars * 2 bore sights * 3 epochs * 4.8 hours / 0.75 observing efficiency = **5760** hours = 0.6 years
- Characterize 30 planets SNR = 10, R = 20 for 10 nJy
  - 30 planets * 4 SNR * 7 R * 4.8 hours * / 0.75 observing efficiency = **5376** hours = 0.6 years
- Characterize 5 planets SNR = 25, R = 20 for 30 nJy sources
  - 5 planets * 25 SNR * 7 R / 3 nJy * 4.8 hours / 0.75 observing efficiency = **1867** hours = 0.2 years

- Total planet survey and characterization time is:
  5,760 + 5,376 + 1,867 = 13,003 hrs = 1.5 years

1.7 LCC-Derived from NGST

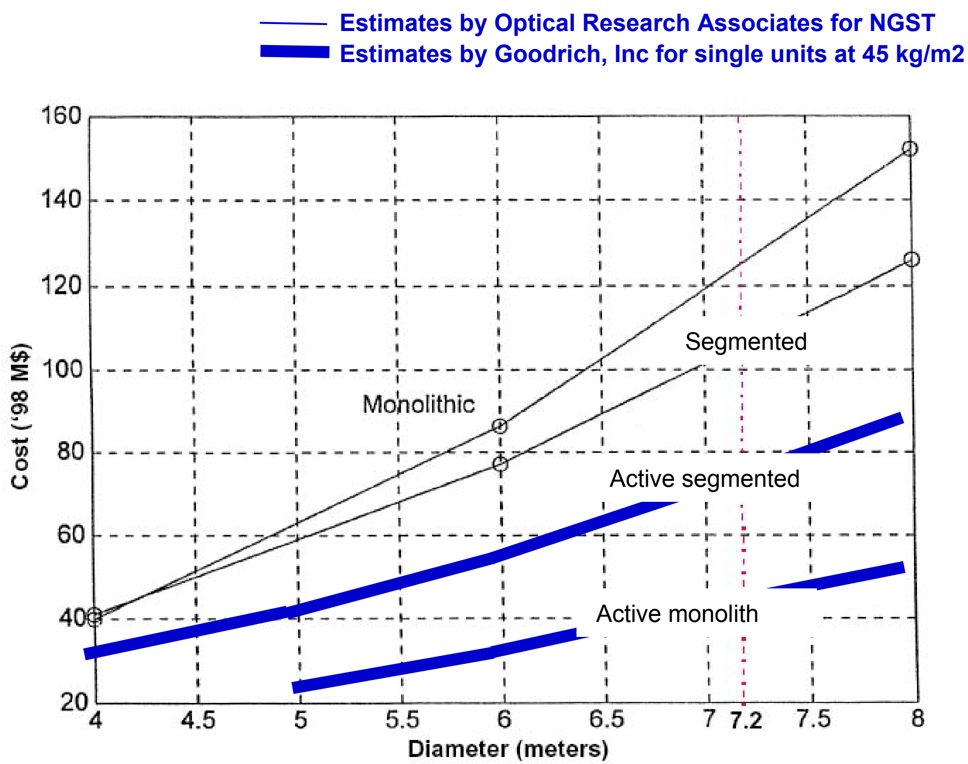
Next Generation Space Telescope

Manufacturing Cost Estimates



Manufacturing Cost Estimates for the Three Independent Studies. These estimates do not include predevelopment studies (Phase AB), technology development, and contingency (~30%). The three teams have allocated certain development costs to different cost elements.

Segmented vs. monolithic mirror OTA cost comparison



FROM NGST 2/98 program review

Next Generation Space Telescope

SRB

1.8.1 A listing of technology needs

- Included in 1.8.3

Technologies most critical to ASA (and other coronagraphic approaches)

- Control diffraction by aperture shape, apodization, field occulting
- Control scatter by creating and maintaining a near-zero wavefront especially at Mid and Low Spatial Frequencies
- Stable structures: Mechanical and thermal effects
- Control stray light and ghosts
- Implementation of technologies in large space borne flight systems
- Understand affect of errors on system performance and error allocation to subsystems by modeling and error budgets

Wavefront Control Technologies

- Manufacture of large lightweight aspheric mirrors with precise Low Spatial Frequency Range (LSFR), Coronagraphic Spatial Frequency Range (CSFR) and Mid Spatial Frequency Range (MSFR)
- Mounting and low order wavefront control of large mirrors
- Extremely uniform optical coating of all mirrors
- In-flight wavefront sensing over LSFR and CSFR
- In-flight wavefront control over LSFR and CSFR
  - Primary Mirror support
  - Deformable Mirror (DM) or other Corrector Element (CE)
- In-flight LOS sensing and control

Wavefront Control and Stray Light Control Technologies

- Large stable structures
  - Sub-micron pupil shear
  - LOS stabilization
- Precise temperature control
  - Structure
  - Mirrors
- Apodizer manufacture and characterization
- Field occulter manufacture and characterization
- System stray light, scatter, and ghost control
- Verification of system modeling and error budgeting
- Ground test of flight system

Four Spatial Frequency Domains

- Low spatial frequency range (LSFR) : 0 to 3 Cycles/aperture (CA)
  - Figure Error
  - Controllable by PM actuators and DM/CE actuators
  - Sensed by LSFR wavefront sensor
  - Stability important
- Coronagraphic spatial frequency range (CSFR): 3 to 100 CA
  - In planet zone of PSF
  - Controllable by DM/CE actuators
  - Sensed by Science wavefront sensor
  - Stability critically important
- Mid spatial frequency range (MSFR): 100 to 10^4 CA
  - Ripple
  - Not actively controllable
- High spatial frequency range (HSFR): > 10^4 CA
  - Surface micro-roughness
  - Not actively controllable

State-of-the-Art Mirror Manufacture Wavefront

Multilayer optics for an extreme ultraviolet lithography tool with 70 nm resolution

Regina Soufli[*a], Eberhard Spiller[a], Mark A. Schmidt[a], J. Courtney Davidson[a], R. Frederick Grabner[a], Eric M. Gullikson[b], Benjamin B. Kaufmann[a], Stan Mrowka[b], Sherry L. Baker[a], Henry N. Chapman[a], Russell M. Hudyma[a], John S. Taylor[a], Christopher C. Walton[a], Claude Montcalm[a], James A. Folta[a]

[a]Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550
[b]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720

SOTA Wavefront Mirror Figure

		Clear Aperture		
		y_0 (mm)	y (mm)	x (mm)
M1	asphere, best-fit R_c= -3055 mm	114.9	± 25	± 56.2
M2	asphere, best-fit R_c= +1088 mm	103	± 49.6	± 78.1
M3	sphere, R_c= -389 mm	0	± 25.4	± 25.4
M4	asphere, best-fit R_c= +504 mm	52.8	± 45	± 59

Table 1: Geometry of the four ETS projection optics. M1, M2 and M4 are sections of aspheres, with a maximum departure of a few μm from a best-fit sphere, in the clear aperture area. M1 and M3 are convex (radius of curvature R_c is negative), while M2 and M4 are concave (R_c is positive). y_0 is the distance between the optical axis and the center of the clear aperture and y, x, define the extent of the clear aperture, measured from its center.

Some EUVL results: MSFR < 1 nm rms Can Be Achieved

	Figure (nm rms)	MSFR (nm rms)	HSFR (nm rms)
M1	0.25	0.21	0.24
M2	0.35	0.20	0.19
M3	0.22	0.15	0.24
M4	0.25	0.22	0.17
Spec	**0.25**	**0.20**	**0.10**

Table 2: Summary of figure and finish results in the clear aperture area of the delivered ETS Set 2 optics, compared to the specifications.

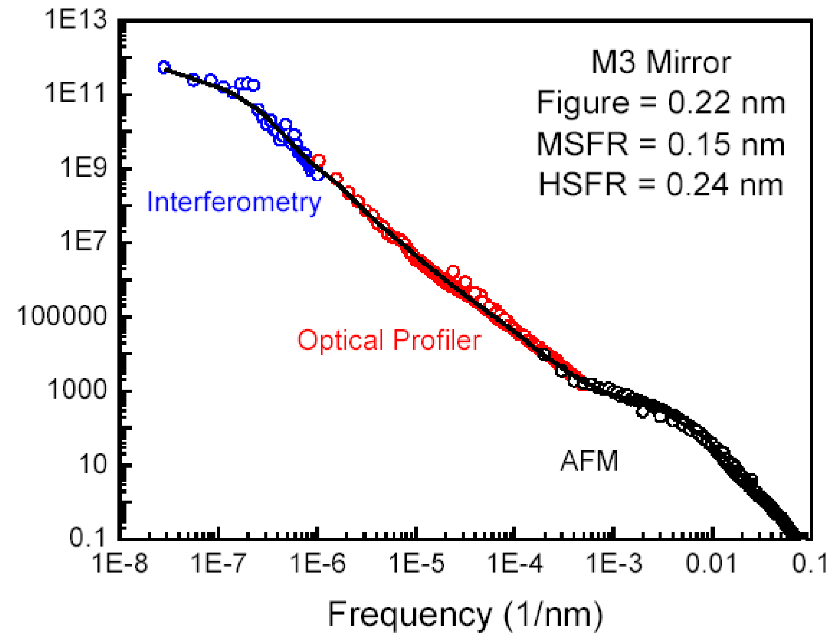


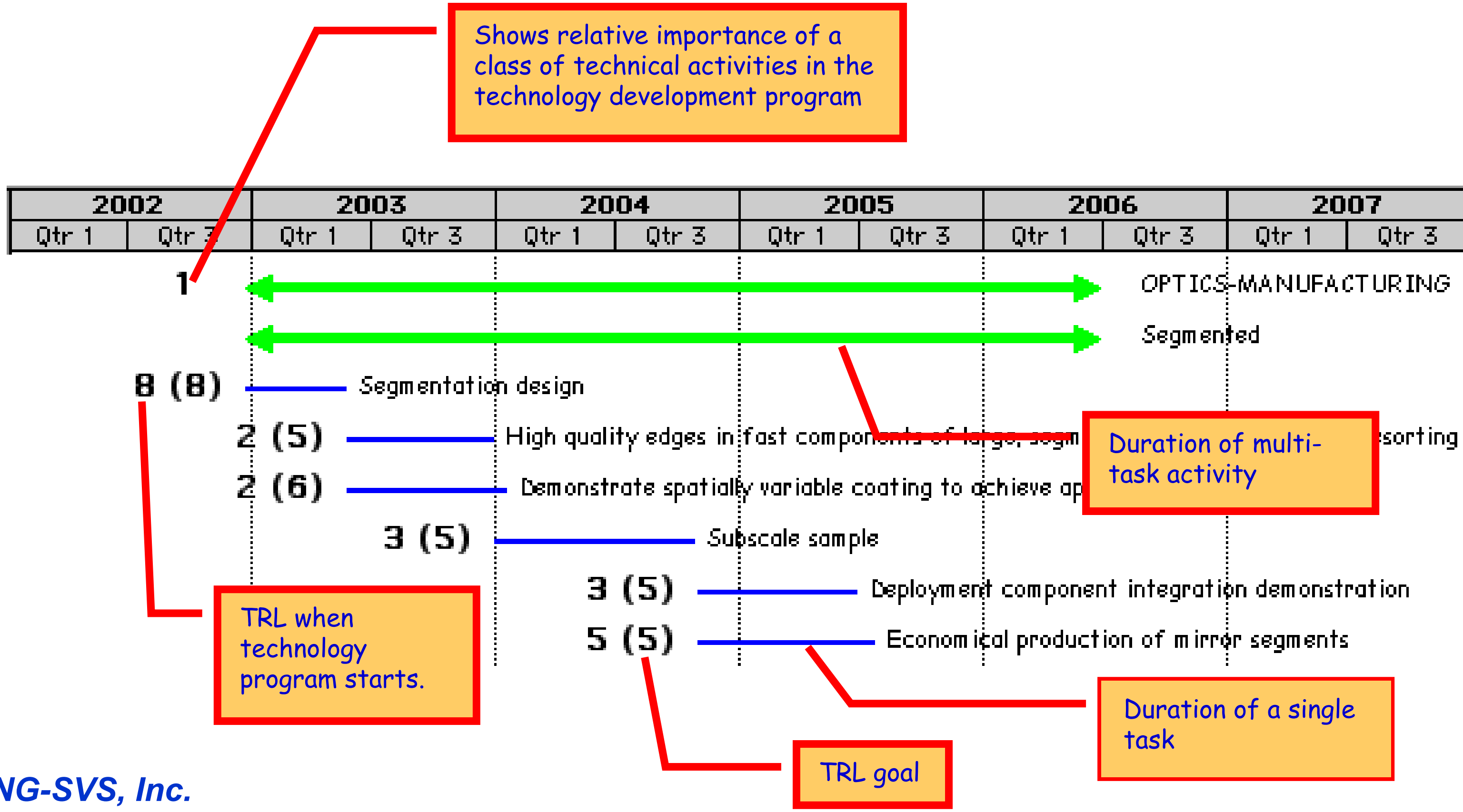
Figure 1: Measured PSD of the M3 substrate surface. For each spatial frequency range, the area under the PSD curve is used to determine the rms value of the roughness.

1.8.2 A roadmap for technology development

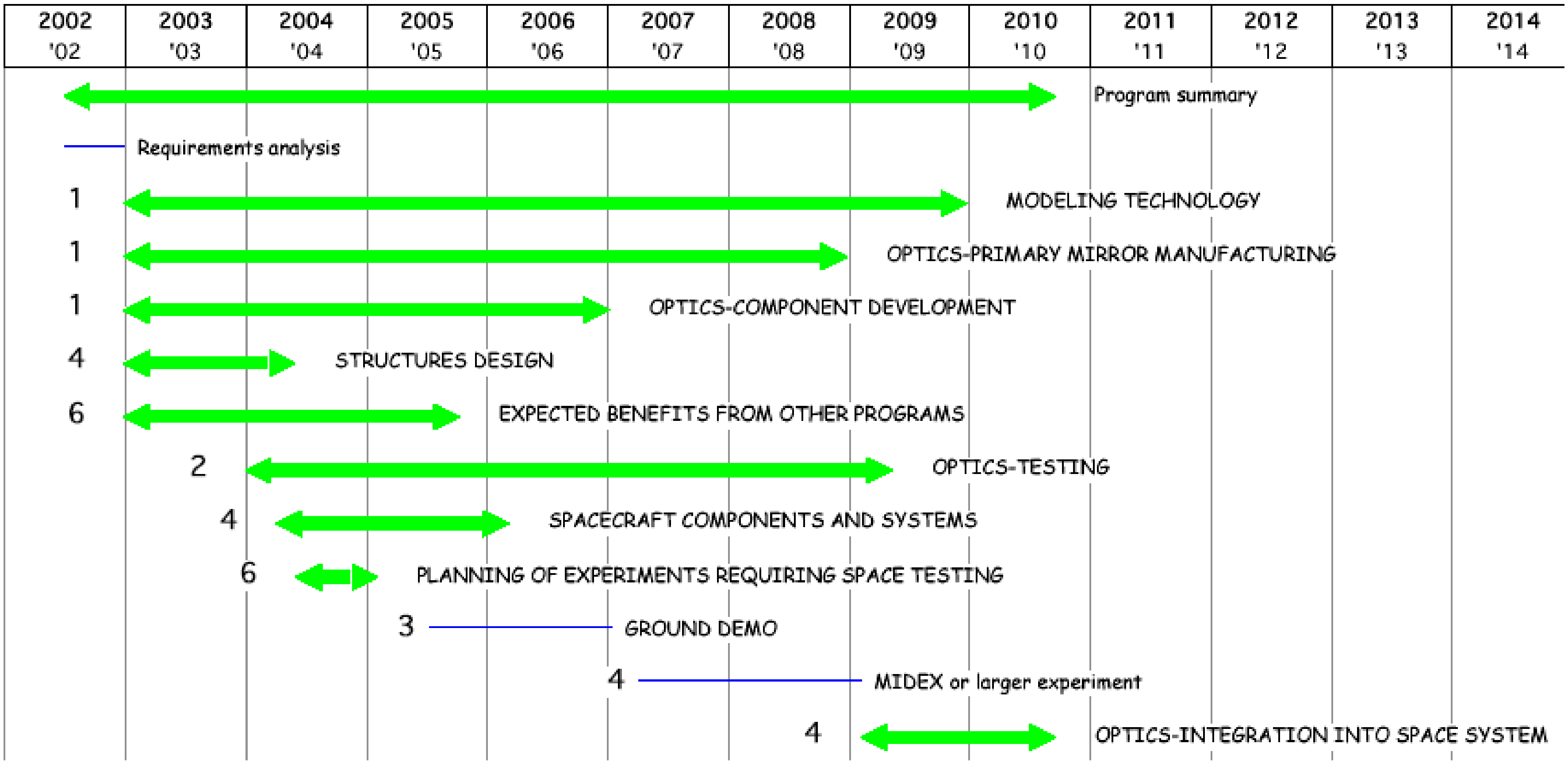
- The following charts illustrate roadmaps, TRL levels and timelines
- Technical topics were chosen using the following criteria
  - Little attention to topics that are under development throughout the community
  - No attention to topics for which there is already substantial technical maturity
  - Focus on topics that enable the ASA mission
- Dependencies are not shown to keep the charts clear

1.8.3 Metrics for assessing technology maturity and readiness

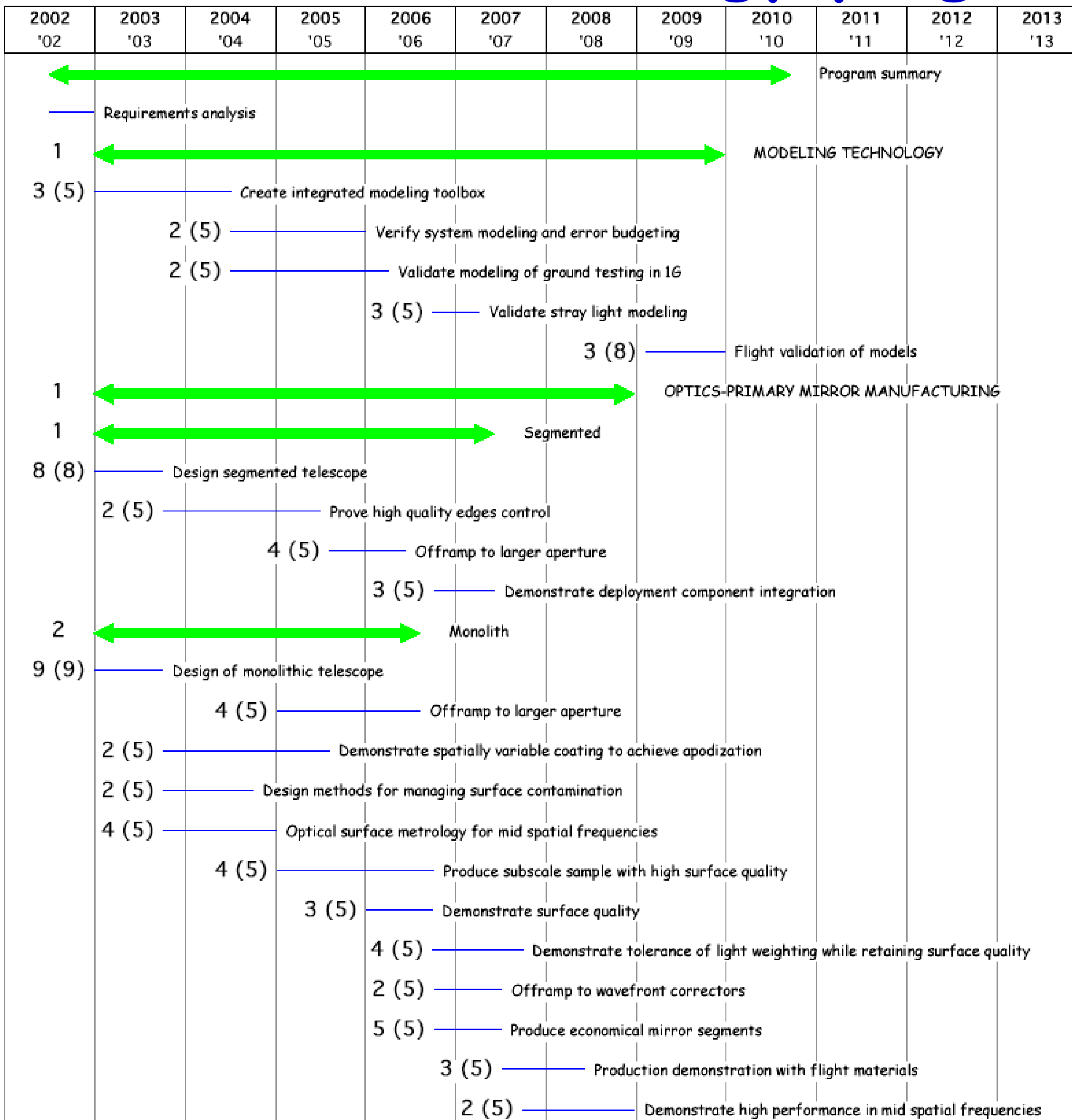
- Our roadmap approach uses various metrics
  - NASA TRL in two ways
  - A qualitative measure of importance of the technology advance



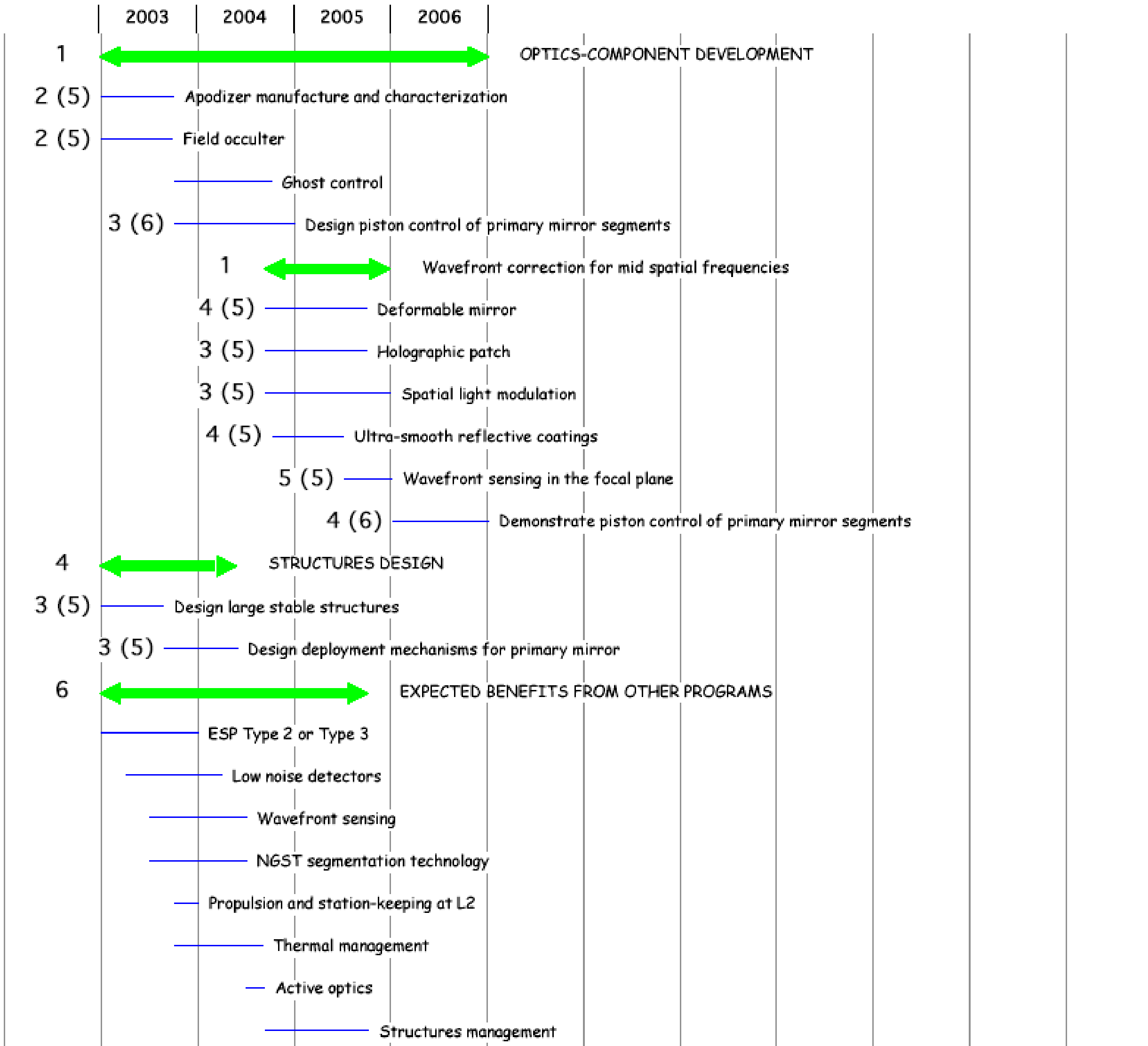
Overall technology program elements



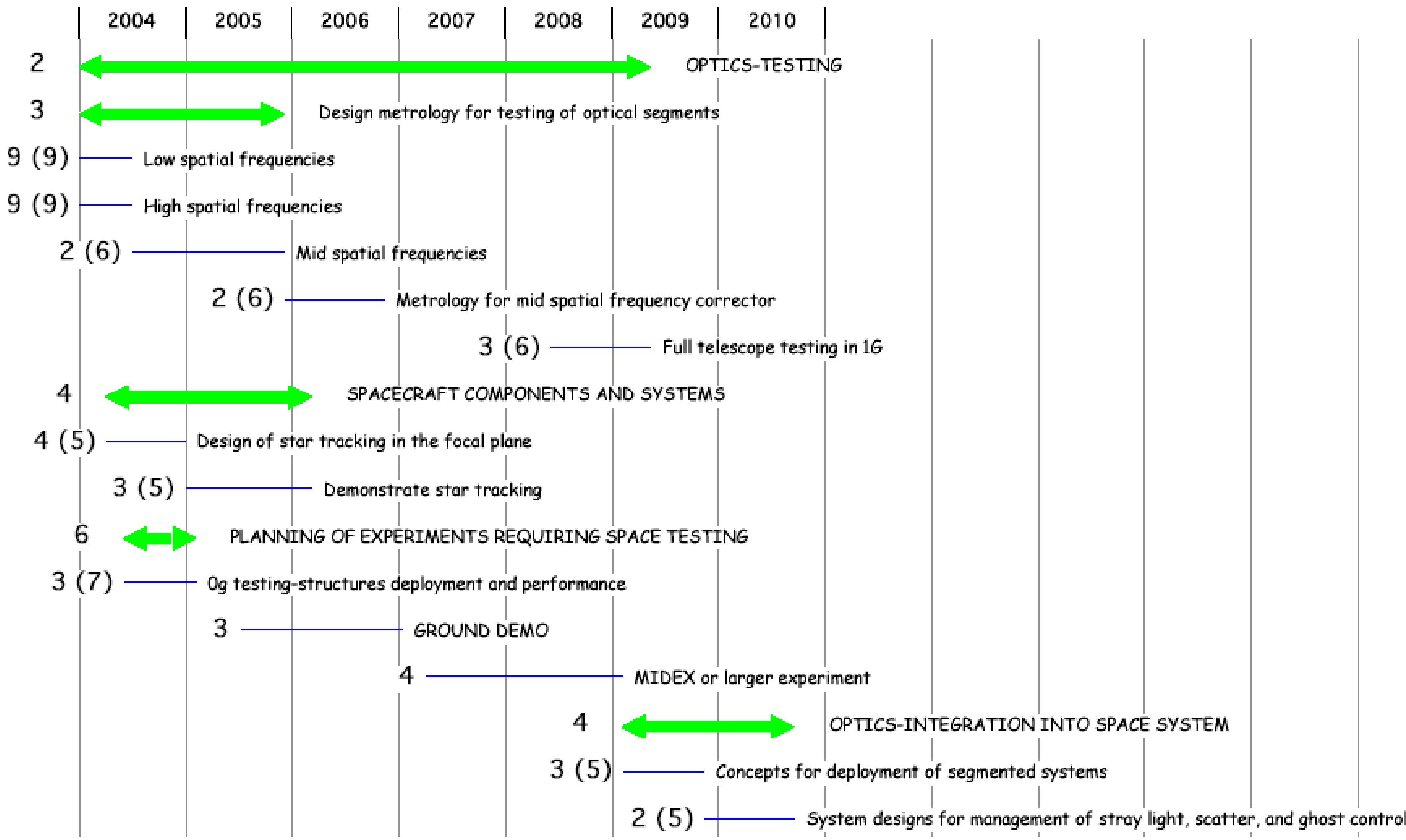
Elements of the technology program (1)



Elements of the technology program (2)



Elements of the technology program (3)

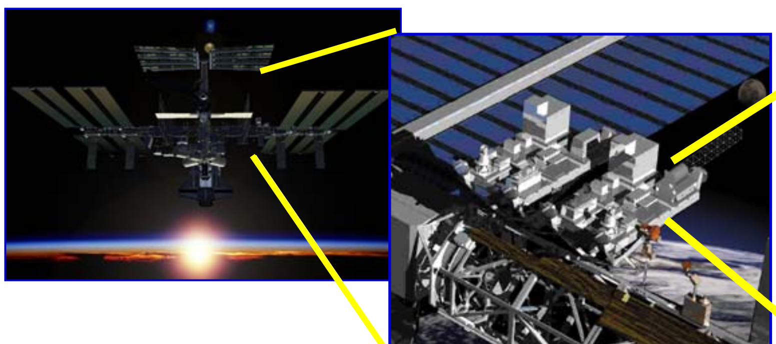


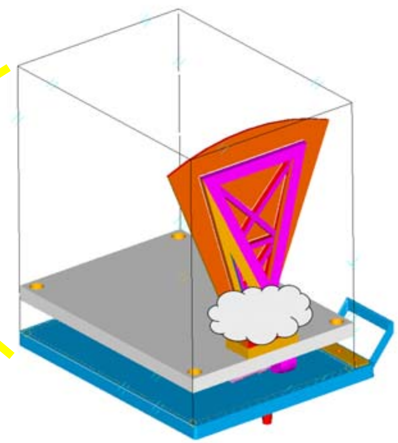
1.8.4 Identification of technologies requiring flight validation

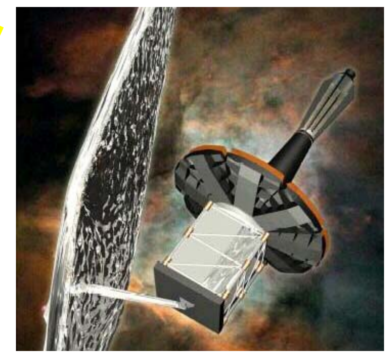
- Structures issues are the only elements of ASA that need flight validation
  - 0g measurement of structural quieting technologies, both active and passive
  - Performance of deployed structures
  - Deployment of structure
  - Performance of structure in a near-cryogenic environment
- The University of Colorado MADE program represents the type of experiment that efficiently provides the necessary flight performance information at minimum cost (~$5M)

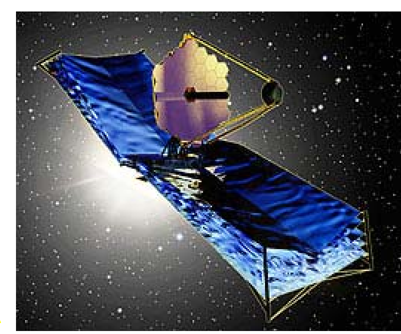
Micron Accuracy Deployment Experiments (MADE) is an Example of a Low Cost Flight Experiment to Validate the Precision Deployment for ASA

Flight Laboratory (Funded by ISS/ERT Program) → Test Article (Funded by Programs/Companies) → Science-Mission Requirements









MADE Capabilities:

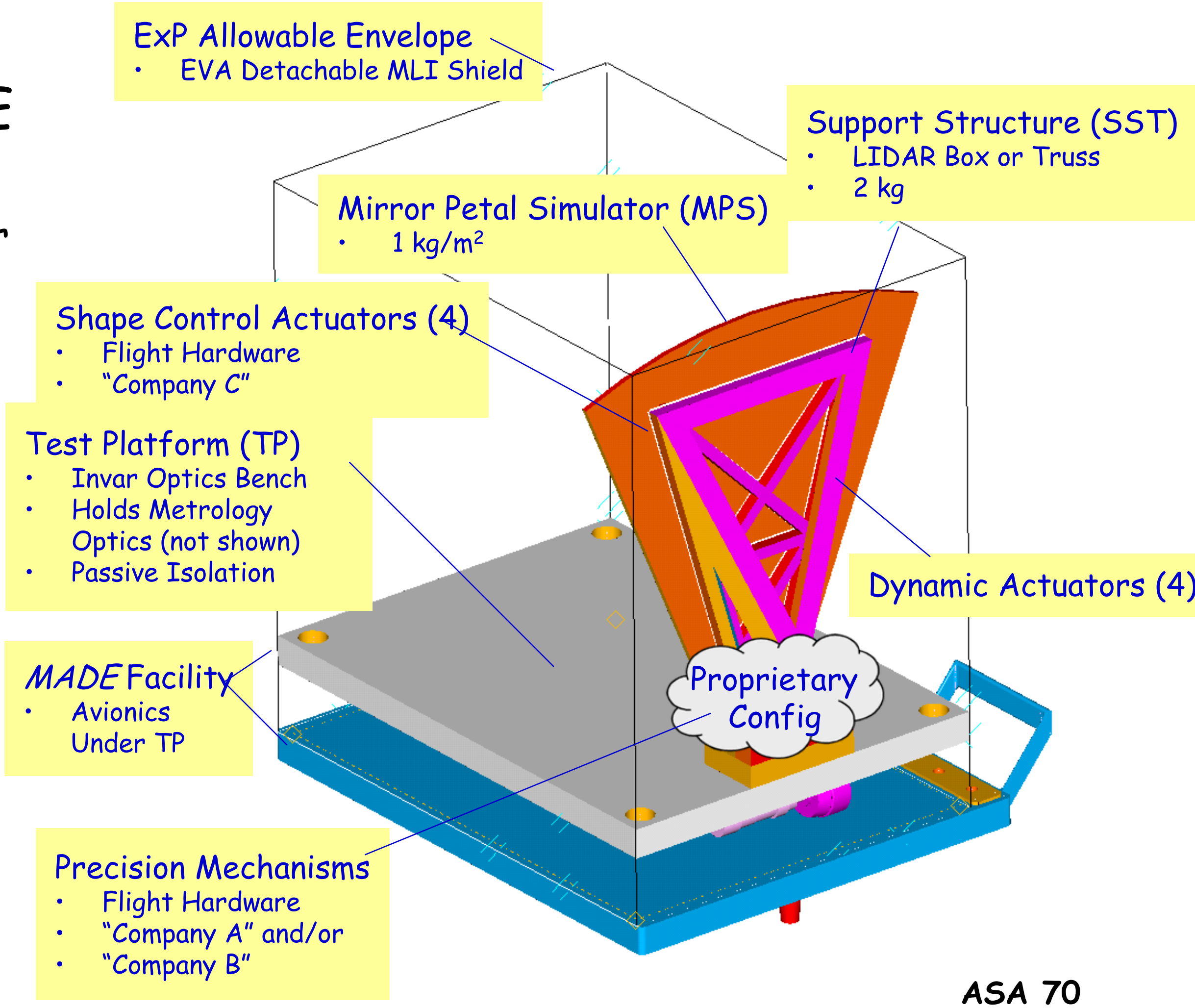
- 6-18 month flights
- Micro-g stabilization
- Nanometer metrology
- Active-control
- Microdynamics
- G-byte data down-link

BOEING

JPL

MADE Structural Test Article Concept

- Potential test concept enabled by a modest augmentation to MADE
- Single deployed panel
  - 45° Segment of 2 meter diameter mirror
  - 5kg/m^2 technology
  - Stows against the TP
  - Deploys within envelope
- Precision mechanisms
- Quasi-static shape control
- Dynamic vibration control



ASA 70

A modest number of technology advances are required for ASA

- Most technical challenges are being addressed by other, prior, missions
  - Operation at L2 and heliocentric orbits
  - Reliability of performance predictions by integrated models
  - Large optics in space
- Key technologies include
  - Production of optics with suitable surface quality in critical spatial frequencies
    - Alternatively, we require success from correction technologies like adaptive optics or holographic plates
    - Motivation on the part of the optics industry to develop this capability, which may have few other applications
  - Solutions that allow deployed optics
  - Evolution of a capability to assemble and test optics on orbit

ASA surface accuracy performance risk has several mitigation paths

- ASA high contrast imaging requirements require excellent mid-frequency wavefront quality
- Fortunately ASA systems can take advantage of several mid-frequency solutions:
  - Primary optical polishing for low rms surface error, or
  - A polished corrective surface can add static correction, or
  - An active optical surface can provide adjustable correction, or
  - A phase mask can be used to improve mid-frequency quality.

The Apodized Square Aperture is a Robust Concept

- Performance risks have several mitigation options
- The requirements for a given target star-planet configuration can be met by a combination of surface quality, wavelength selection and aperture size
- Under-performance in surface quality can be compensated for with aperture size or integration time
- Integration times for planet characterization can be significantly reduced (e.g., 10x) by placing the planet in a dark speckle location

ASA system reliability and robustness

- ASA has a number features that make it robust
  - Insensitivity to piston errors in primary mirror
  - No cryo mechanisms
  - No mechanical cryo cooler requirements
  - Tolerance of the low order wavefront errors common in most large telescopes
  - Symmetric features of the speckle pattern facilitate flat fielding and functional redundancy
  - A field of view small enough to facilitate its manufacture but still provide astrophysical capability
- ASA is a scalable solution

Science and Technology legacy that ASA provides for future planet detection and characterization missions

- ASA is expected to offer a non-interferometric solution to the planet detection and characterization effort
  - Science products
    - Discover, image and characterize terrestrial and gas planets on xx stars within xx parsecs of earth
    - Provide repeat observations of each star to assure that planets are detected with high probability
    - Perform spectroscopy on detected planets with high efficiency, once orbits are defined
    - Distinguish between gas and ice giants with Jupiter and Uranus analogs
    - Complement continued planet detection provided by Doppler shift and astrometry by providing characterization of the detected planets
    - Product of albedo and surface area
    - Monitor photometric variations that indicate seasonal variations
    - Perform extra-galactic astrophysical studies on faint structure around stars and quasars
    - Complement similar work done by IR interferometric systems
  - Technology products
    - Prove the ASA concept, its scalability, its suitability for use at L2 or in heliocentric orbit
    - Confirm the performance of coronagraphic methods of planet detection in space, using super-polished mirrors

Availability of precursor missions relevant to the required science and technology

Future Missions	Optics and opto-electronics	Structures and controls	Launch, navigation and orbit environment	Science
SIM	• Validated integrated modeling	• Large, deployed structure • Materials and methods to manage damping	• Operations in 'drift away' orbit • Shuttle launch	• Finds target systems
NGST	• Large lightweight optics • Precision pointing • Validated integrated modeling	• Validated integrated modeling • Deployable structures • Passive damping	• Operation at L2 including fuel management for station-keeping, communications • Orbits to L2 • Concepts for flight demonstrations at L2	• Define high contrast astrophysics targets
Proposed				
ESPI	• Validates space application of ASA concept, science and engineering			• ASA science precursor
Kepler				• Provides statistics of planetary systems