Introduction to Optics part II

Overview Lecture

Space Systems Engineering

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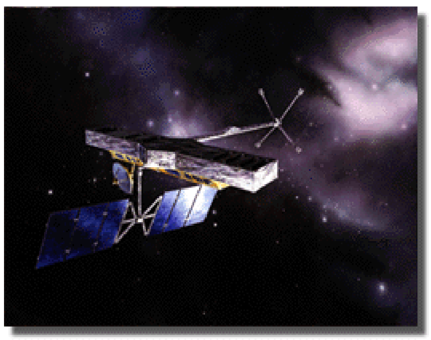
Interferometer Types (NASA, AirForce)

SIM-2006

Michelson Interferometer

Precision Astrometry



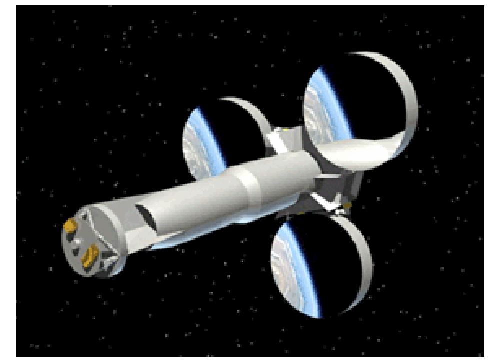
Space Technology 3-2005

Michelson Interferometer

Air Force UltraLITE

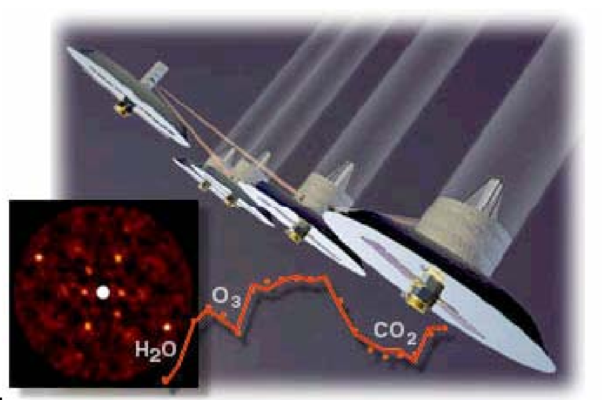
Fizeau Interferometer

Earth Observing Telescope



TPF - 2011

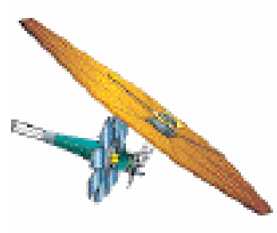
Michelson Interferometer



NGST - 2007

A Common Secondary Mirror (MMT, Fizeau)

Primary Mirror = 8 m diameter



Interferometer Types (Ground)

Keck Interferometer-2006

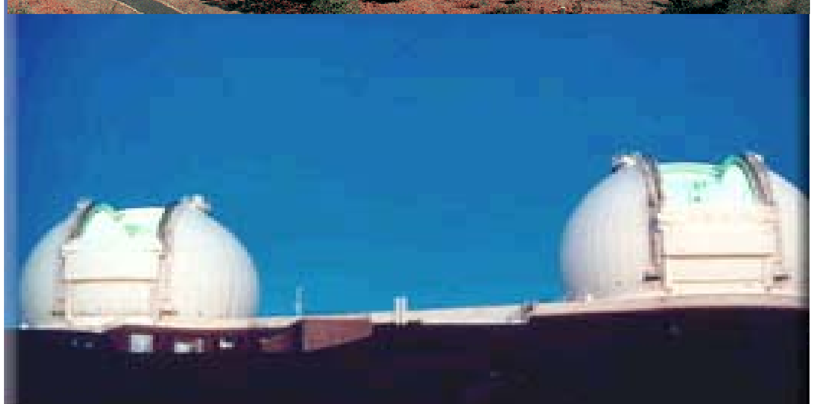
Michelson Interferometer (Infrared)
Twin 10 m Keck Telescopes and four 1.8 m outriggers
Baseline 85m

Palomar Testbed Interferometer

Michelson Interferometer (Infrared)
Testbed for Keck and SIM

Mark III Interferometer

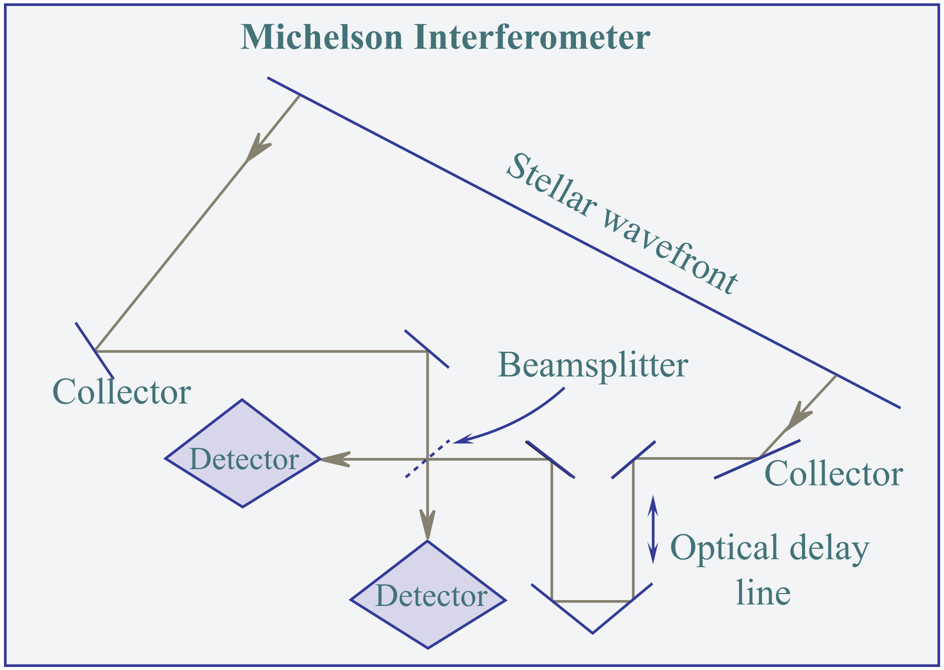
Michelson Interferometer (Visible)

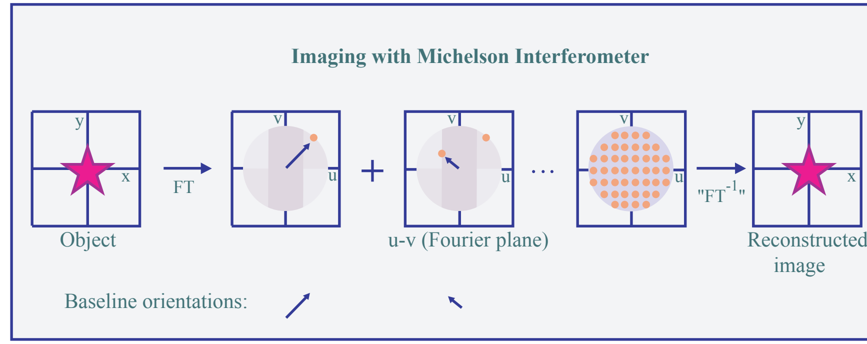


Keck Observatory:
Multiple Mirror Telescope (MMT)

Fizeau Interferometer (Visible, Infrared)
36 hexagonal segments => 10 m overall aperture

Michelson Interferometer

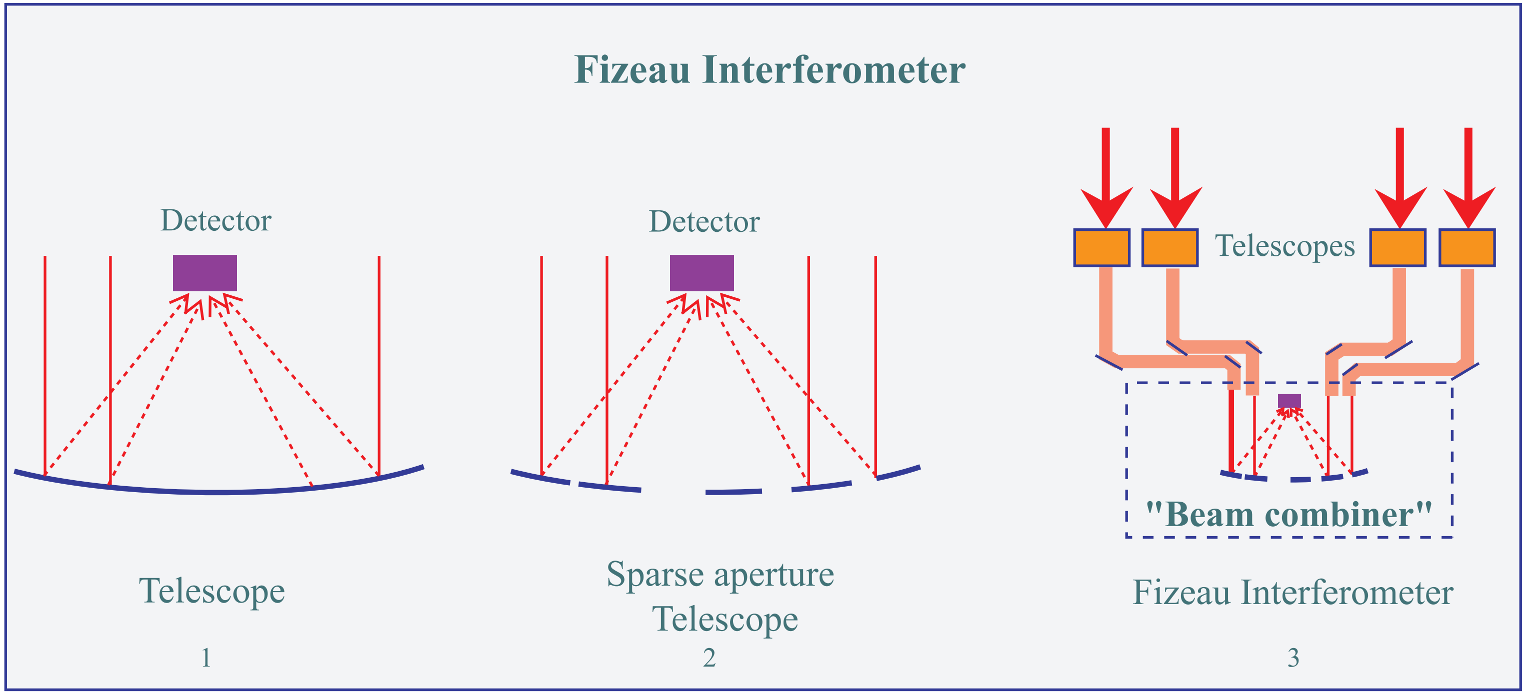




Independent Light Collectors feed light to a common beam combiner. Get interfered fringes => Inverse Fourier Transform (CLEAN,MEM)

Suitable for Astronomical Objects: Unchanged over a long period of time

Fizeau Interferometer



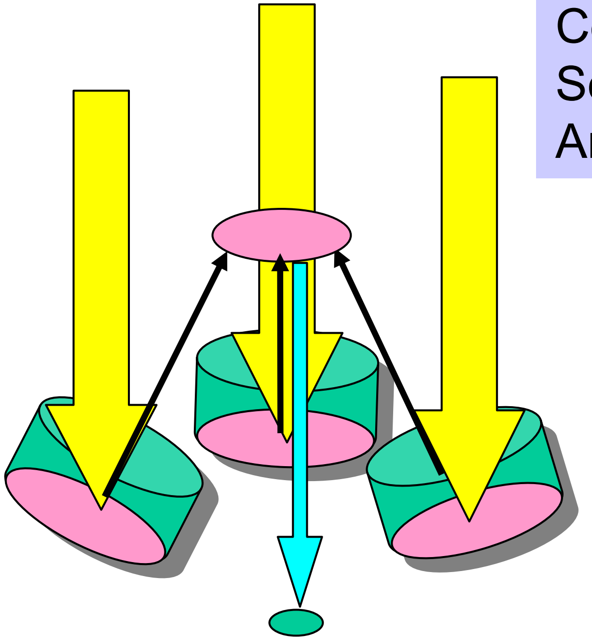
Gives a direct image of a target from a large combined primary mirror, and a wide field of view (Imaging applications in space and MMT)

→ **Suitable for Wide Angle Astrometry**
And for rapidly changing targets (Terrestrial, Earth Objects)

Comparison (Fizeau, Michelson)

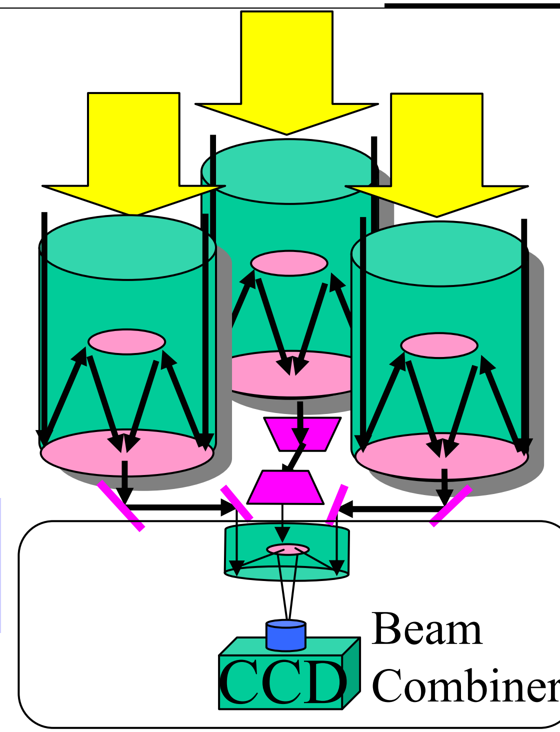
Fizeau Interferometer	***Michelson Interferometer***
Produce a direct image of its target (Full Instant u-v coverage provided)	Takes a subset of u-v points obtained a period of time.
Wide angle(field) of view imaging applications	Astrometry, Nulling Interferometry
Rapidly Changing targets (Terrestrial, Earth Objects)	Target unchanged (Astronomical Objects)
Takes the combined science light from all the apertures and focuses it into CCD	Measures points in Fourier transform of images => Inverse FFT needed
U-V resolution depends on both the separation and the size of apertures	Angular resolution depends solely on the separation of apertures
Optimal Configuration: Golay (minimum aperture size)	The angular resolution improves as the separation increases

Common Secondary vs Sub Telescope



Common Secondary Mirror Array

Phased Sub-Telescope Arrays

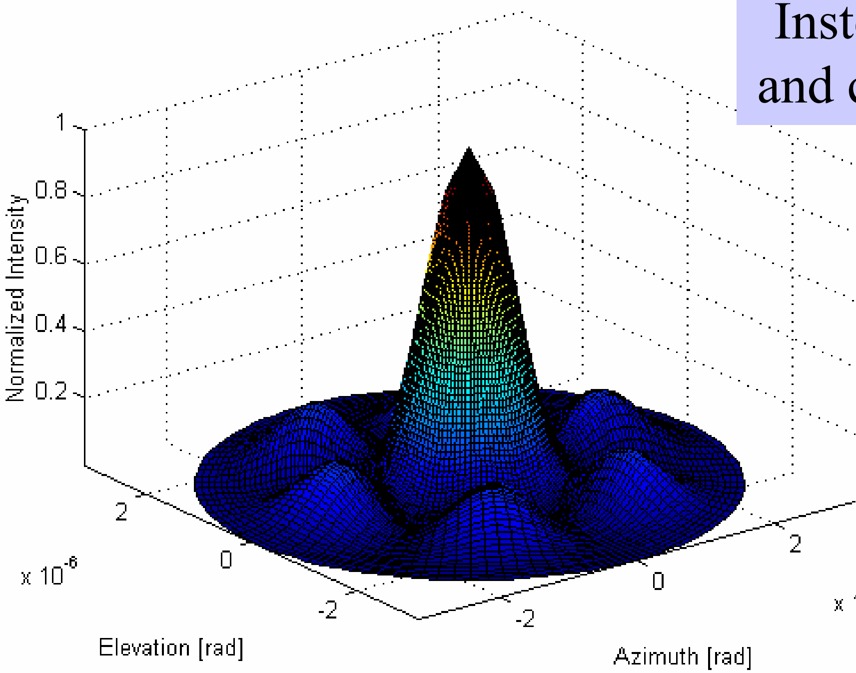


Common Primary	Sub Telescope Fizeau
Precise Off Axis Configuration Off Axis Optical Aberration	Need Combiner + Phase sensing and compensater mechanism (complex)
Less Central Obstruction(Off Axis)	On Axis Suffers Central Obstruction
Hard to change the Configuration	Can employ Off-the-shelf telescopes

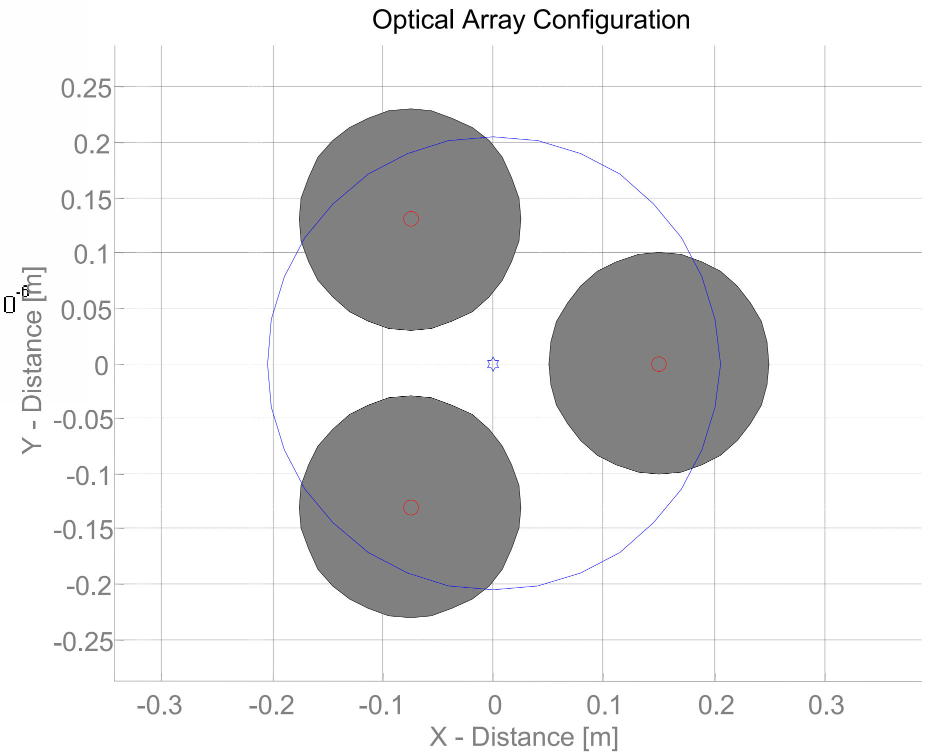
AirForce is studying two options for UltraLITE(Golay 6)

Optical Arrays

Instead of using a single aperture use several and combine their light to form a single image



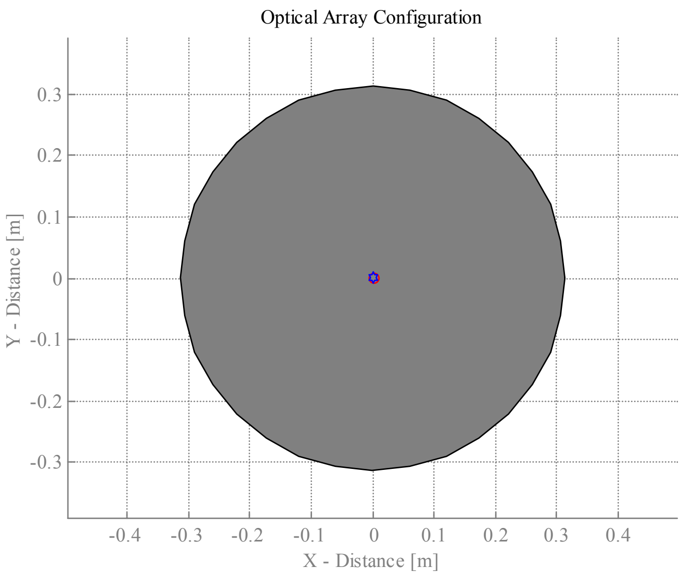
Aperture positions (uv) are critical - look at combined PSF / Transmissivity of the Optical Array



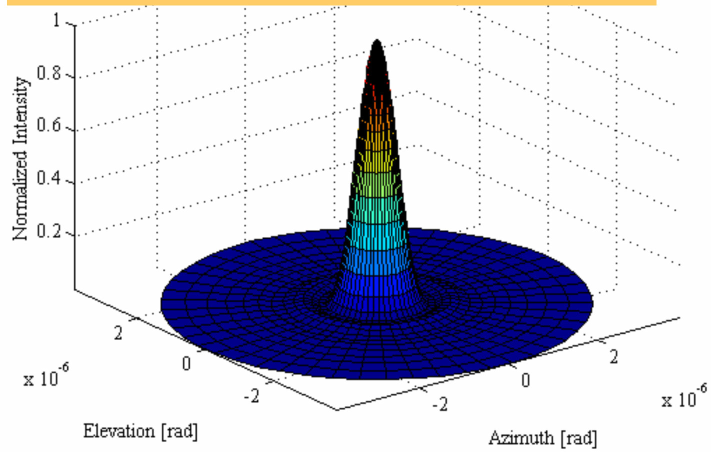
Transmissivity Function:

Derivation see separate handout (Mennesson)

CDIO: Breaking the Paradigm



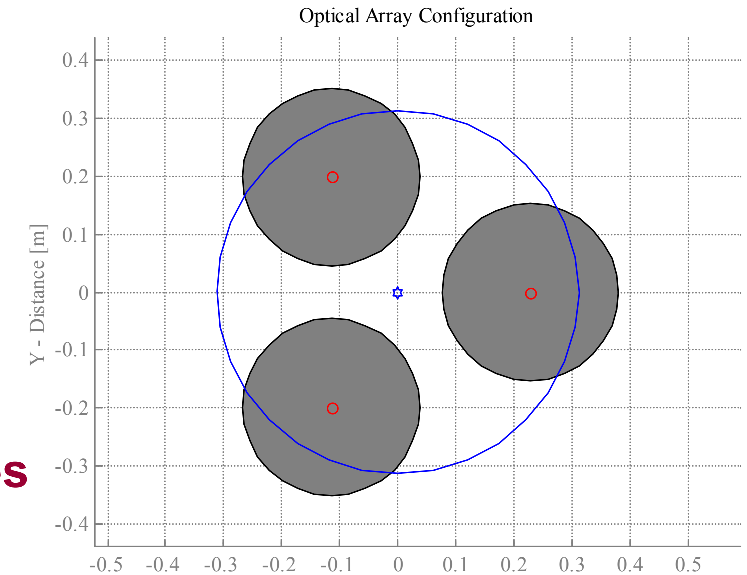
Monolithic 0.6 m telescope



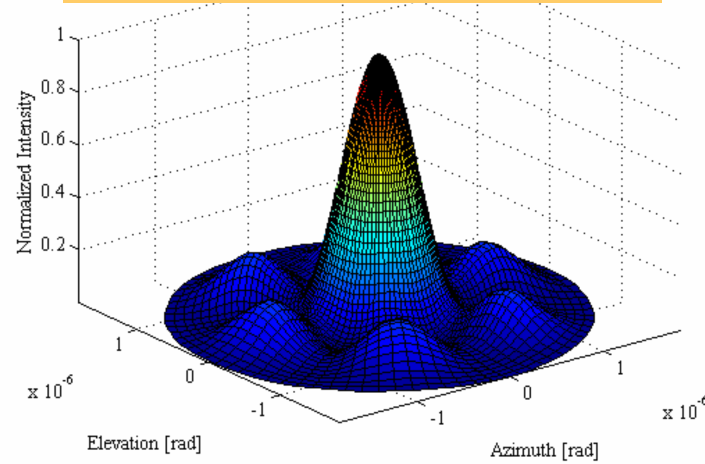
Physical Aperture Layout

Compare Architectures with Quantitative Metrics

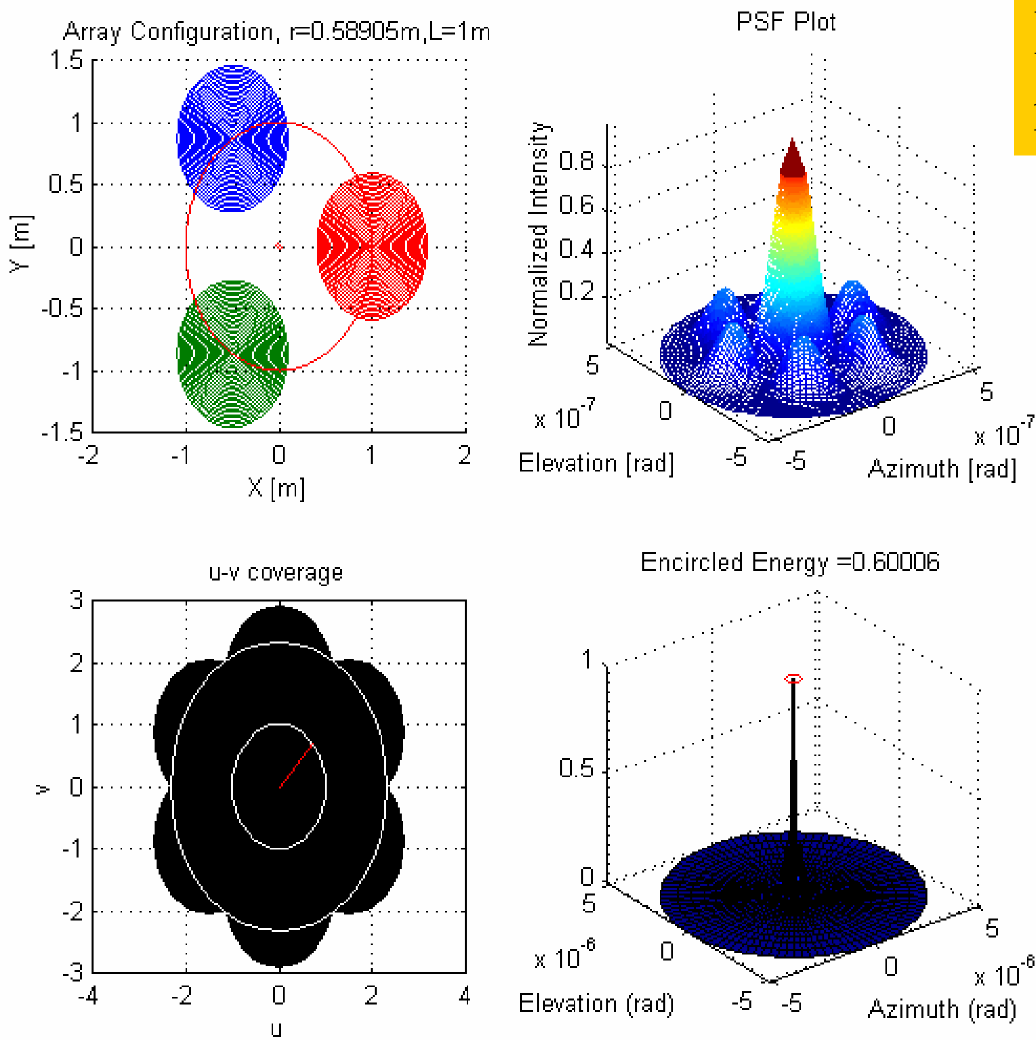
PSF



Golay-3 0.6 m telescope



Effective Radius of Optical Array



How to find the effective radius(Reff) of the array?

- R_{eff} =the radius of the array thought as that of a monolithic aperture.
- UV coverage plot

$$u = \pm \frac{x_2 - x_1}{\lambda} \quad v = \pm \frac{y_2 - y_1}{\lambda}$$

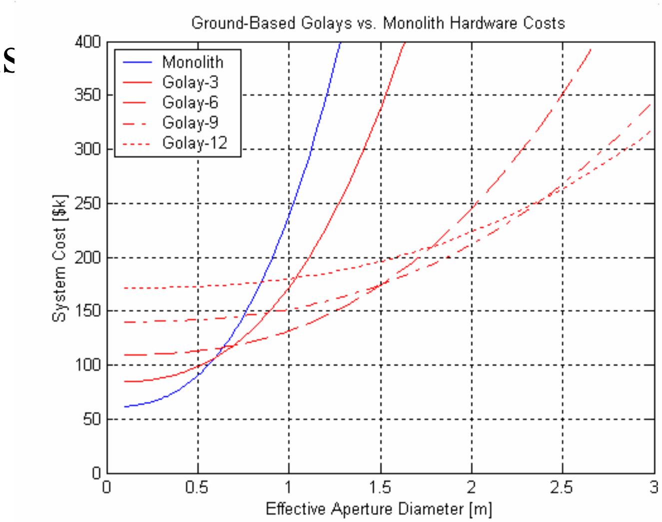
x,y is any point within aperture

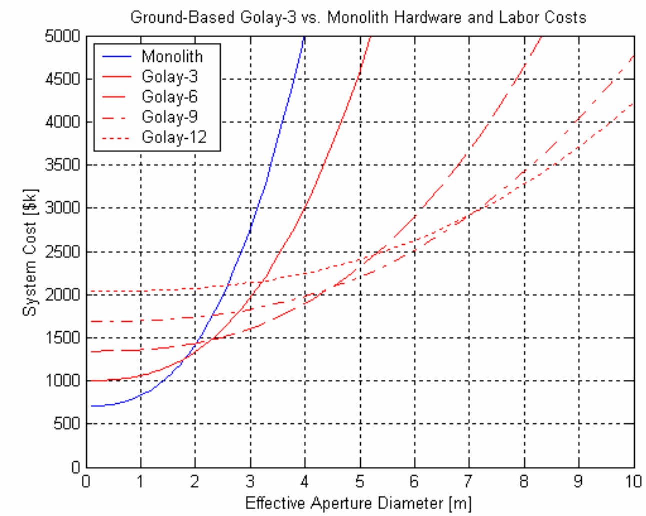
- R_{uv} : the maximum radius of uv plot without any holes
- $R_{eff} = 0.5 R_{uv}$

- Fill Factor: the array's total collecting area over the area of a filled aperture with the same uv coverage(the same Reff)

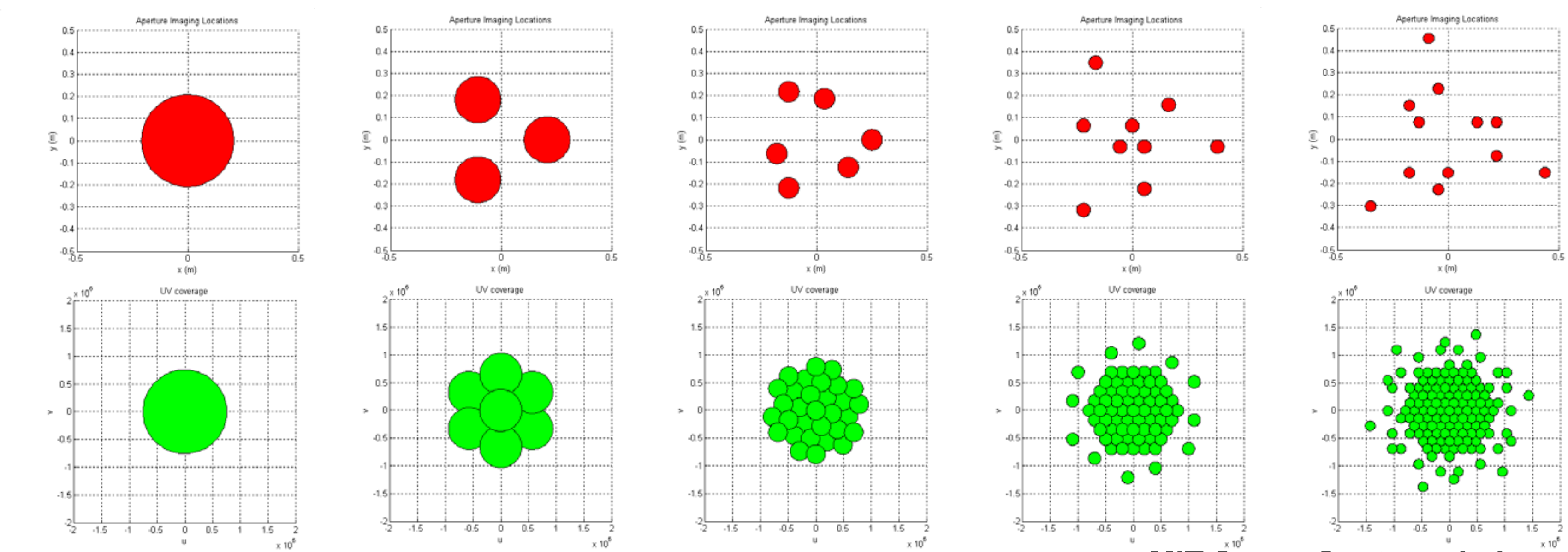
Golay Configurations

- Optimum Golay is D_{eff}-dependent
- Labor moves Golay benefits to larger D_{eff}
- Golay's sacrifice Encircled Energy





EE=83.5% | EE=26.4% | EE=9.3% | EE=3.6% | EE=2.2%



Technological Trends

- Lightweight (Low-Area-Density) Optics - 15kg/m^2
- Deployable Optics
- Adaptive and Active Optics
- Membrane Mirrors and Inflatables
- Ultra-Large Arrays (CCD Mosaics)
- Distributed Optical Arrays
- Space Based Astronomy
- White light interferometry

Optical Performance Criteria

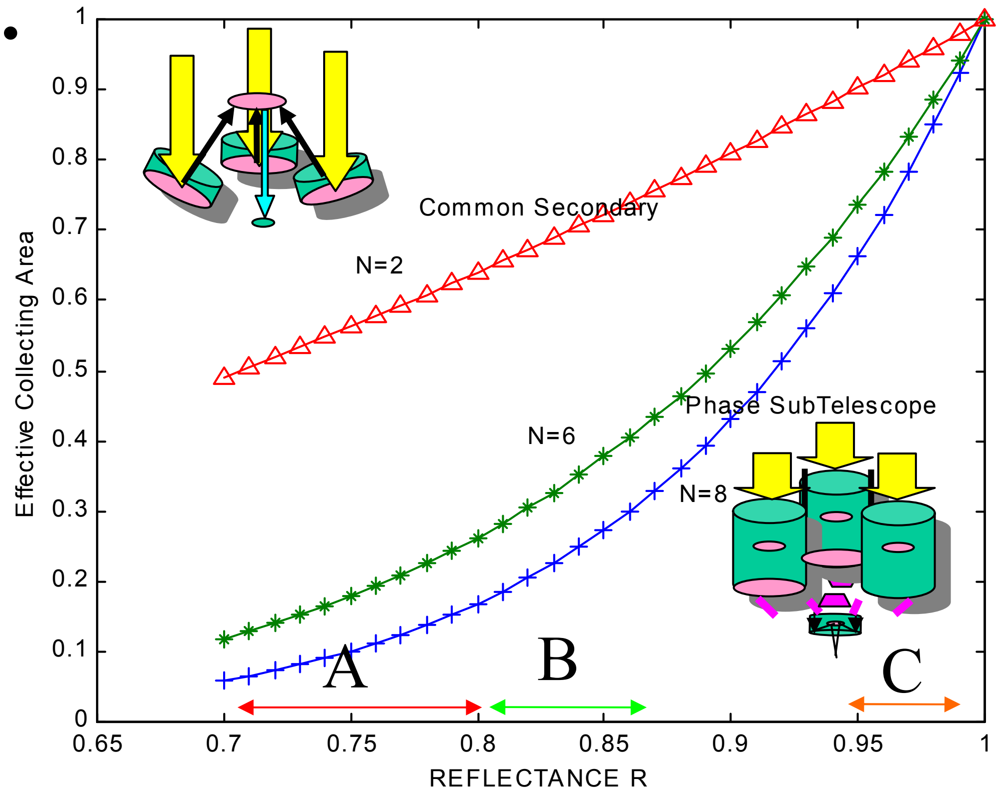
- Sensitivity(Effective Collecting Area)
- Point Spread Function(PSF): Frequency used merit function(Irradiance distribution),Can measure Phase difference, can derive Resolution,EE, MTF(OTF)
- Encircled Energy: particularly relevant merit function of the optic performance of an optical system whose purpose is to collect light and direct it thru the entrance slit of a spectrometer
- Modulation Transfer Function(MTF): For many imaging applications involving extended objects containing fine structure, the MTF is a more appropriate performance criterion than PSF. Practical Cutoff Frequency(Fr) -> Cutoff Frequency(Fc)

Optical Sensitivity

- Sensitivity of Phased Telescope Array (Effective Collecting Area)

$$A_{eff} = A_{geo} R^N$$

R: the reflectance
N: the number of reflections

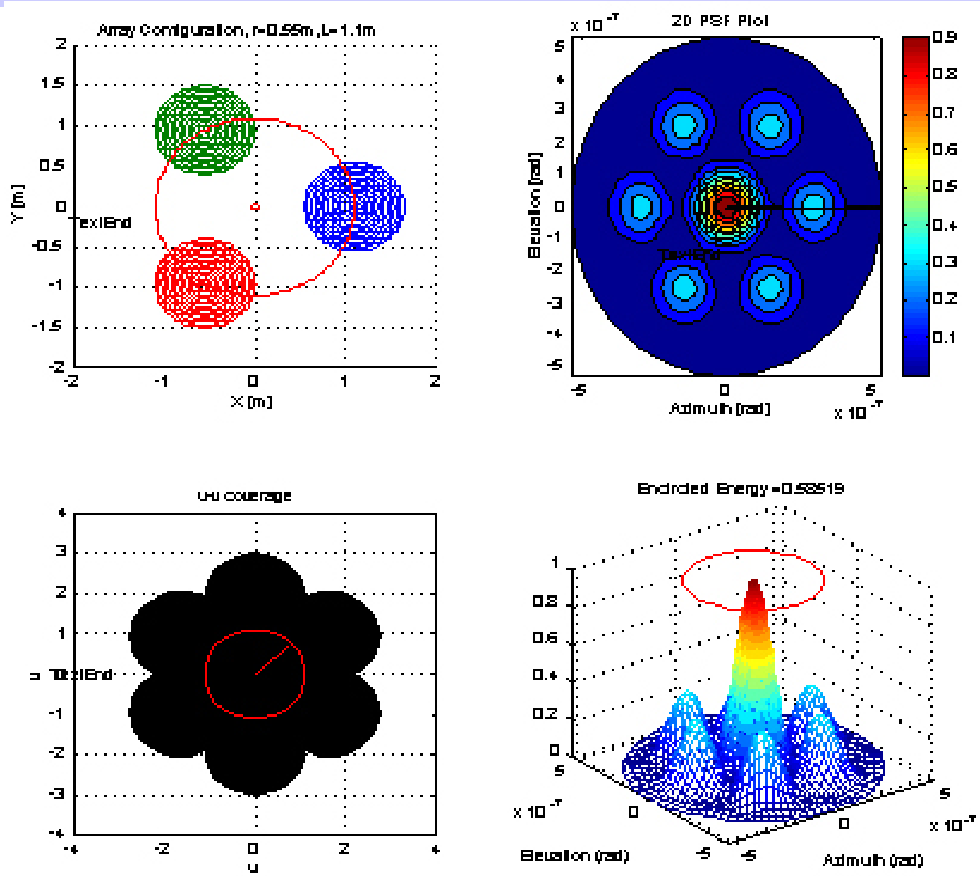
- 

2 types may be viable concept for quasi-monochromatic applications; however, phased telescope arrays will suffer substantial sensitivity losses for broadband spectral applications

A Region: UV
B Region: Visible (Color)
C Region: Quasi-Monochromatic

PSF,EE (Golay Array –3)

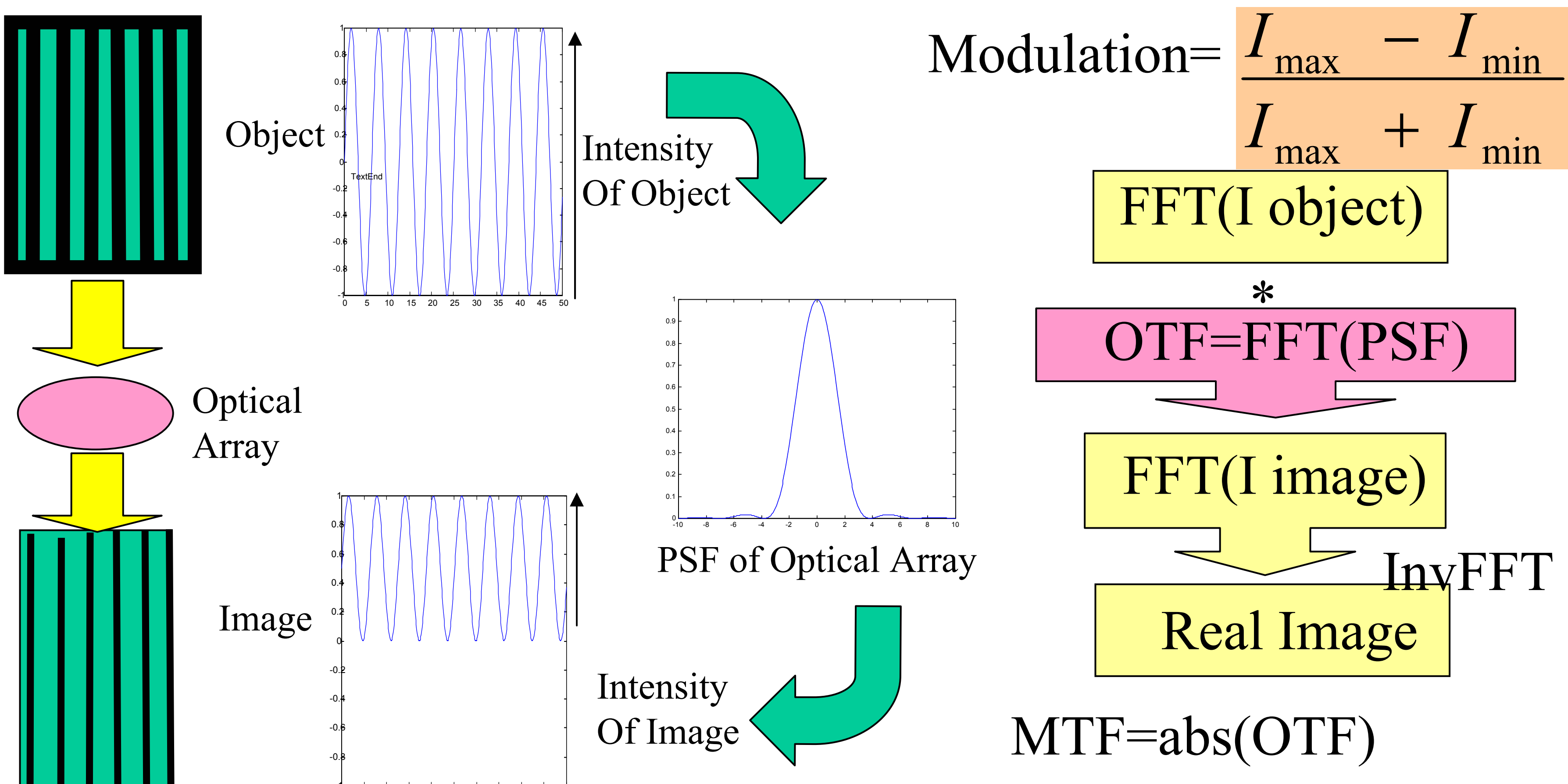
Preliminary Calculation(0.3m GR) => D=2.0m,approx needed !!
For Reff=1m, r=0.5m and Array Radius(L)= 1.m (Golay 3,monochrome)
r=0.3685m and Array Radius(L)= 1.1m (Golay 6,monochrome)



Using Analysis Tool:
Evaluate Configuration Using
- PSF(Point Spread Function)
- Encircled Energy
- MTF(Modulation Transfer Function)
- FF(Fill Factor)

Modulation Transfer Function

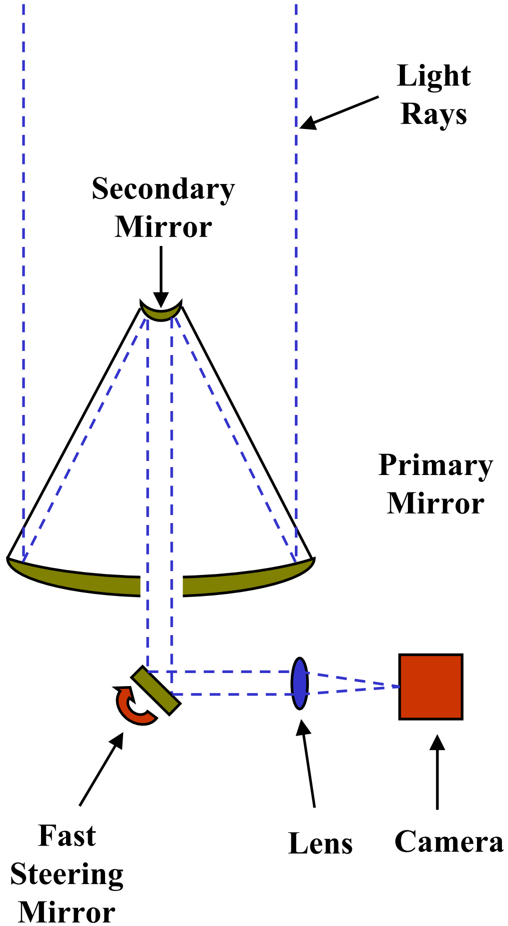
- An image of an extended object is far more complex thant point source(e.g) astrometry. PSF is not enough! -> MTF of each configuration is necessary
- Both Resolution and Contrast (Modulation) Transfer IMPORTANT



Optical Control and Beam Combining

- Optics Control
  - Actuators
    - Piezoelectric translators (PZTs)
    - Fast steering mirrors (Tilt and Tip)
    - Optical delay lines (or inchworm positioners)
    - Alignment mirrors
  - Sensors
    - Laser interferometers
    - Quad cells
    - Charge Coupled Device (CCDs) cameras
    - Avalanche Photo Diodes (APDs)

Fine Optical Pointing and Phasing: Single Aperture



- Light path
  - Light enters spacecraft by reflecting off primary and then secondary, after which it is collimated (not converging or diverging except for diffraction effects)
  - Reflects off two-axis (tip and tilt) Fast Steering Mirror (FSM)
    - FSM controls out the low level line-of-sight (LOS) jitter in the deadband of the attitude control
  - Lens focuses light onto camera
- LOS jitter control using FSM
  - Feedforward attitude sensors to command FSM
  - If bright point source in FOV, measure motion on camera and command FSM to minimize its motion

Beam Combiner

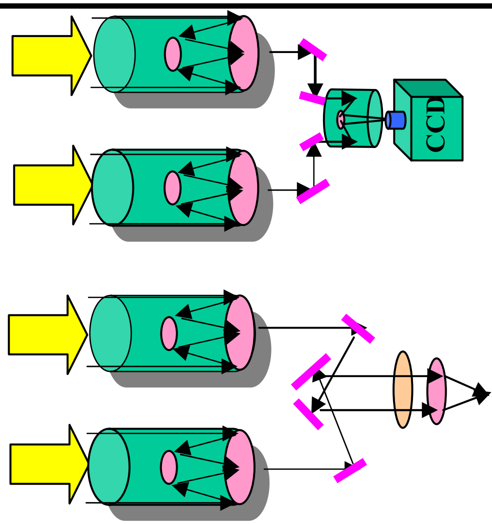


Fig.10, Cassegrain Type beam combiner (above) and refractive lense combiner

<u>Phase(Piston Error) Contributor:</u>

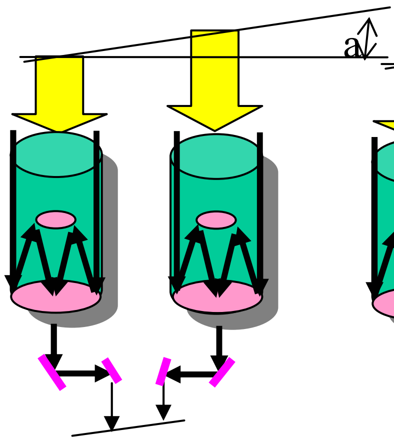
1. Lateral Pupil Geometry Error (Pupil Mapping Error)
   =>the elimination of this error : golden rule of separated telescope (significant in wide field of view telescope)
2. Piston Error: part of piston error is induced by pupil geometry e
3. Tilt Error : Measured separately from piston error. X-Tilt Error, Y-Tilt Error

<u>Beam Combining Goal:</u>

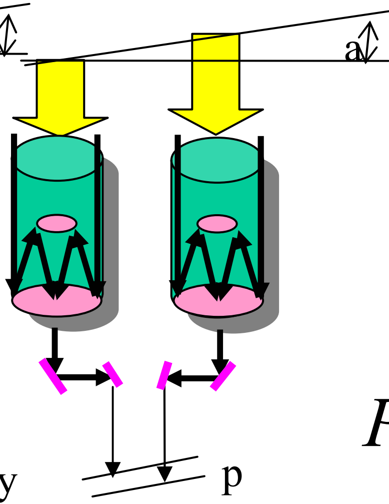
1. maintain the optical phase difference of each beam to a fraction of a wavelength
2. align images from telescopes to within a fraction of a resolution element over the whole field of view

(Additionally) Field of curvatures on the order of wavelength, finer than required for conventional telescopes

Lateral Pupil Geometry Error



Correct Pupil Geometry

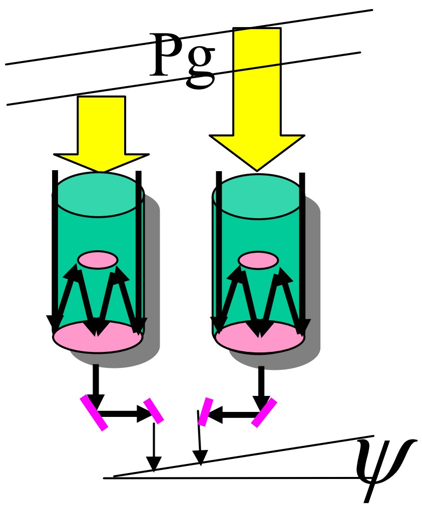


Incorrect Pupil Geometry

Physical Meaning:

If the subapertures of the entrance pupil have a D, and separated by S, with magnification M, the exit pupil must have dimensions for D/M and separation S/M

$$P = \varepsilon \sin(aM)$$



$$P_g = \varepsilon \sin(\frac{\psi}{M})$$

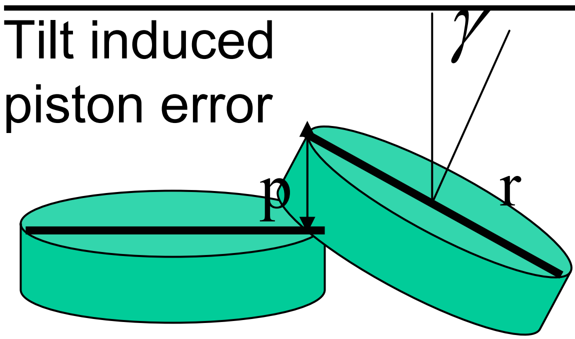
ε :lateral pupil geometry error

Difficult to measure lateral pupil geometry => abstract optical quantity

Use the relationship and Kalman filter to estimate ε

Optical Tolerance

Tilt induced piston error



$$P_t = r\sin(\gamma)$$

Total Piston Error

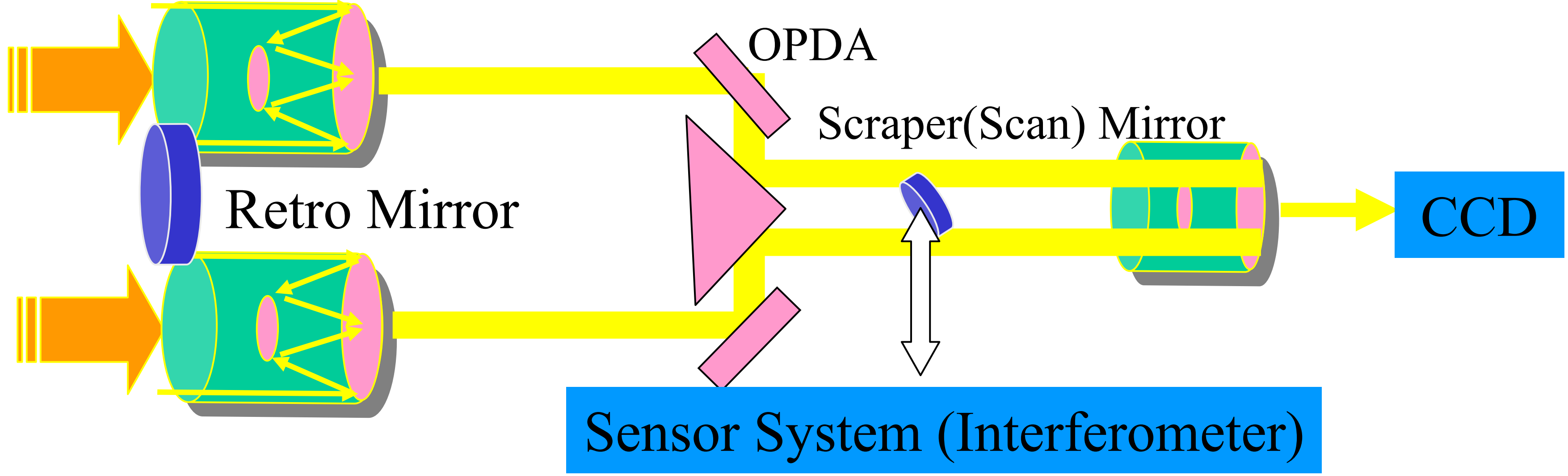
$$m_p = p_t + (p_g + p)$$

$$= r\sin(\gamma) + [\varepsilon \sin(\frac{\psi}{M}) + p]$$

P :the optical path difference between beams

Errors	Tolerance
Piston	1/10 of wavelength = 55 nm
Tilt	1/10 of λ, r=0.5m => 110 nrad
Lateral pupil Geometry Error	FOV=4km,h=500km,piston error55nm =>1μm
Alignment Error (Image Rotation)	<1/10 of Airy Disk Diameter $\Delta\Phi < \frac{(0.1)(2.44\lambda)}{FOV_{HalfAngle} D}$ => 33 μrad

Beam Combining Layout

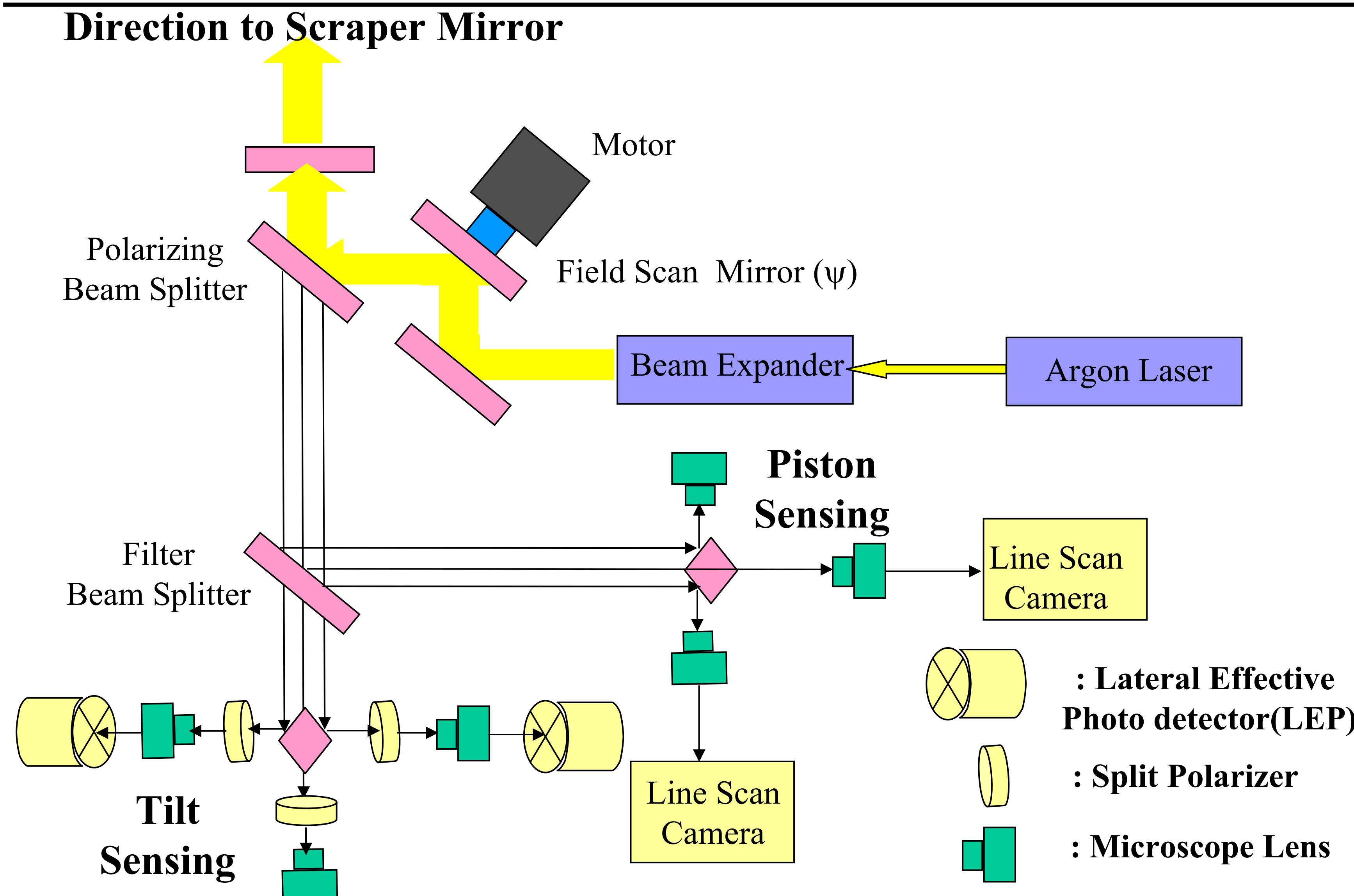


OPDA(Optical Path Difference Adjuster) :is driven by

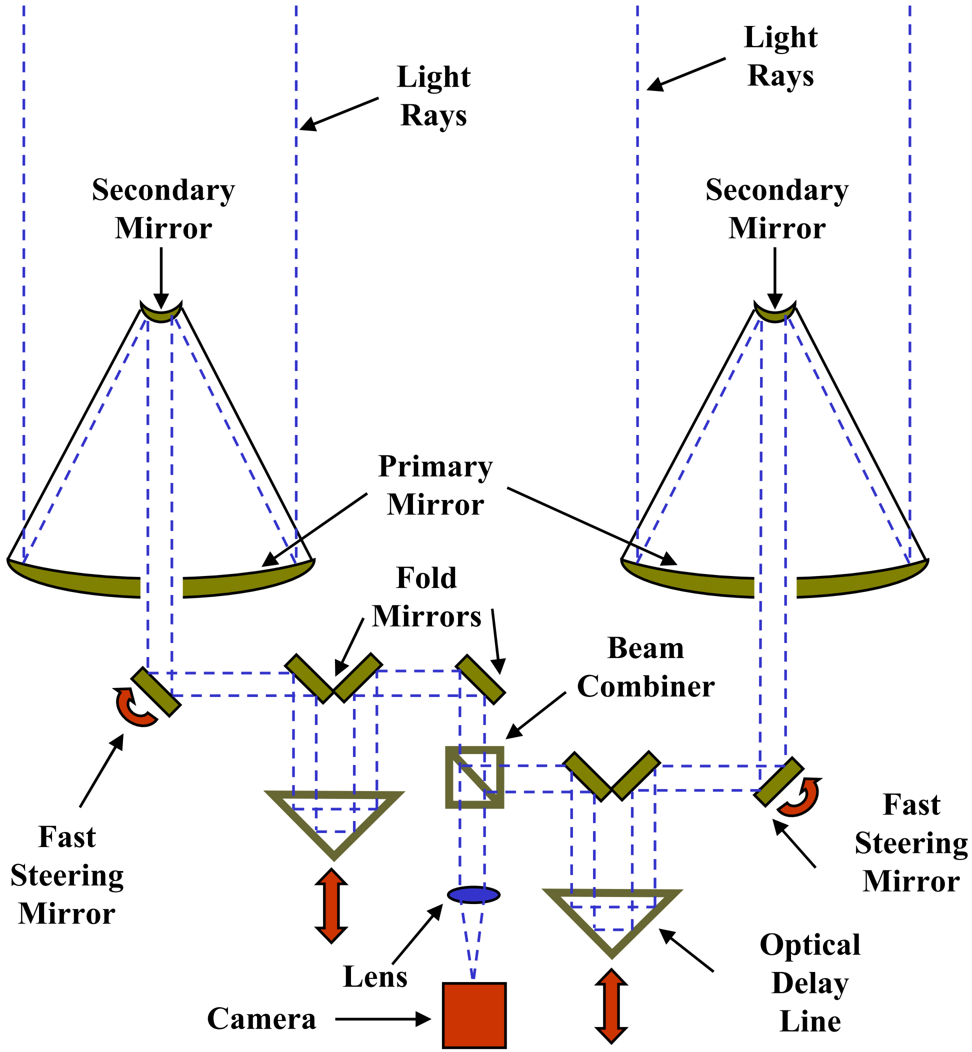
•Piezoelectric translator(PZT) = Fine Control
Translation Range (-12 μm),Resolution(5nm), SlewRate(4.5 μm/s)
Angular Tilt Range(700 μrad),Resolution (200 nrad)

•Burleigh inchworm positioners = Coarse Control
Translation Range(5mm) with a resolution of 0.1 μm

Sensor System Optics(Example from AFRL)



Fine Optical Pointing and Phasing: Multiple Aperture



- Now need to stabilize both absolute and relative LOS jitter (Differential Wavefront Tilt)
- Also need to interfere same wavefront of light at combiner
  - Use Optical Delay Lines (ODLs)
    - ODLs add and subtract optical pathlength from the companion telescope to the combiner.
    - Used to control small positional mis-alignment and S/C attitude error
    - Typically a multi-stage device with voice coils and piezoelectrics

References

[1] Larson, W.J., Wertz, J.R., "Space Mission Analysis and Design", Second Edition, 9.5 Designing Visual and IR Payloads, pp.. 249-274, Microcosm, Inc,1992

[2] Born Max, Wolf Emil, "Principles of Optics", Electromagnetic Theory of propagation interference and diffraction of light, Sixth Edition, Cambridge University Press, 1998

[3] Hecht E. "Optics", Addison-Wesley, 1987

[4] Günter Diethmar Roth, "Compendium of Practical Astronomy", Volume 1, Instrumentation and Reduction Techniques, Springer Verlag, Berlin, New York, ISBN 3-540-56273-7, 1994

Optical System Design Process

From SMAD Chapter 9

1. Determine Instrument Requirements
2. Choose preliminary aperture
3. Determine target radiance
4. Select detector candidates
5. “Optical Link Budget”, SNR considerations
6. Determine Focal Plane architecture and scanning schemes
7. Select F# and telescope/optical train design
8. Complete preliminary design and check MTF
9. Estimate weight, power and ACS requirements
10. Iterate and document - code optics software module