Lecture 2

Telescope architectures

University of Arizona

January 23, 2013

Dr. James Breckinridge

Adjunct Professor

College of Optical Sciences

jbreckin@optics.arizona.edu

Today

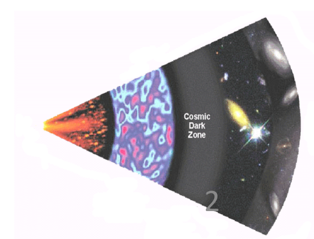
Thursday, January 23, 2014

- Work breakdown structure
- Telescope system architectures
  - Filled, segmented, sparse, interferometers
- Requirements development
  - Science measurements, technology risk map science into realized engineering

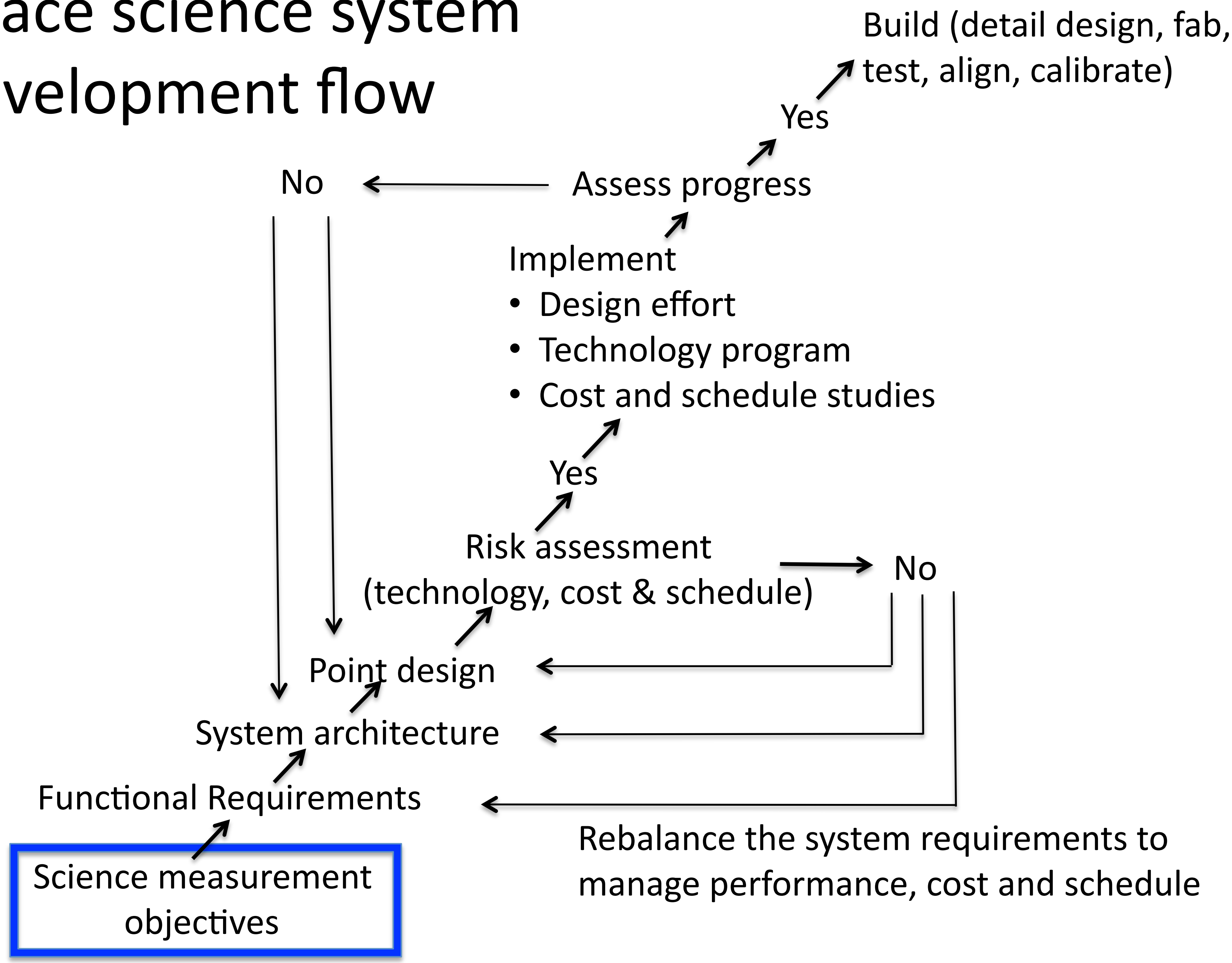
****

- Diameter increases angular resolution
- Area increases radiation collected – more power

Today



Space science system development flow



How do we build a large, complicated system?

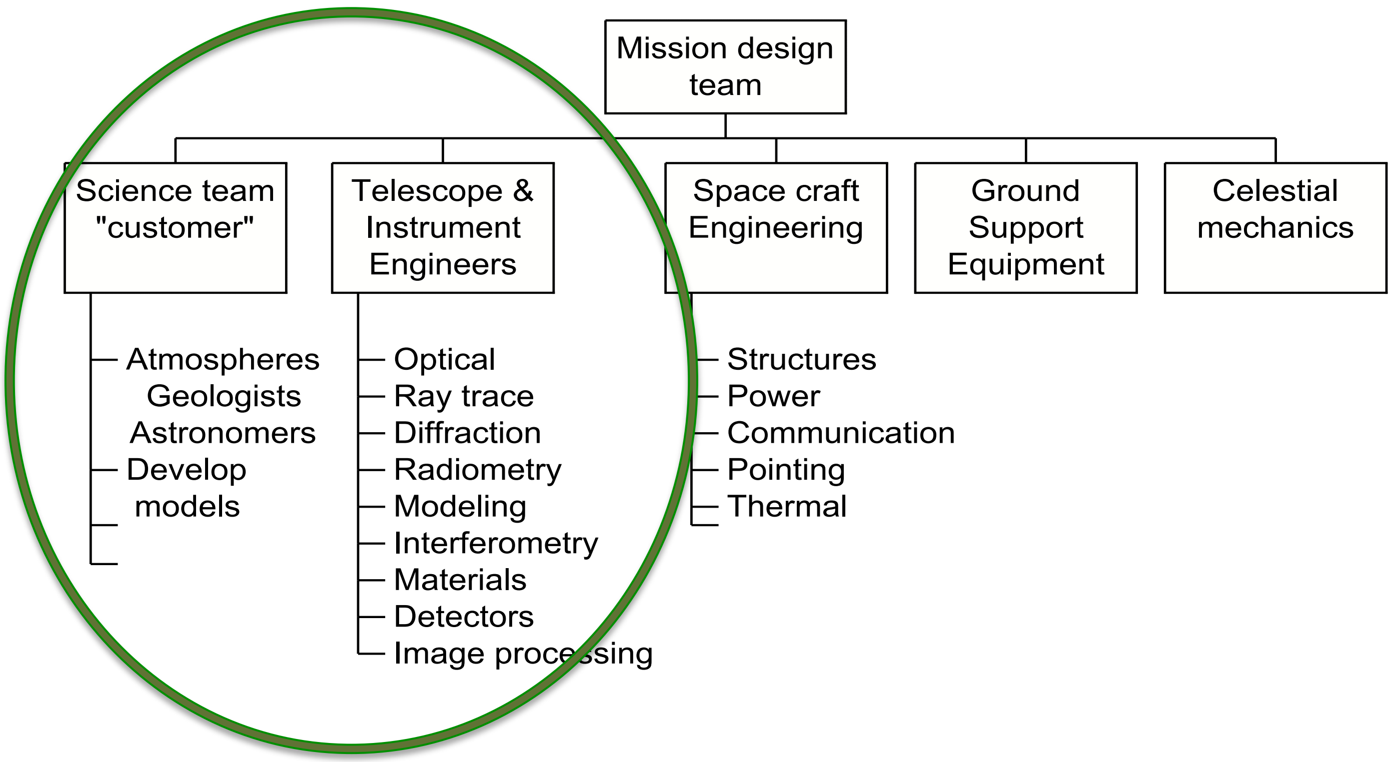
- Create a work-breakdown structure (WBS)
- Assign personnel to jobs in the WBS you know they can do – or accept responsibility to do
- Create a work plan with schedule, cost and performance
  - Develop a list of tasks that need to be done
  - Negotiate with your team who is going to do which task
  - Ask each one how long it will take them to do their tasks and what the cost is

What is a work break down structure?

- Identifies all tasks required
- Presents tasks in a format aligned with doing the work
  - talent, skill level and software & equipment
- Provides a structure for the schedule
- Every WBS is different because no two telescopes, instruments, staffing and facilities are the same.
- Create a WBS to enable you to manage success of the project/task
- Now you have a plan to move forward

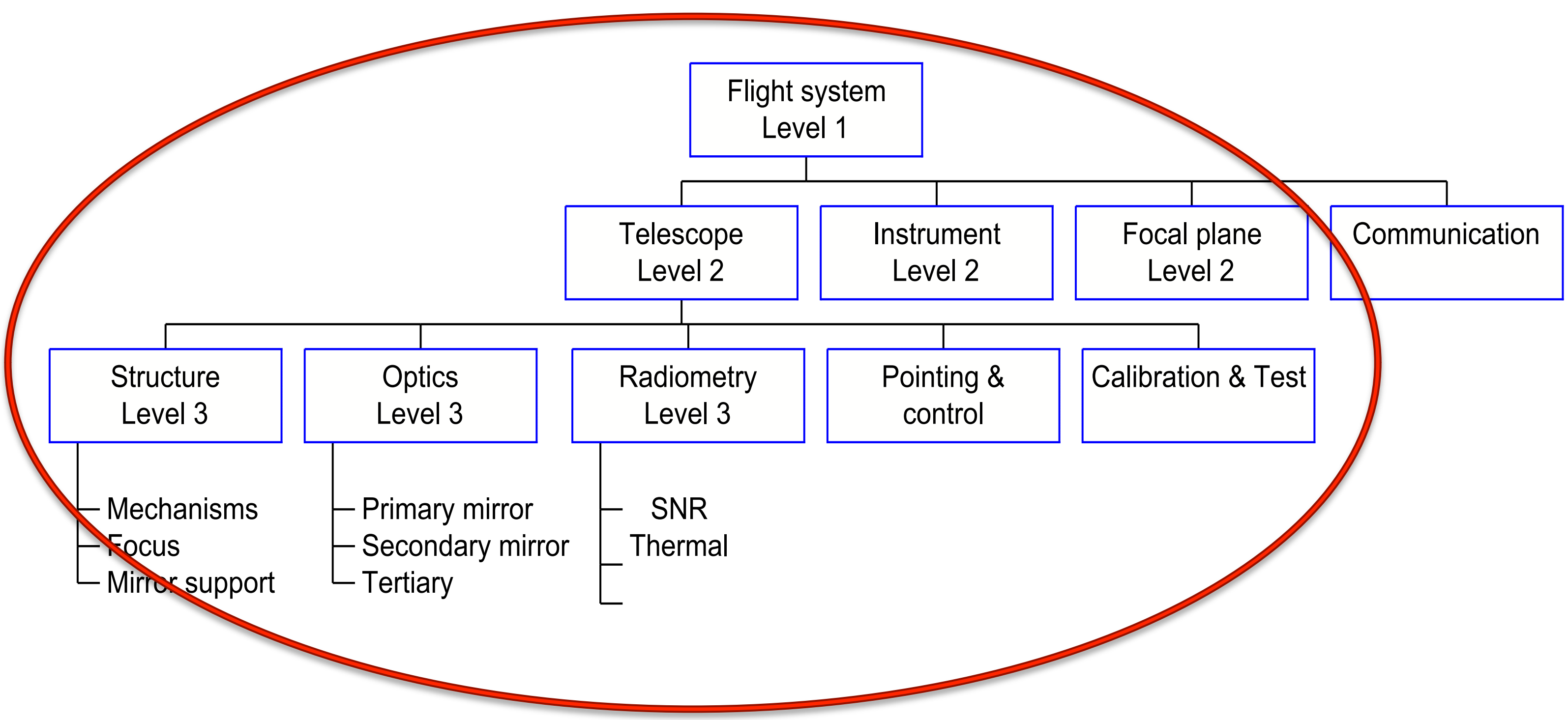
Mission development

- Create ideas for new missions to make new high priority measurements
- Develop justification for the mission
  - Performance, schedule, cost

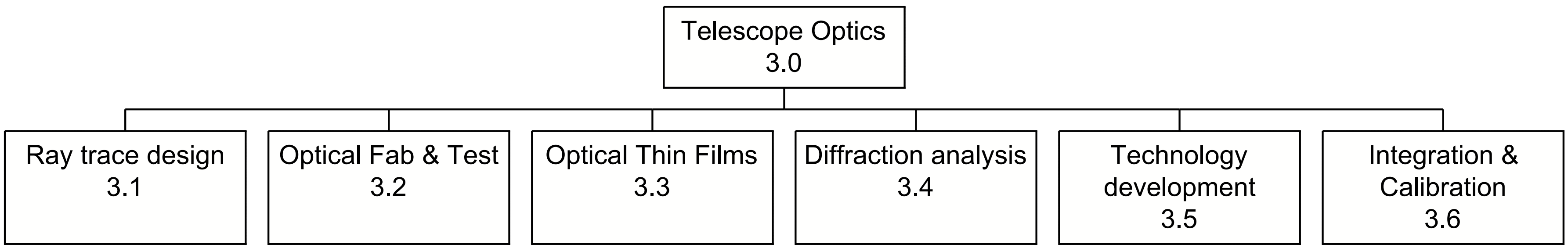


Where do we start?

- Develop system requirements
- Divide the system up into manageable subsystems
  - Work break-down structure
- One person's subsystem is another person's system.



Example WBS



Each box is assigned a leader & given a $$ budget to accomplish work

Tasks accept work from others, provide additional work and then makes deliveries of his product

Project Milestones

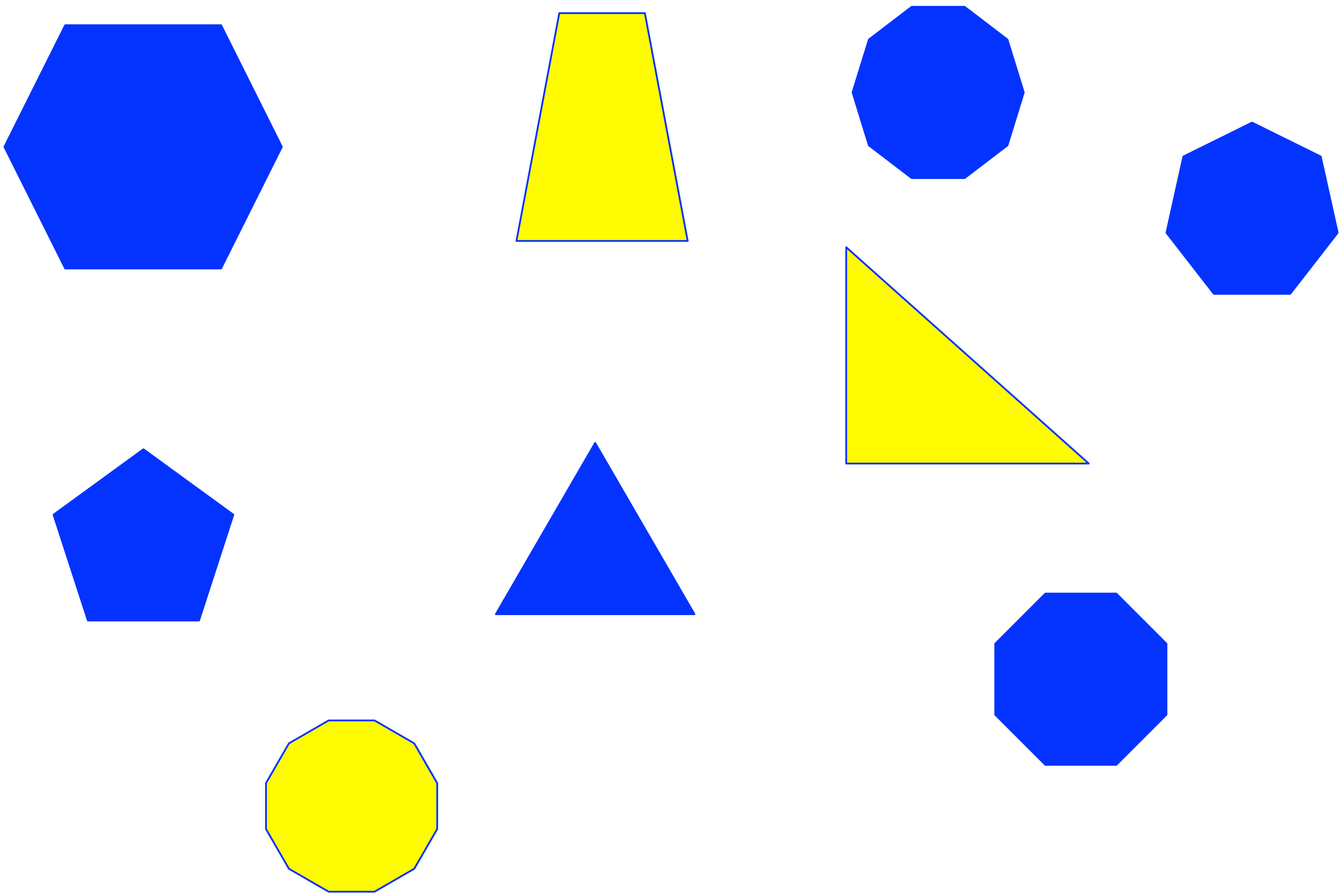
1. Mission concept review (MCR)
   - Science clearly stated measurement concept
2. System definition review (SDR)
3. Preliminary design review (PDR)
   - Assembly drawings
4. Critical design review (CDR)
   - Detail design complete ready to "cut metal (glass)"
5. Pre-ship readiness review

How do we create a "point design"

Telescope aperture

- Cannot always afford a monolith
  - Replace the stiffness needed for an optical telescope with electronics
    - <u>Wavefront sensing & control</u>
    - <u>Optical metrology</u>
- Segmented
- Sparse
- Interferometry
  - Spatial interferometry
  - ~~Temporal frequency interferometry (FTS)~~

Segmented telescopes

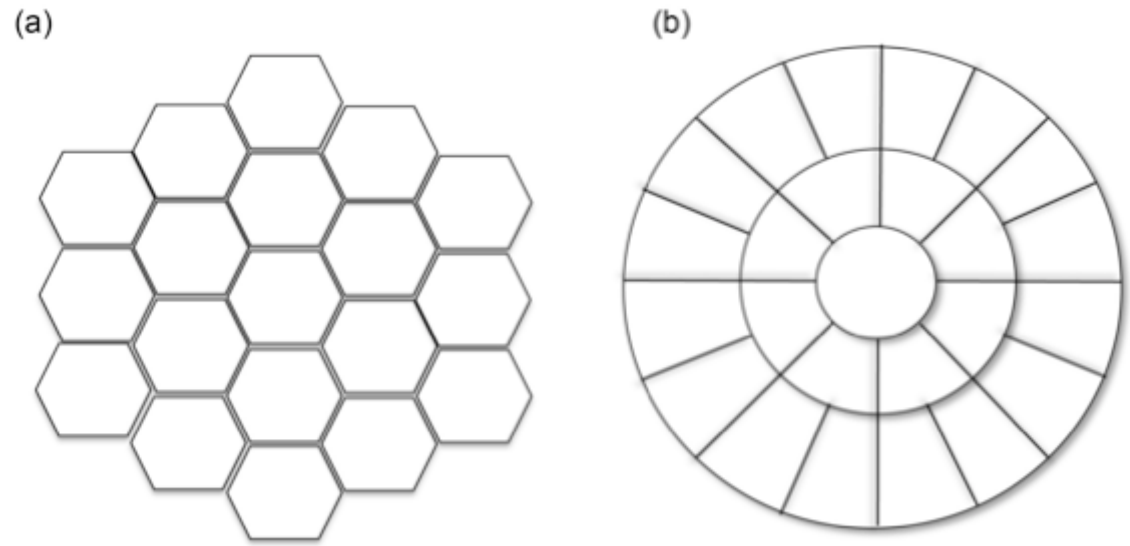


Segmented primary mirrors

- A segmented primary mirror is used for several reasons:
  - A single monolithic mirror is too heavy for a cost-effective ground or space telescope
  - The telescope needs to fold up to occupy a smaller volume for those launch vehicles that are volume-shroud constrained (inexpensive!)
  - Fabrication of the segmented large primary mirror can be achieved with ease and speed
  - The aperture is too large to launch all in one piece and mirror-sats with assembly in space is used to make the telescope

Segment the primary mirror (pupil)

K_{rings} is given by $K_{segments} = 3K_{rings}\left(K_{rings} + 1\right)$



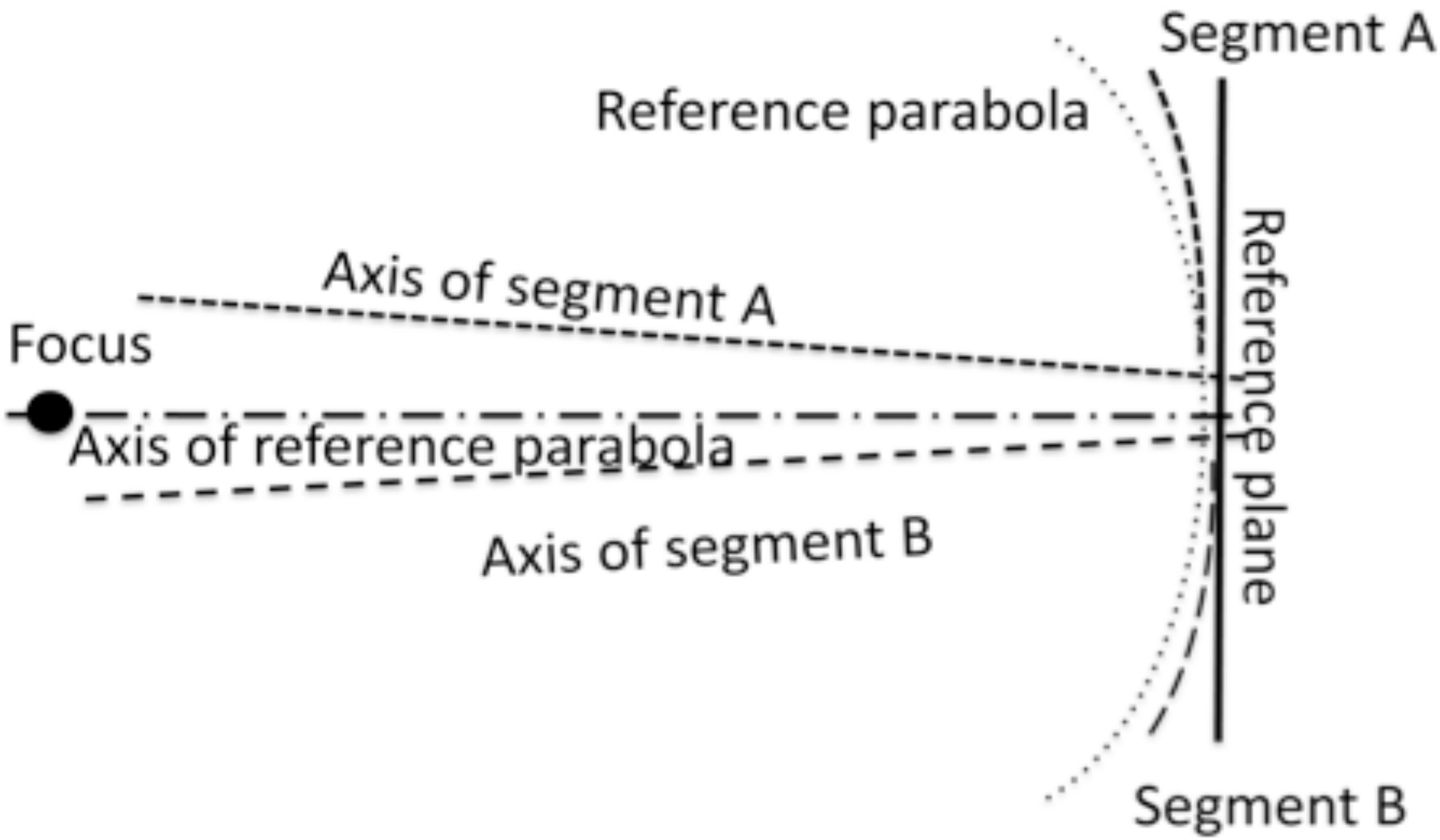
The side length l of the hexagon required for an equivalent circular area D is given by

$$l = D\sqrt{\frac{\pi}{6\sqrt{3}\cdot K_{segments}}}.$$

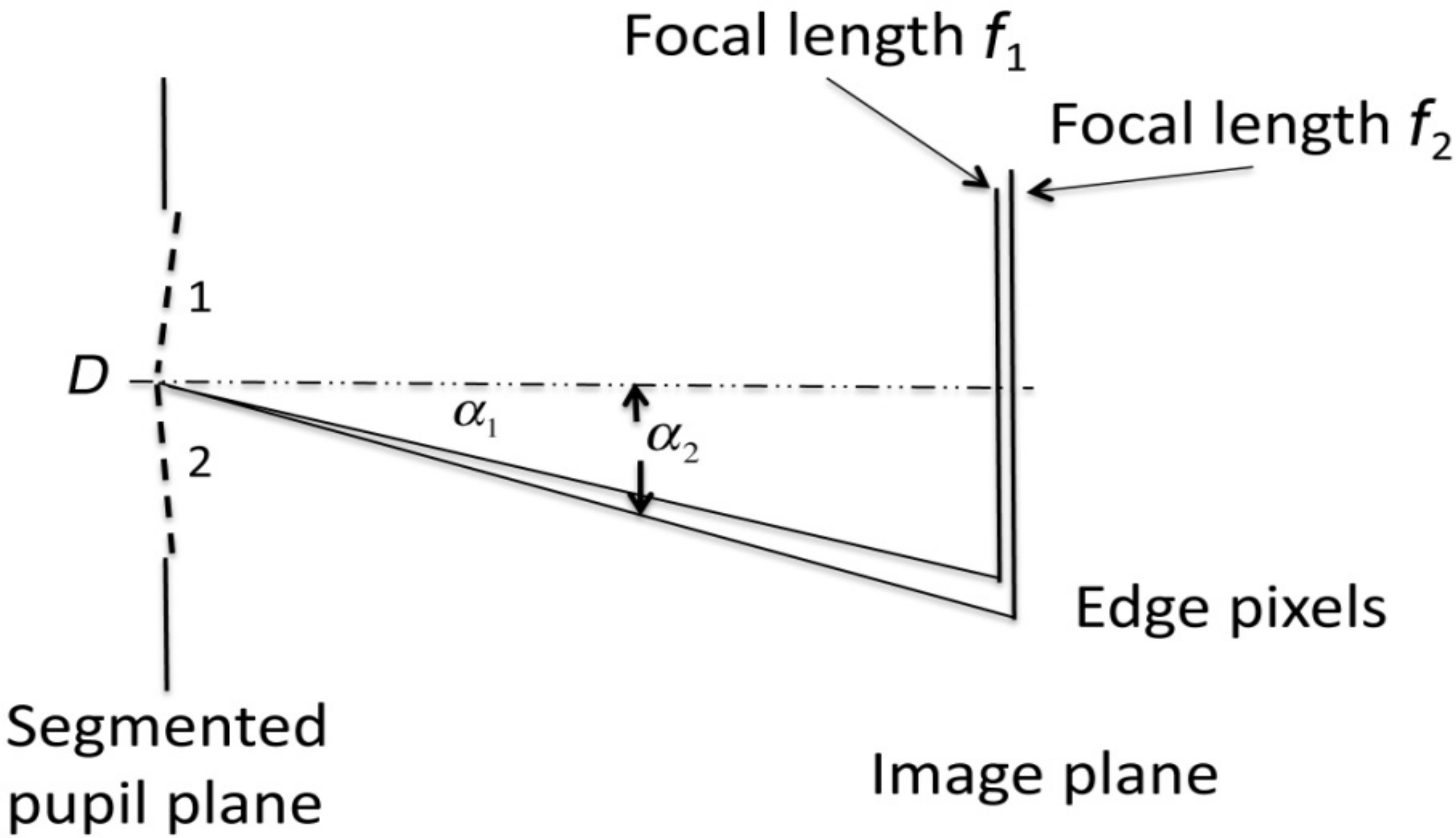
Alignment issues

- The surface of each segment is an off axis section of a conic (parabola or hyperbola)
- Each segment has its own optical axis
- These axes all need to be aligned collinearly
- Each curved surface needs to lie on an imaginary conic surface to within a few microns error

Segment radii of curvature tolerance



Tolerance on the radius



Tolerance on the radius of curvature match of the segments depends on the field of view required

Figure shows a pupil plane of diameter D and two image planes. One image plane, indicated by focal length f_1, is shorter than the second focal plane of focal length $f_{2.}$. The image plane scale for the two focal lengths is, of course, different; one focal plane is shown larger than the other. The chief ray makes angle with the axis for image plane formed by focal length f_1, and the chief ray makes angle with the axis for the image plane formed at focal length f_2. As an example, we will consider a particular case. Assume the following system parameters:

Tolerance on the radius of curvature match of the segments depends on the field of view required

The segmented mirror has an outside diameter *D* of 10 m.
The effective focal length (EFL) of the telescope is 60 m.
There are no off-axis aberrations.
We use an 8192×8192 pixel focal plane.
The field of view radius in units of pixels is equals
5,792 pixels.
The pixels are 4-µm pitch in size, so the field of view radius *r*, center to edge at the image plane is 23.2 mm.

The diameter *d* of the diffraction spot is given by

$$d = \frac{2.44\lambda}{D} \cdot 60 \text{ m} = 7.3 \ \mu\text{m}$$

.

Tolerance on the radius of curvature match of the segments depends on the field of view required

If r_1 and r_2 are the heights (radius from the axis to the corners) of the image for the system with focal length f_1, and for the system with focal length f_2, respectively, then we can write

$$r_1 = \alpha_1 \cdot f_1 \text{ and } r_2 = \alpha_2 \cdot f_2$$

If we assume that an image quality analysis will allow for the 4-µm square pixel to have an allowable error of 0.2 pixels, then the allowable shear error between the two planes is 0.8 µm at maximum,

$$r_1 - r_2 = \Delta r = 0.8 \ \mu\text{m}$$

Tolerance on the radius of curvature match of the segments depends on the field of view required

We see that

$$\Delta r = \alpha_2 \cdot f_2 - \alpha_1 \cdot f_1$$

It is reasonable to assume that $\alpha_1 \cong \alpha_2 \cong \alpha$; therefore,

$$\Delta r = \alpha \left(f_2 - f_1 \right)$$

.

$$\Delta r = \frac{r}{f} \cdot \Delta f \text{, then } \Delta f = \frac{f}{r} \cdot \Delta h$$

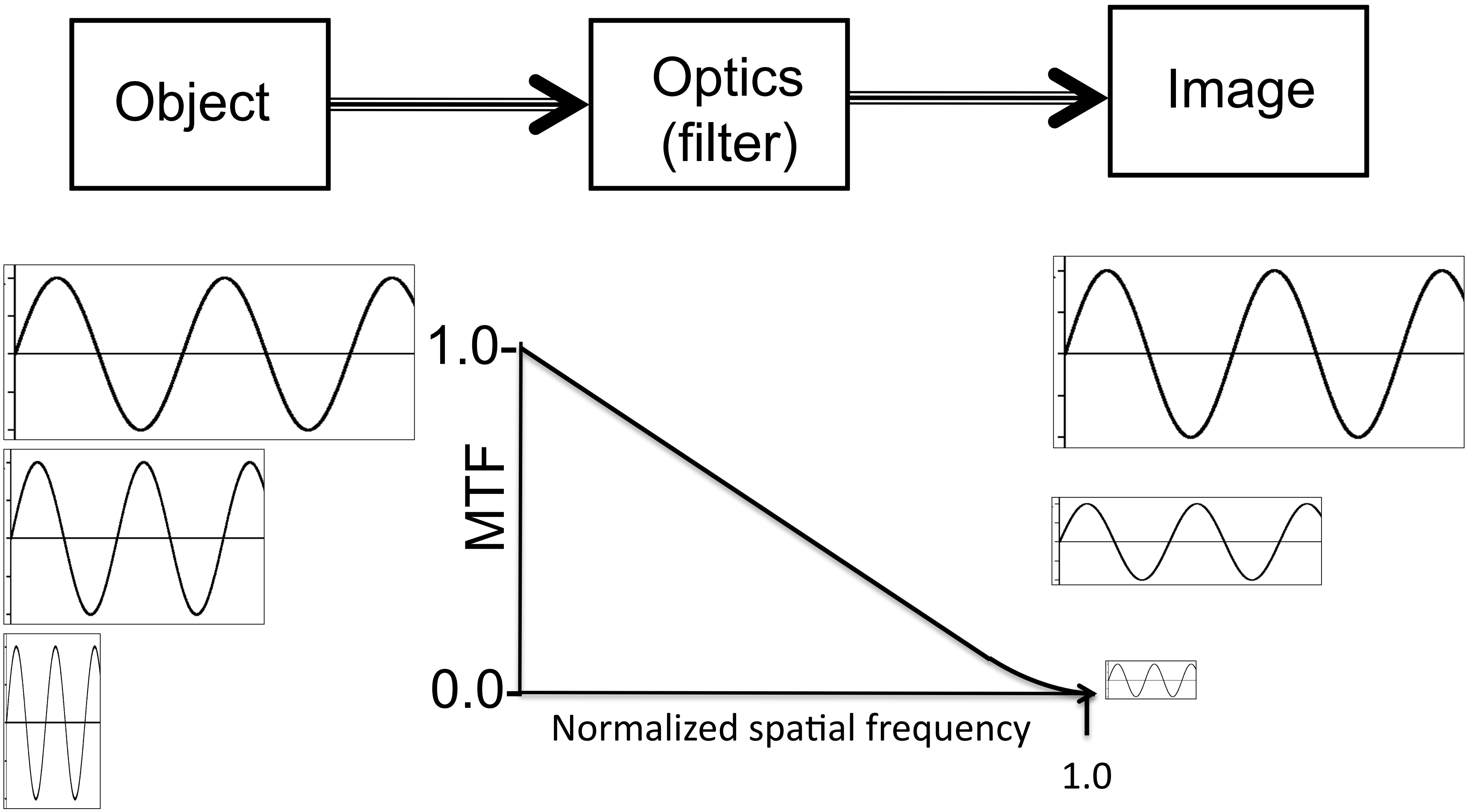
$$\left| < f > - f_k \right| < 2.0 \text{ mm}$$

Discuss the spatial stationarity of the image

Segmented telescopes

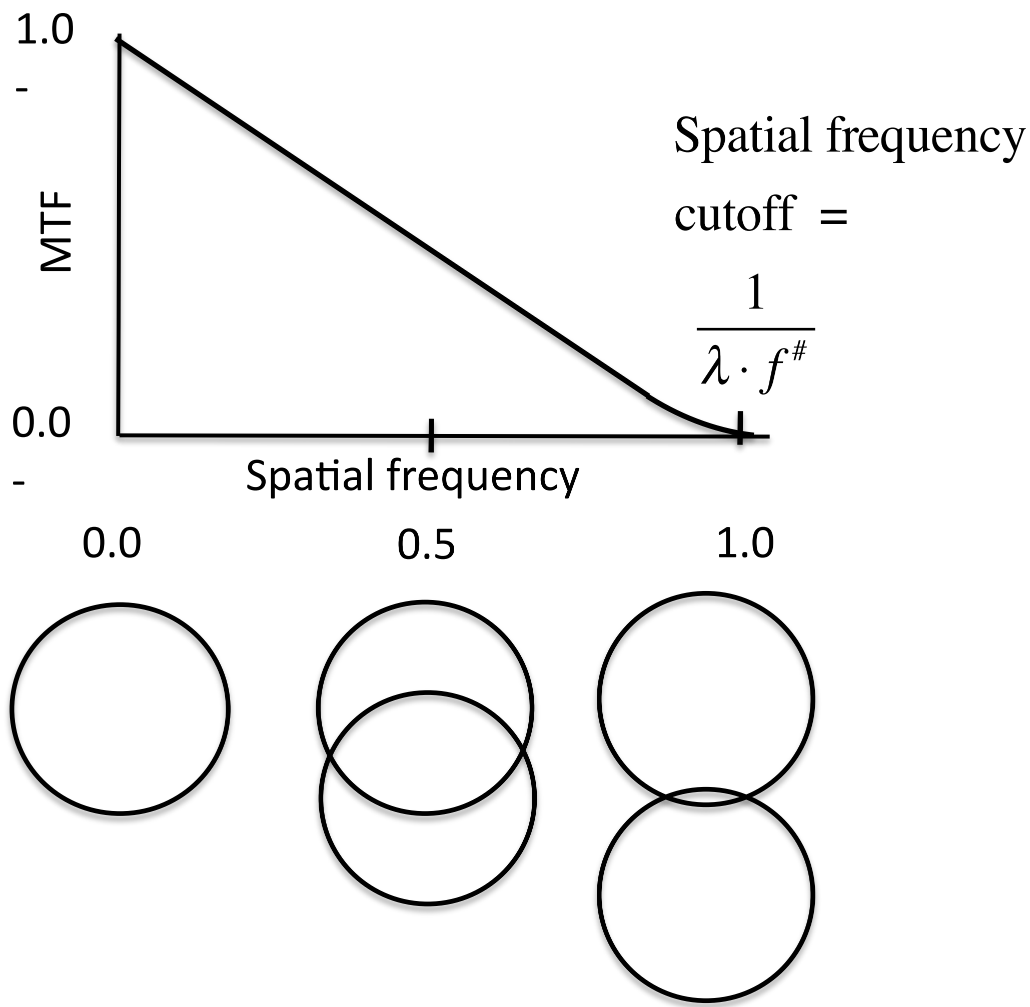
- JWST
- Keck 1 and Keck 2
- Next generation 16 meter (ACCESS)
- Others

The telescope is a spatial frequency filter



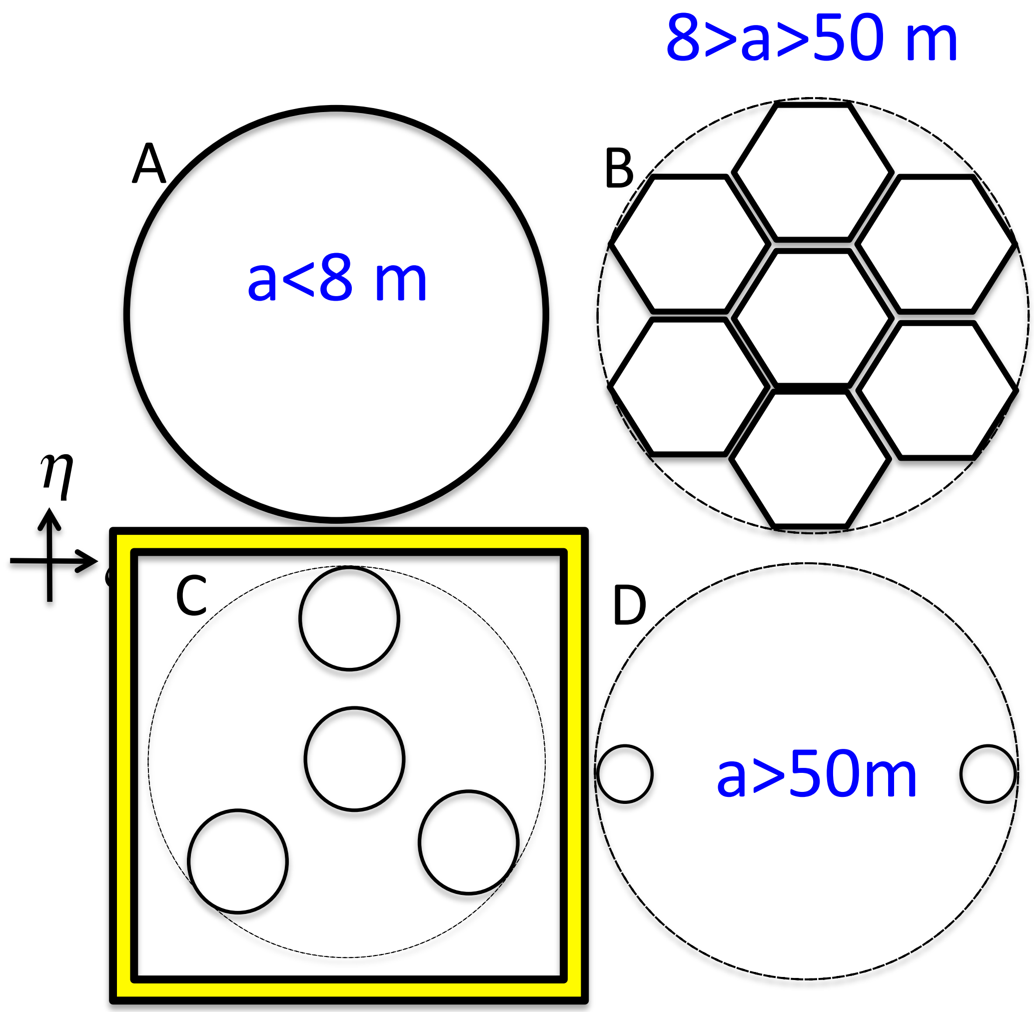
The modulation transfer function (MTF) is related to the autocorrelation of the pupil

Assumes a diffraction-limited system



Sparse apertures

- Redundant
- Non-redundant
- Smallest telescopes to reconstruct filled aperture angular resolution



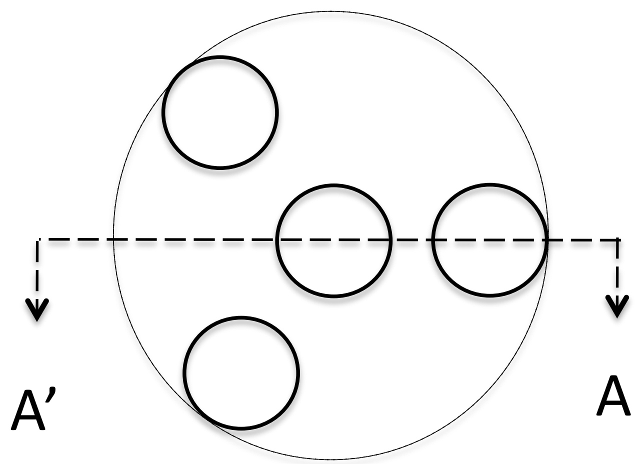
Sparse aperture telescope => PSF?

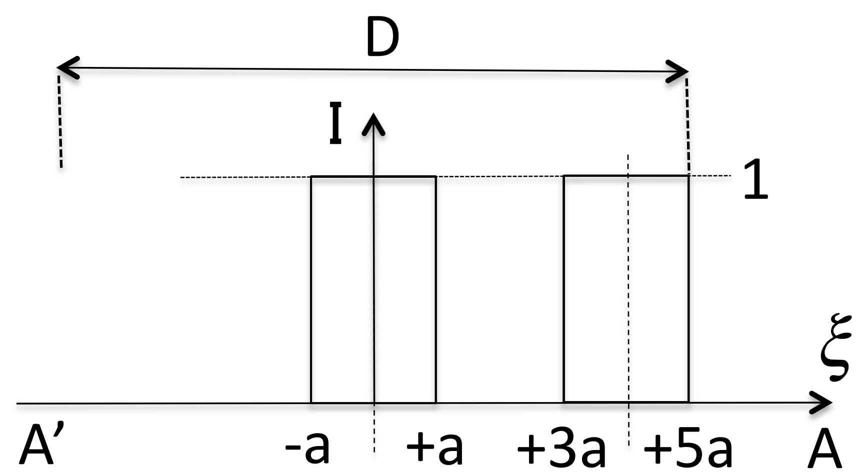
Astronomers recognized in the mid-1960s that an expensive single large-aperture optical telescope could be divided into a series of less-expensive smaller apertures coherently interconnected to provide nearly the same performance as that given by the large single aperture. The penalty was in more-extensive ground data processing to reconstruct an image and extensive real-time controls software and hardware to maintain the alignment of the telescope subsystems. Radio astronomers implemented it first followed 25 years later by optical astronomers.

Sparse aperture telescope => PSF?

In a sparse-aperture telescope we increase the size of the gaps between the reflecting surfaces of a segmented telescope to expand the aperture and increase the angular resolution. In this way, we obtain higher angular resolution but sacrifice the radiation-gathering area of the pupil, which, in turn reduces the system sensitivity at higher spatial frequencies.

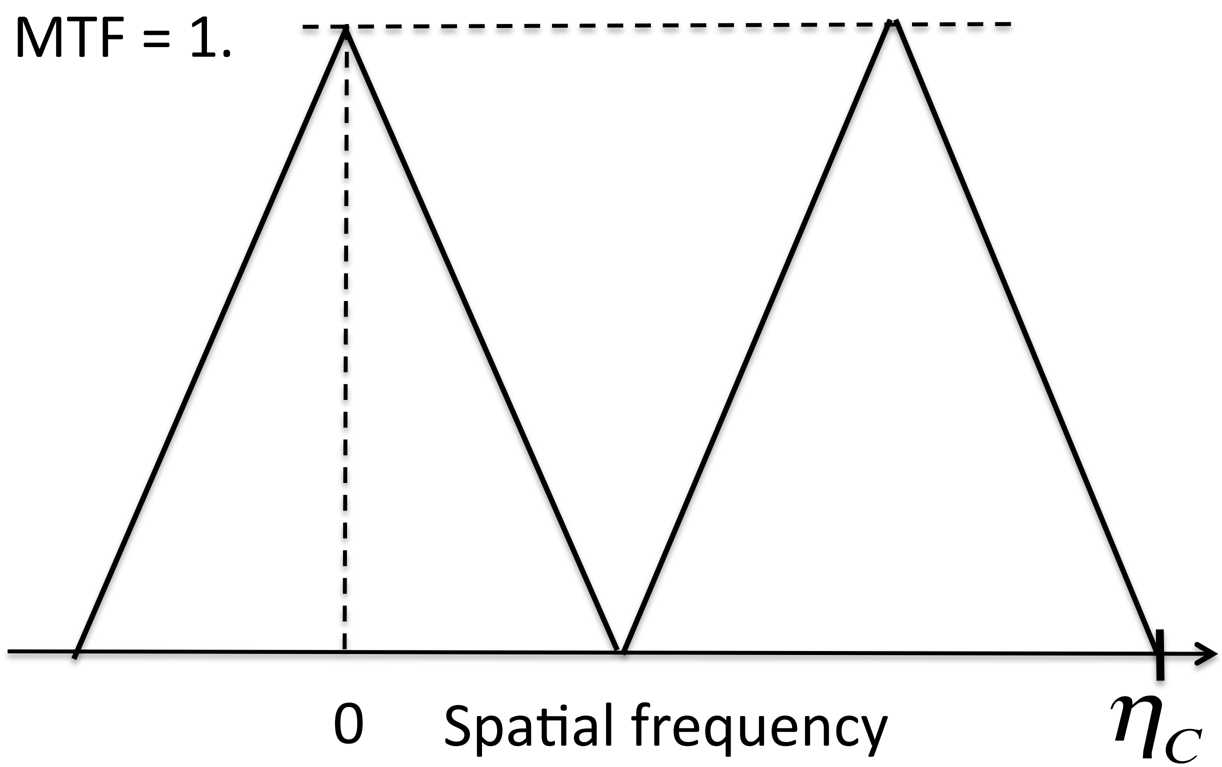
Sparse aperture telescope (pupils)





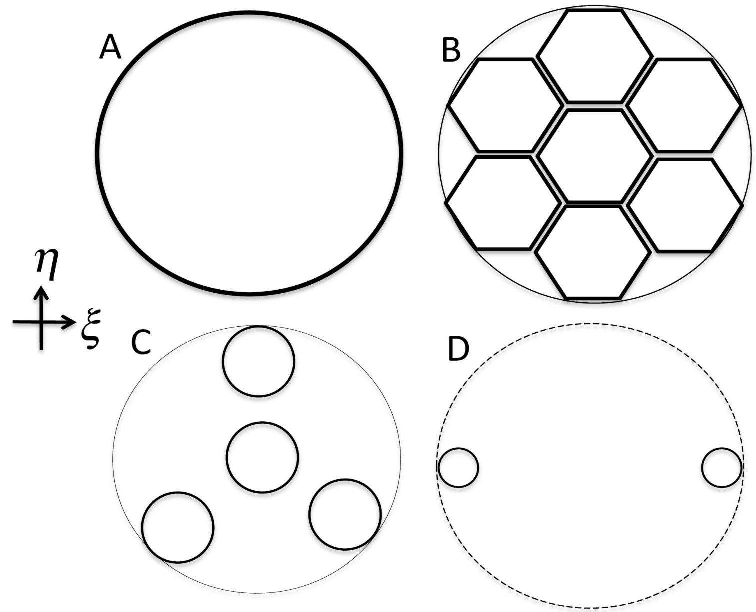
$$T(\xi,\eta) = circ[2a\xi, 2a\eta] + circ[2a\xi, 2a(\eta - 4a)]$$

The modulation transfer function (MTF) is the autocorrelation of the pupil



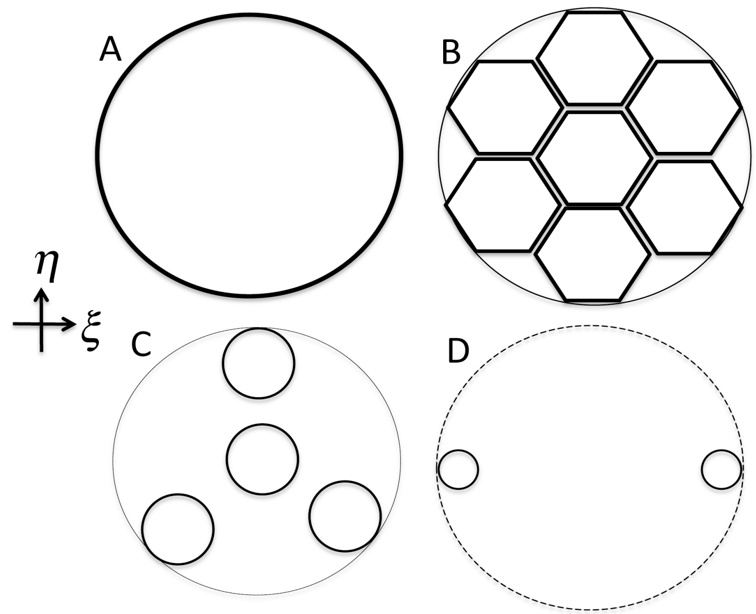
Since they do not overlap the pupil is said to be minimally redundant

Sparse aperture telescope => PSF?



Sparse-aperture optical systems are characterized in terms of redundant and nonredundant apertures, aperture fill factor, and beam recombination geometries. An example of a nonredundant aperture is shown labeled D on the lower right in this figure. This aperture is characteristic of the MSI.

Sparse aperture telescope => PSF?



In theory, aperture D in this figure can deliver the same information to the focal plane as can the filled aperture A. To acquire the same information as that acquired by aperture A, the two areas in aperture D are moved about inside the aperture confines of A and the signals are added after detection. In this manner information at all baselines and azimuths are obtained; however, the noise levels in the image are higher.

Sparse aperture equivalent resolution

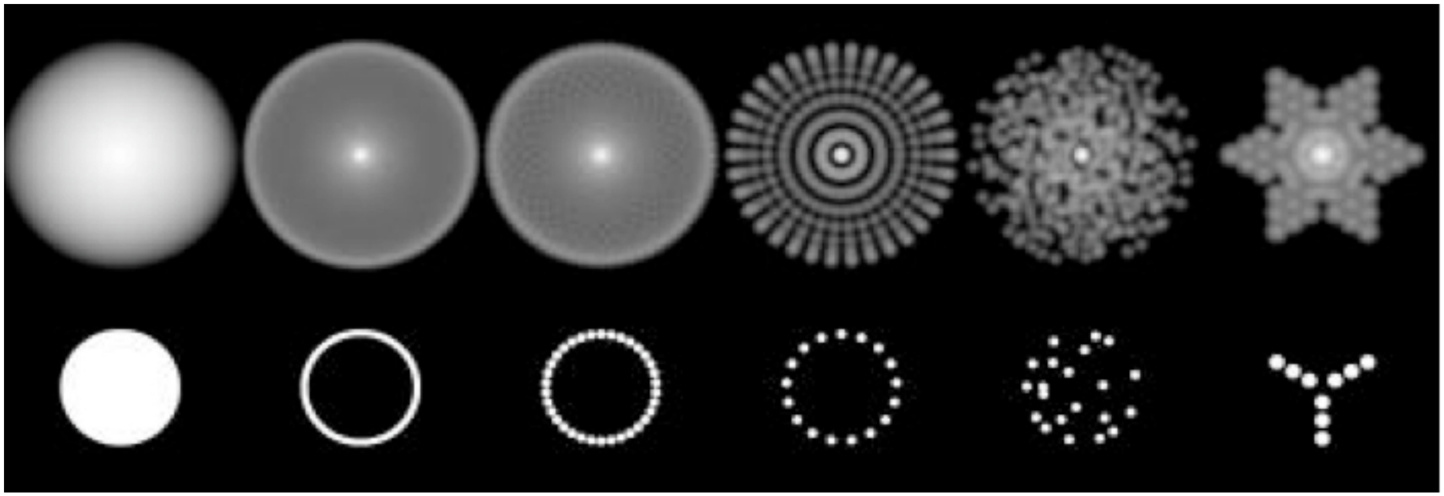
- Aden Meinel in 1970 was the first astronomer to recognize the potential of aperture synthesis to optical astronomy
- Marcel Golay was the first optical scientist that there exists a set of a minimum number pupil topographies needed to fill the ξ, η pupil plane
- These are called Golay apertures

Dilution factor

The aperture is said to be dilute because it is not filled, and a dilution factor *D* is defined as the ratio of the area of the smaller apertures to the area of the larger aperture being synthesized. The dilution factor *D* is often referred to as **fill factor**.

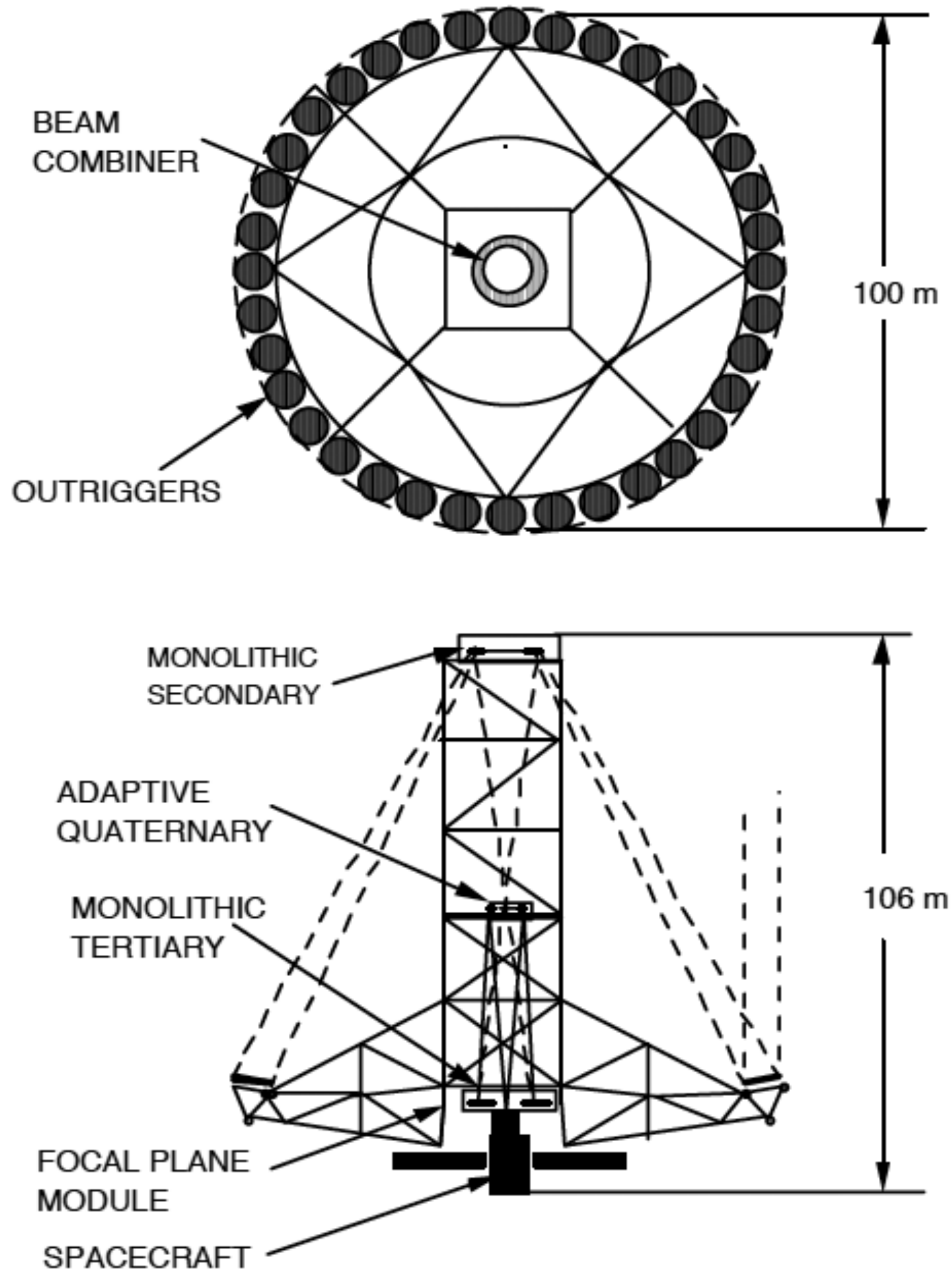
$$D = \frac{\sum_{1}^{i=n} A_i}{A_{encircled}}$$

PSF for Sparse apertures



$$I_i(x,y) = \left| \mathcal{F}\left\{ t_2(\xi,\eta) \right\} \right| \otimes I_O\left(x,y\right)$$

Sparse aperture deployable space telescope design by Aden Meinel

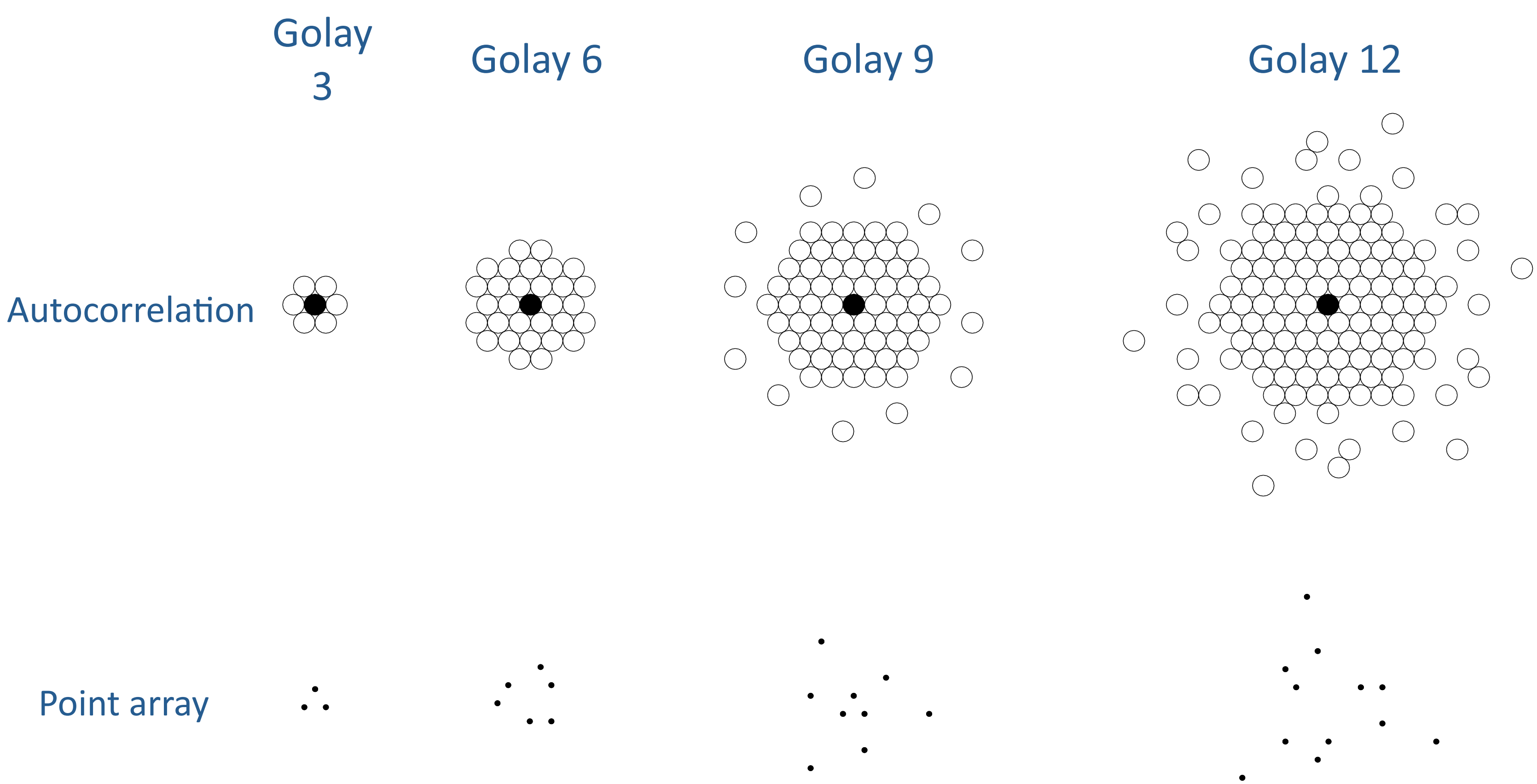


Sparse telescope image quality

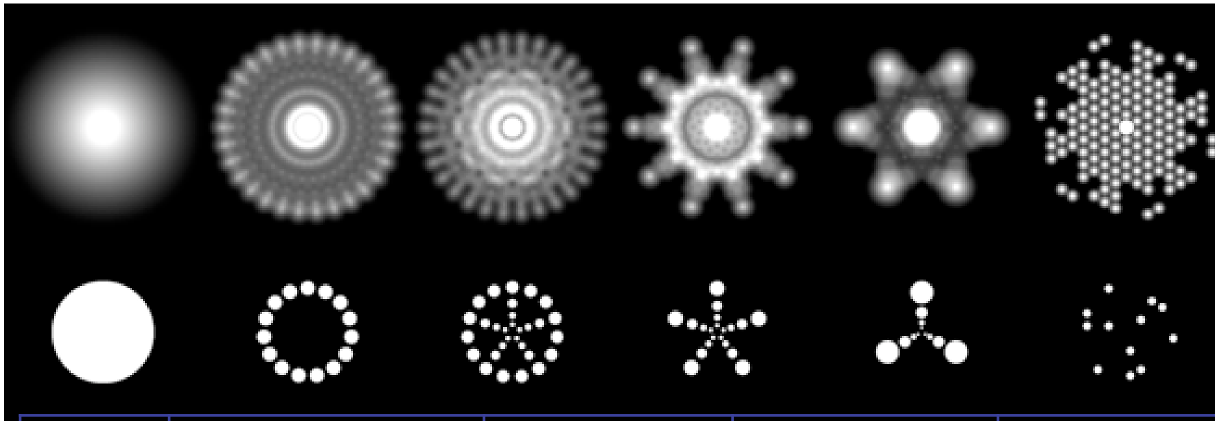
- We numerically simulate the image formation process using several sparse aperture pupil topographies.
- Several parameters impact the image quality restored from an extended, white-light, broadband scene of low & intermediate contrast as found in planetary & satellite surfaces, resolved images of stellar surfaces and images of the Earth's surface. These are:
    - Scene contrast (which restricts signal to noise)
    - Pupil shape and it's resulting optical transfer function
    - Frequency (U-V) domain coverage
    - Spectral bandwidth
    - Phasing errors between primary aperture mirror elements
    - Detector full-well
    - Exposure time

Optimized two-dimensional arrays

Golay described point arrays having compact nonredundant autocorrelations



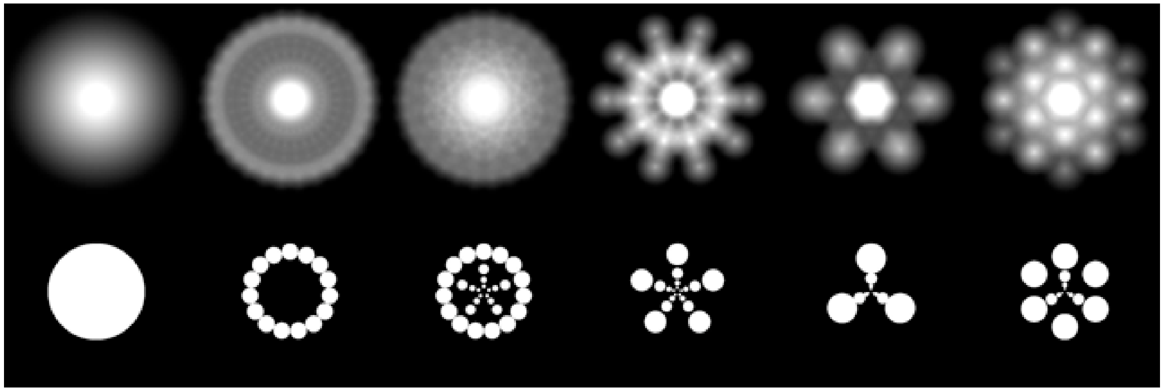
20 % Contrast



$$\text{Exposure} = \left(\frac{1}{\text{fill factor}}\right)^{X}$$

Pupil	Description	FF % by area	Detected photons required	Exposure time relative to filled	Exposure in sec	Exponent
1	filled	100	1,300	1	0.00065	-
2	Touching	29.6	90,000	234	0.152	4.48
3	Necklace + 5 arms	30.1	80,000	204	0.132	4.43
4	5 arms	18.6	108,000	446	0.290	3.63
5	3 arm Y	20.2	90,000	343	0.223	3.65
6	Golay 12	7.5	2.0E+06	20,568	13.37	3.83

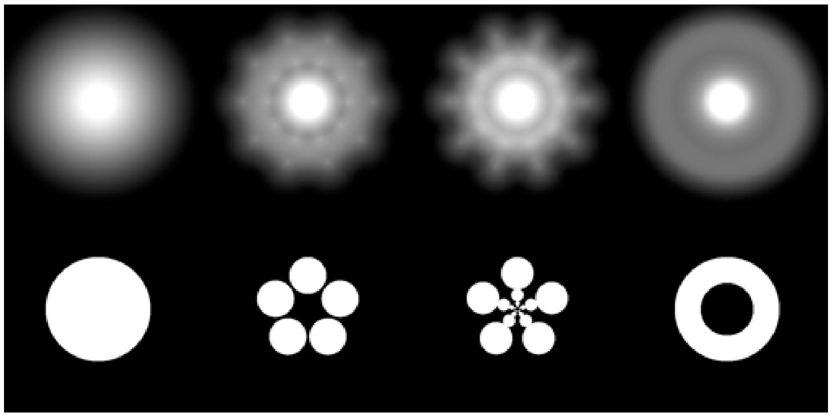
10 % scene contrast



$$\text{Exposure} = \left(\frac{1}{\text{fill factor}} \right)^{X}$$

Pupil	Description	FF by % Area	Detected Photons Required	Exposure relative to filled	Exposure time (sec)	Exponent
1	filled	100	6,000	1	0.003	-
2	Touching	44.2	135,000	50.9	0.153	4.81
3	Necklace + 5	51.7	76,500	24.7	0.074	4.86
4	5 arms	33.7	145,000	71.7	0.215	3.93
5	3 arm Y	33.6	92,000	45.6	0.136	3.50
6	Ring of 6 + 3 arms	48.5	59,000	20.3	0.061	4.15

5% input scene contrast



$$\text{Exposure} = \left(\frac{1}{\text{fill factor}}\right)^{X}$$

Pupil	Description	FF % by area	Detected photons required	Exposure relative to filled	Exposure time (sec)	Exponent
1	Filled	100	23,400	1	0.0177	-
2	Touching	61.8	90,000	6.22	0.073	3.80
3	Necklace +5 arms	56.0	100,000	7.63	0.089	3.50
4	Annulus	74.2	104,000	5.99	0.070	6.00

Image quality effects

- It turns out that sparseness is only one factor.
- The overriding factor is the ability to deconvolve the sparse image in the presence of noise. Each pupil has its own characteristics, best described by its MTF.
- When the MTF becomes low, noise corrupts those spatial frequencies, requiring a higher than expected signal-to-noise ratio to successfully deconvolve the image.
- In order to solve this primary problem, a combination of both a “cooperative” pupil and a reasonable fill factor is required.

Fellgett Dis(advantage) in optics

- First assume that we are imaging the scene with a filled aperture, and that pixel A receives n photons. The best signal to noise ratio is obtained by assuming that each photon is recorded and then the statistical distribution of the noise is Poisson, or

$$SNR_{best} = \frac{n}{\sqrt{n}}$$

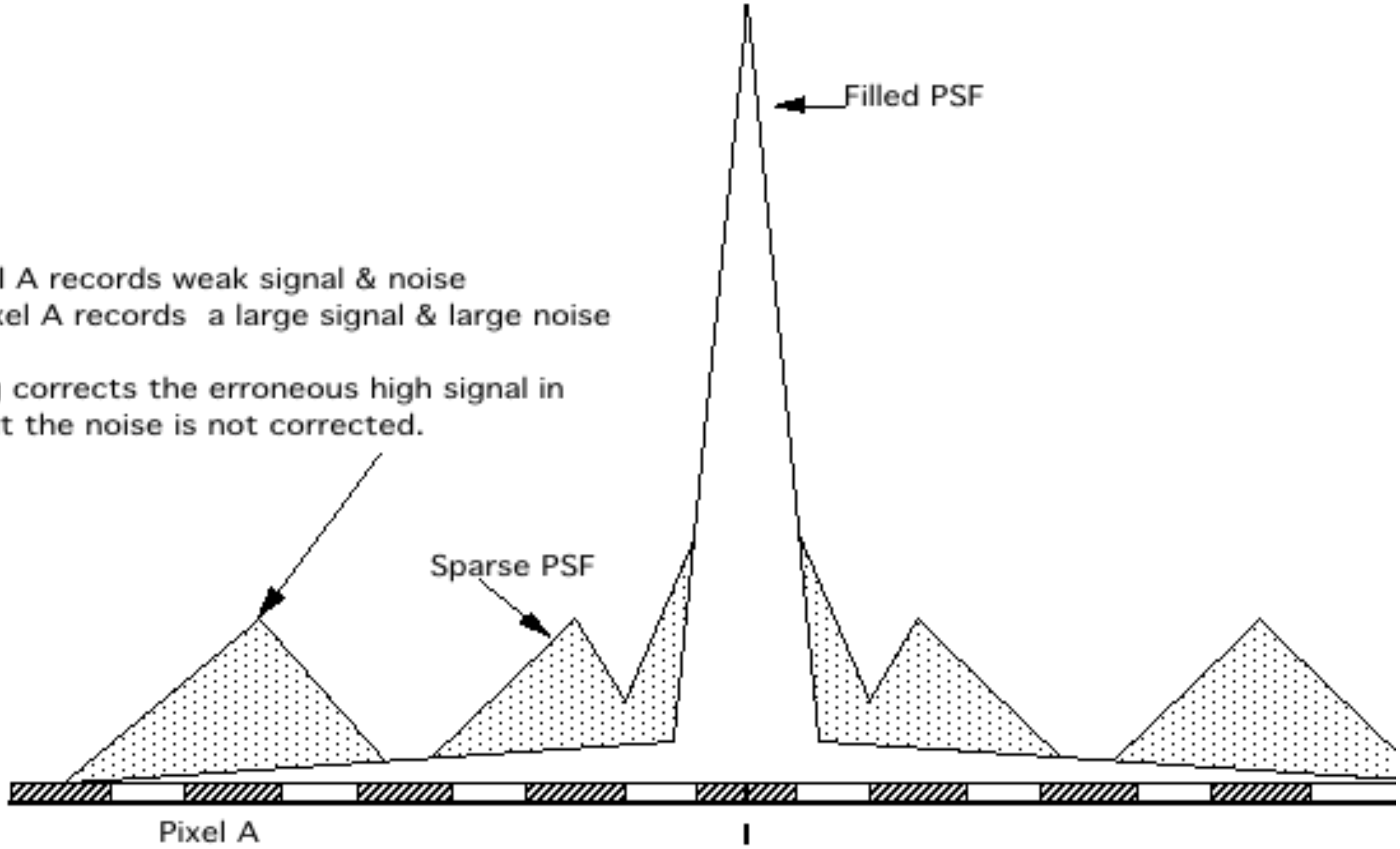
- Then let us assume we are imaging the same scene with a sparse aperture, which has the characteristically high side lobes. Pixel A then records N photons, where the upper case N is used for sparse aperture imaging. The signal to noise ratio of this measurement is

$$SNR_{SparseAperture} = \frac{N}{\sqrt{N}}$$

Why noise in sparse aperture systems grows fast with dilution?

Filled: Pixel A records weak signal & noise
Sparse: Pixel A records a large signal & large noise

Processing corrects the erroneous high signal in pixel A, but the noise is not corrected.



The effect of processing is to remove the scene information from Pixel A and place it back into t "filled" point spread function where it was diffracted from, but the noise, which cannot be less t the square root of the recorded signal at A, connot be corrected for and remains a part of the s to mask information.

Conclusions (1)

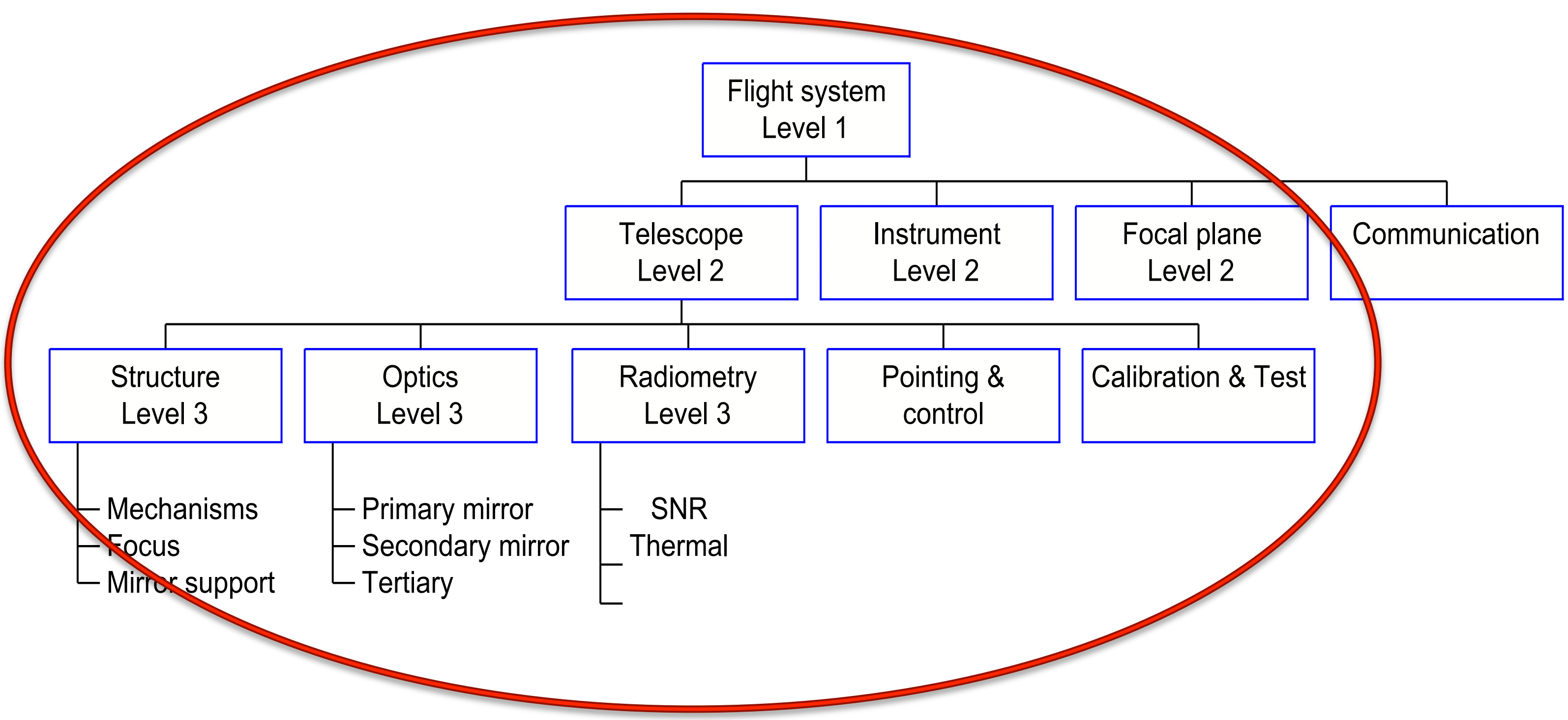
- 1,000 detected photons may be adequate for a filled pupil but much larger numbers are required to enable deconvolution for sparse apertures. For example the annulus at 40,000 detected photons is equivalent in quality to the filled pupil at only 1,000 detected photons.
- Pupils which have holes in U-V coverage at low spatial frequencies are incapable of producing quality imagery. Notice the images for the 17 element necklace.
- Nearly non-redundant pupils with MTF's which are very low in places produce poor images in the presence of noise. Compare the images of the 21 non-redundant pupil (next to bottom) between the 1,000 and the 40,000 cases. This failure is due to random noise overwhelming information located at low MTF. All Golay designs will be vulnerable unless the elements are increased in size to overlap in the UV plane.
- An annulus can be mimicked by a string of circles.

Conclusions (2)

- 20% contrast requires a fill factor of 30% and 100,000 detected photons.
- 10% contrast requires a fill factor of 40% and 100,000 detected photons.
- 5% contrast requires a fill factor of 50% and 100,000 detected photons.

Where do we start?

- Develop system requirements
- Divide the system up into manageable subsystems
  - Work break-down structure
- One person's subsystem is another person's system.

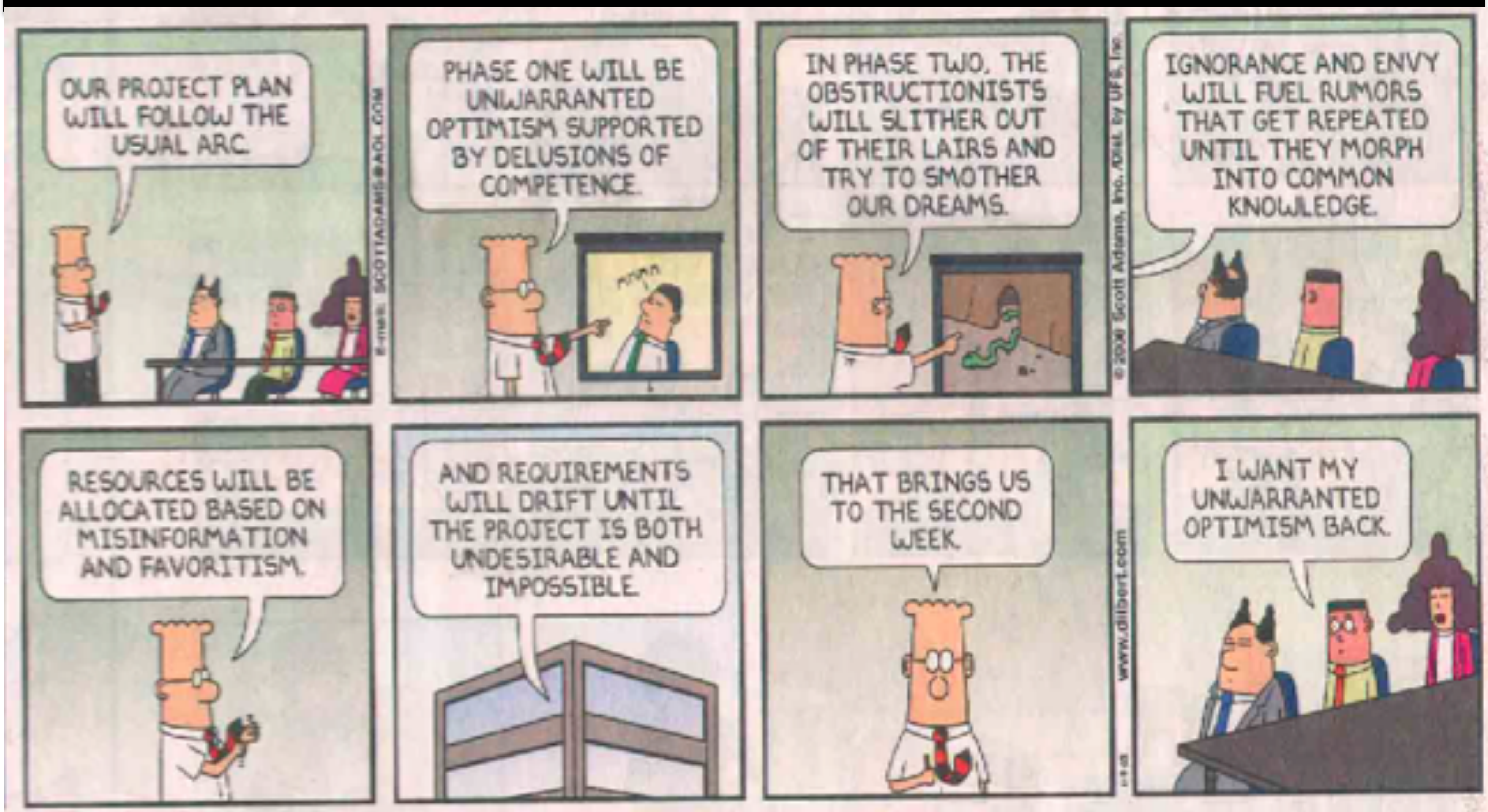


Tuesday, January 28, 2014

- The NASA process – technology
  - New missions require new measurements & most new measurements require new technology
    - Thermal IR, High angular resolution, high contrast, UV
  - "we know the theory-it will work!" - Too much risk of failure
    - Exception is very low cost cube sat experiments
  - Technology development metrics

Tuesday, January 28, 2014

- Challenges to space operation
  - Radiation (sun, fields, ions and particles)
  - Thermal
  - Electrostatics
  - Launch vibration
  - Pointing and control
  - The sun, earth & the moon “get in the way”
  - Mismatched system engineering

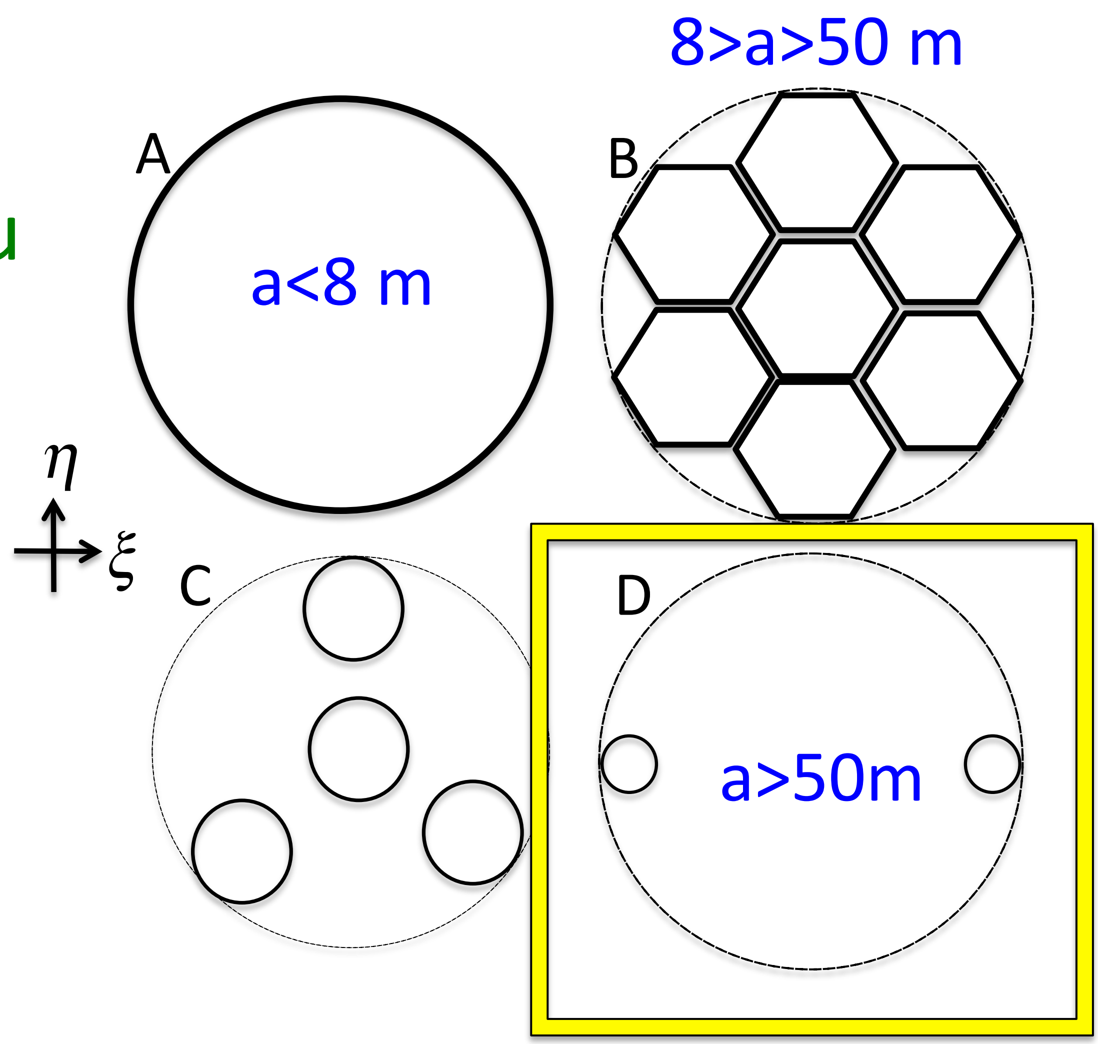


OUR PROJECT PLAN WILL FOLLOW THE USUAL ARC.
PHASE ONE WILL BE UNWARRANTED OPTIMISM SUPPORTED BY DELUSIONS OF COMPETENCE.
IN PHASE TWO, THE OBSTRUCTIONISTS WILL SLITHER OUT OF THEIR LAIRS AND TRY TO SMOTHER OUR DREAMS.
IGNORANCE AND ENVY WILL FUEL RUMORS THAT GET REPEATED UNTIL THEY MORPH INTO COMMON KNOWLEDGE.
RESOURCES WILL BE ALLOCATED BASED ON MISINFORMATION AND FAVORITISM.
AND REQUIREMENTS WILL DRIFT UNTIL THE PROJECT IS BOTH UNDESIRABLE AND IMPOSSIBLE.
THAT BRINGS US TO THE SECOND WEEK.
I WANT MY UNWARRANTED OPTIMISM BACK.
E-mail: SCOTTADAMS@AOL.COM
© 2008 Scott Adams, Inc./Dist. by UFS, Inc.
www.dilbert.com

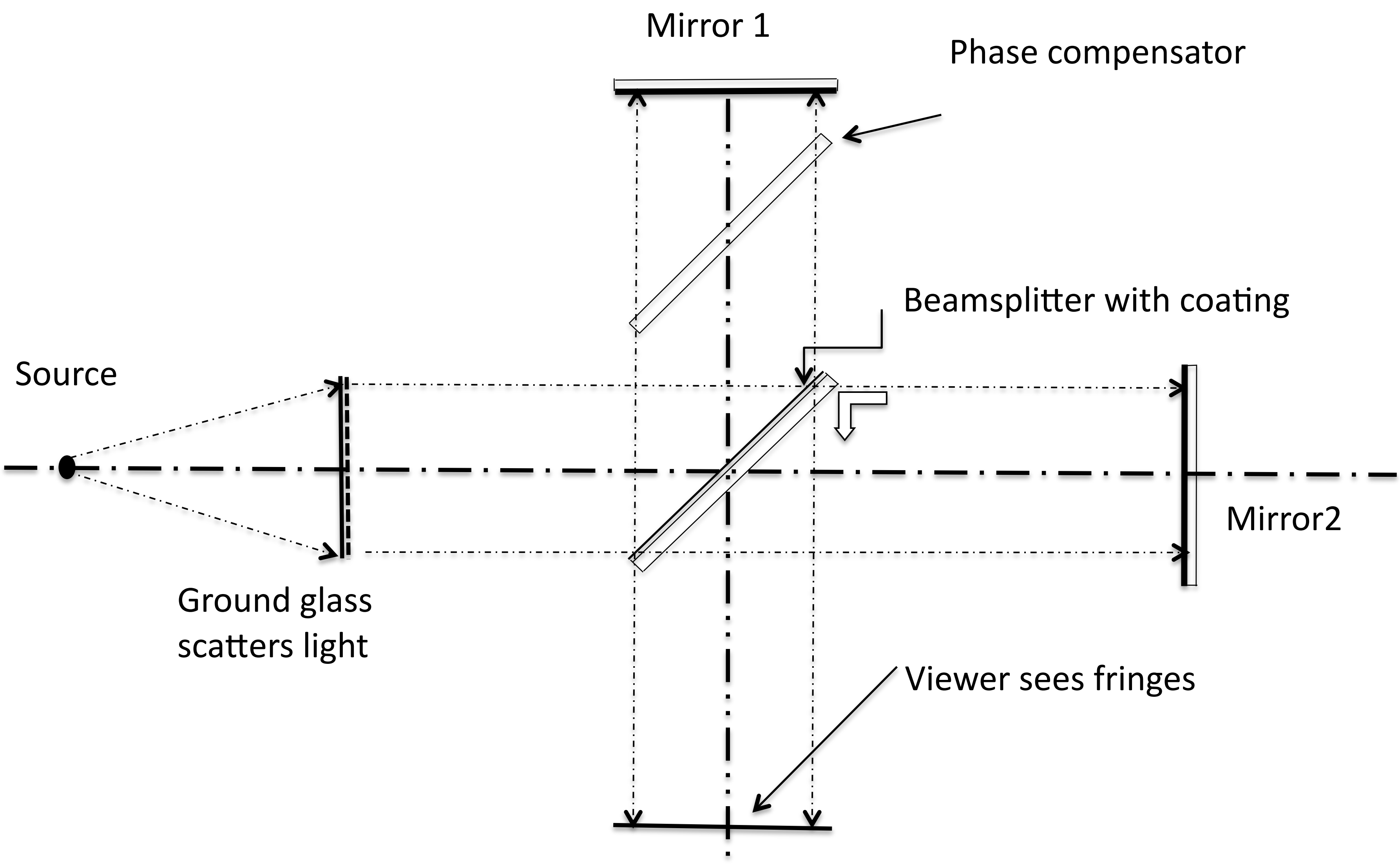
Interferometry

interferometer aperture

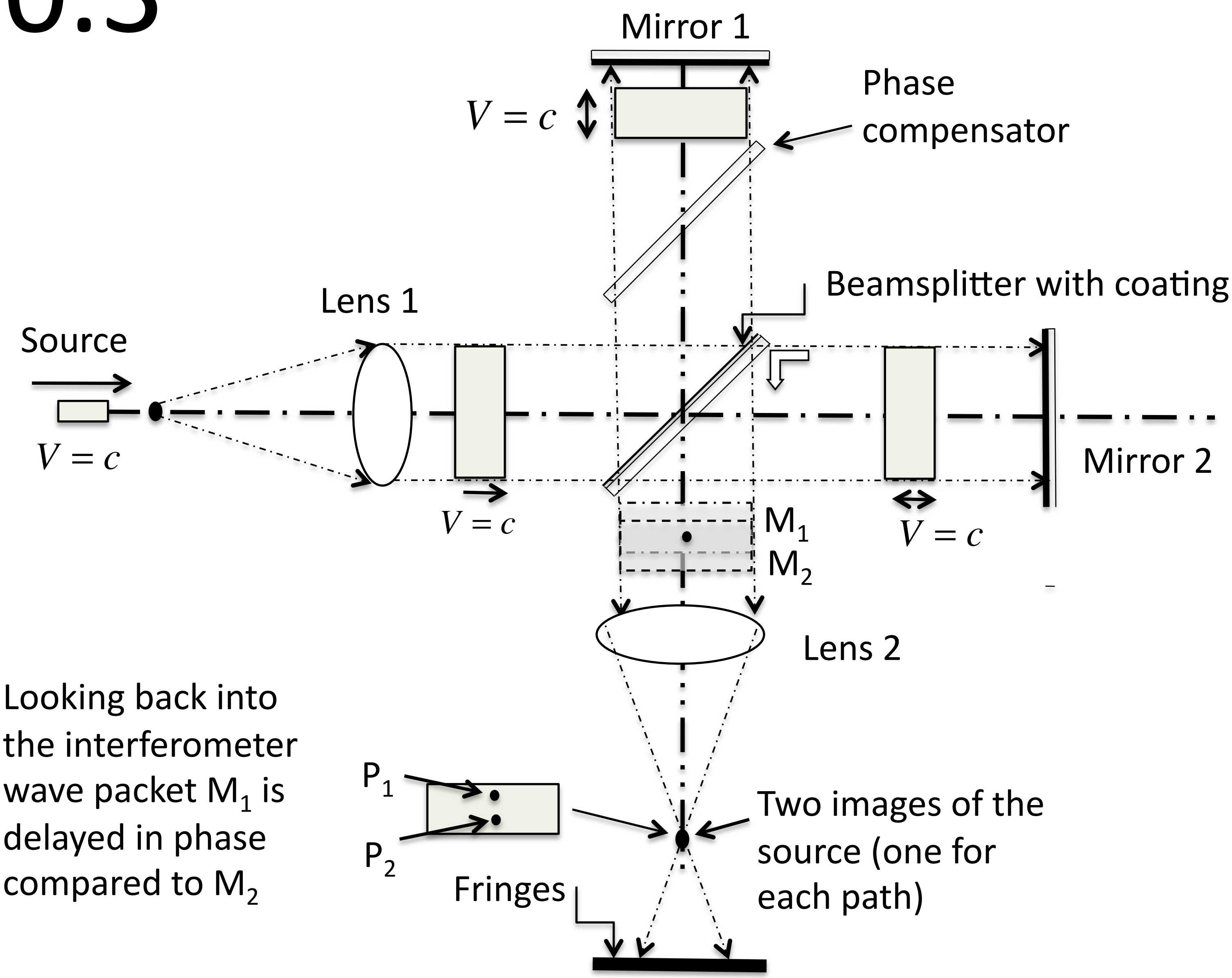
- What kind of aperture are you going to build?
- Angular resolution is more important than power at the image plane



Michelson Interferometer

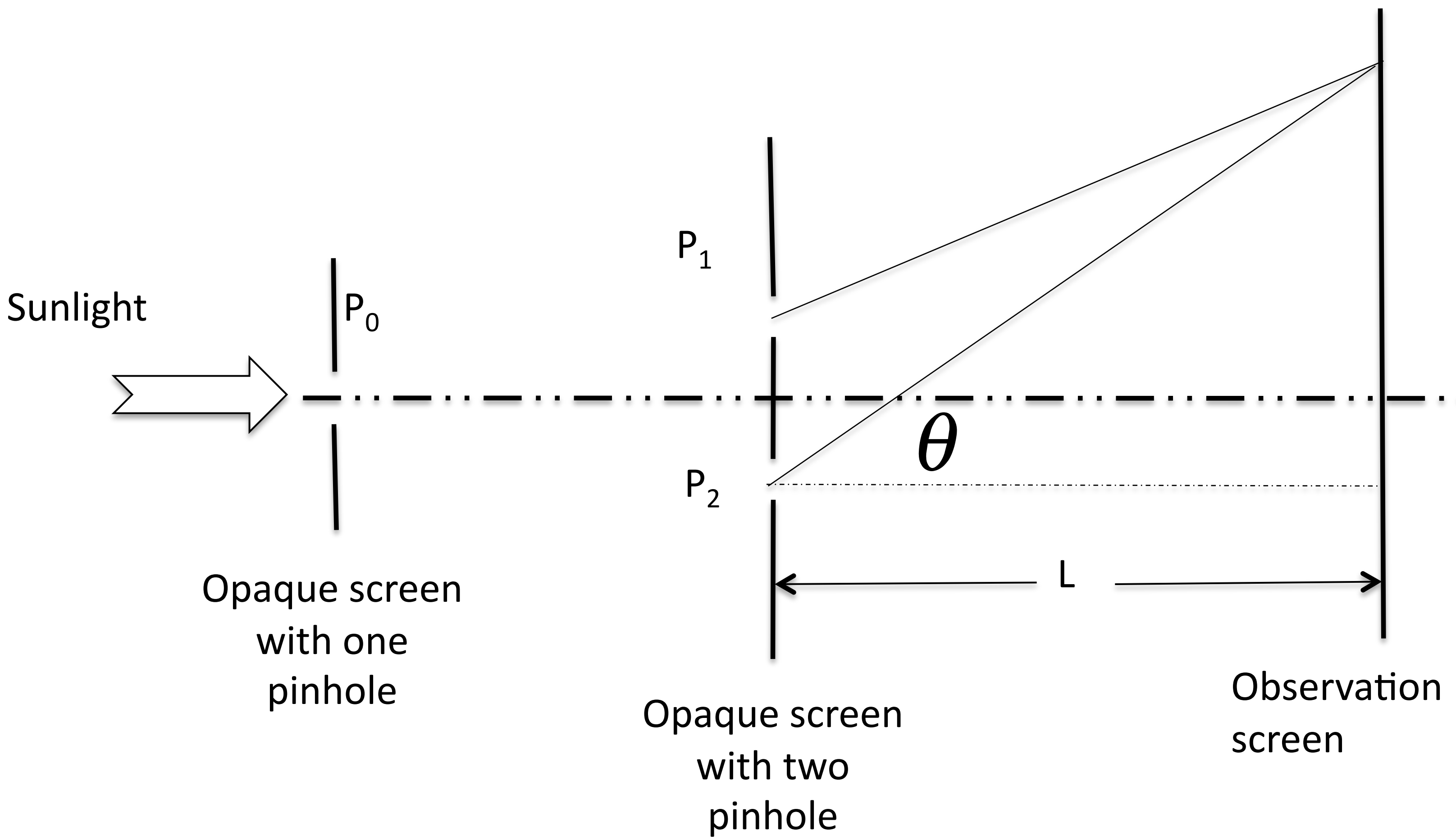


10.3

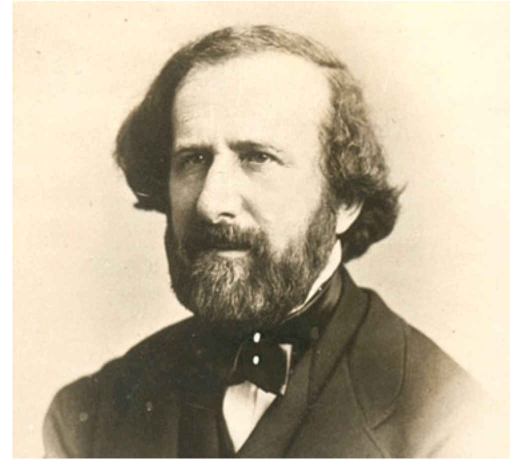


Looking back into the interferometer wave packet M_1 is delayed in phase compared to M_2

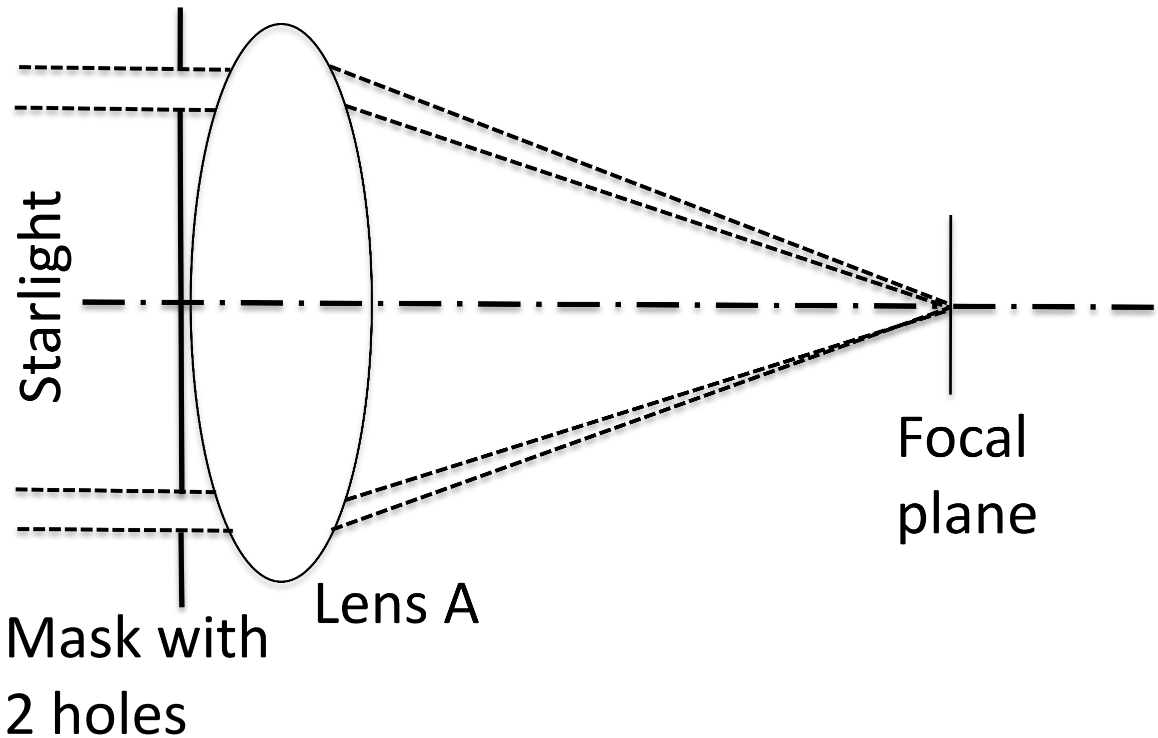
Young's double slit experiment



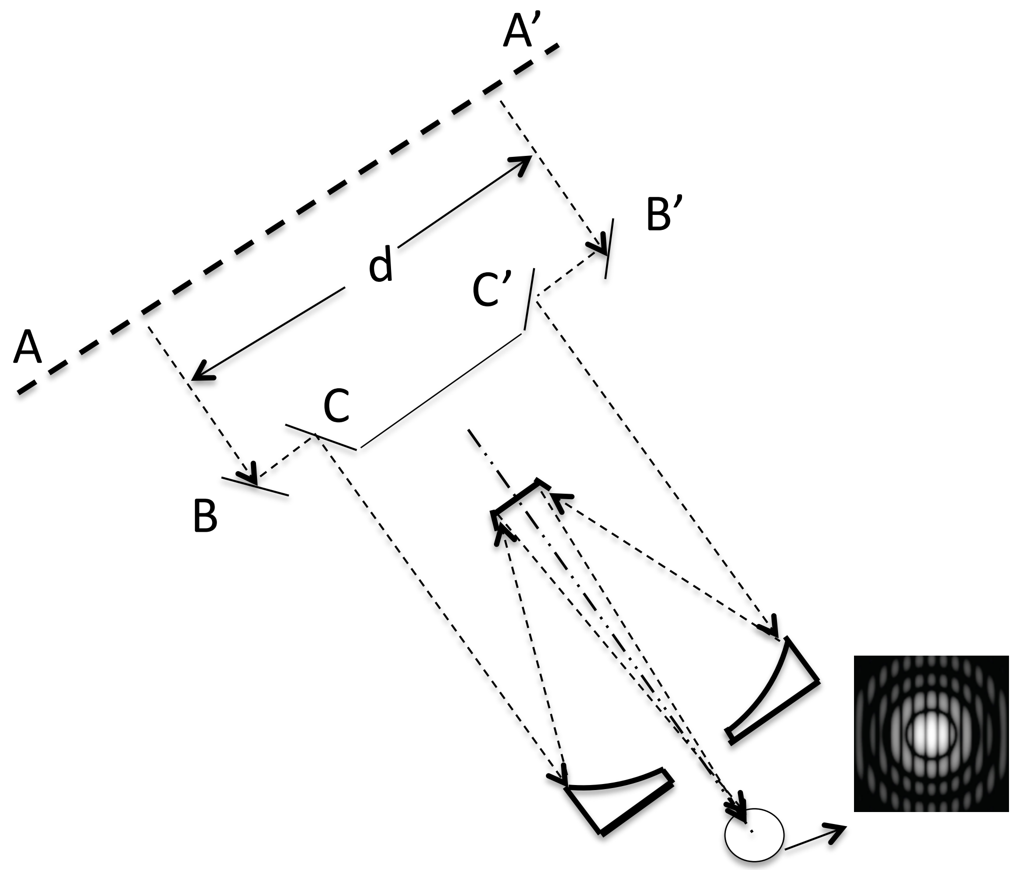
Fizeau Interferometer



He took Young's **WHITE-LIGHT** double slit experiment and used its principles for astronomy



Michelson's WHITE LIGHT Interferometer 1920



Michelson's Interferometer @ 100-inch