Space Optics (1)
AstrOpt2016

J. B. Breckinridge

Adjunct professor

Caltech & College of Optical Sciences

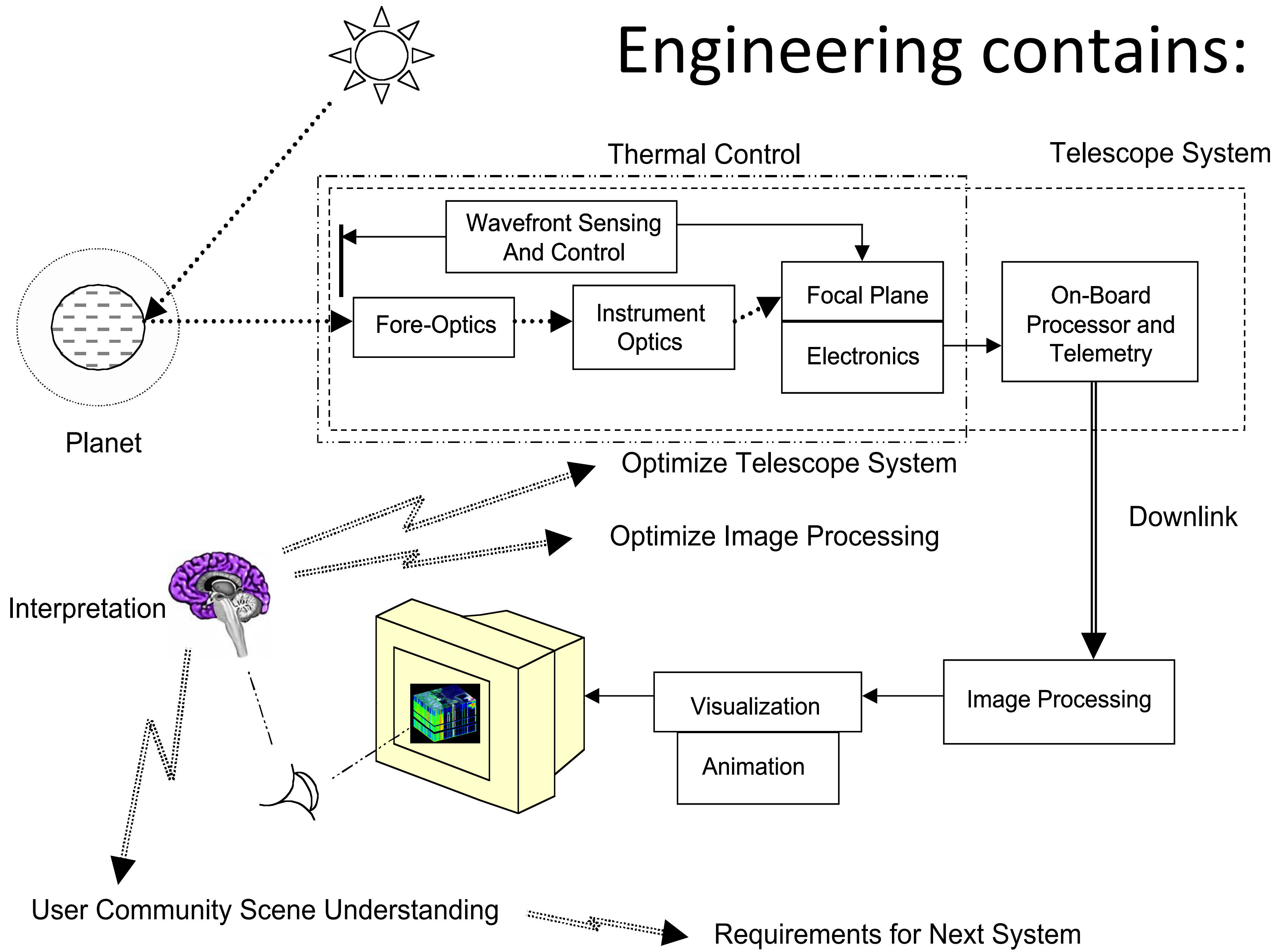
Who am I?

- PhD in Optical Science, College of Optical Sciences, University of Arizona, Tucson
- **12 years at Kitt Peak National Observatory, Tucson & 33 years at JPL building instruments and developing technology**
  - Developed space telescopes and instruments for astrophysics, earth and planetary remote sensing
  - *Managed section of ~ 100 for 12 years: Optics Technology and Flight Optical Systems for remote sensing: WF/PC2, Galileo and Cassini Imaging spectrometers & JPL Technologist for advanced imaging systems for Dod*
  - NSF 3 yrs: Advanced Technology & Instruments PM
  - *NASA 1 yr: Chief technologist of the NASA Exoplanet Program*
- Optical Engineering class at CALTECH ('82-current)
  - Authored a book: Basic Optics for the Astronomical Sciences

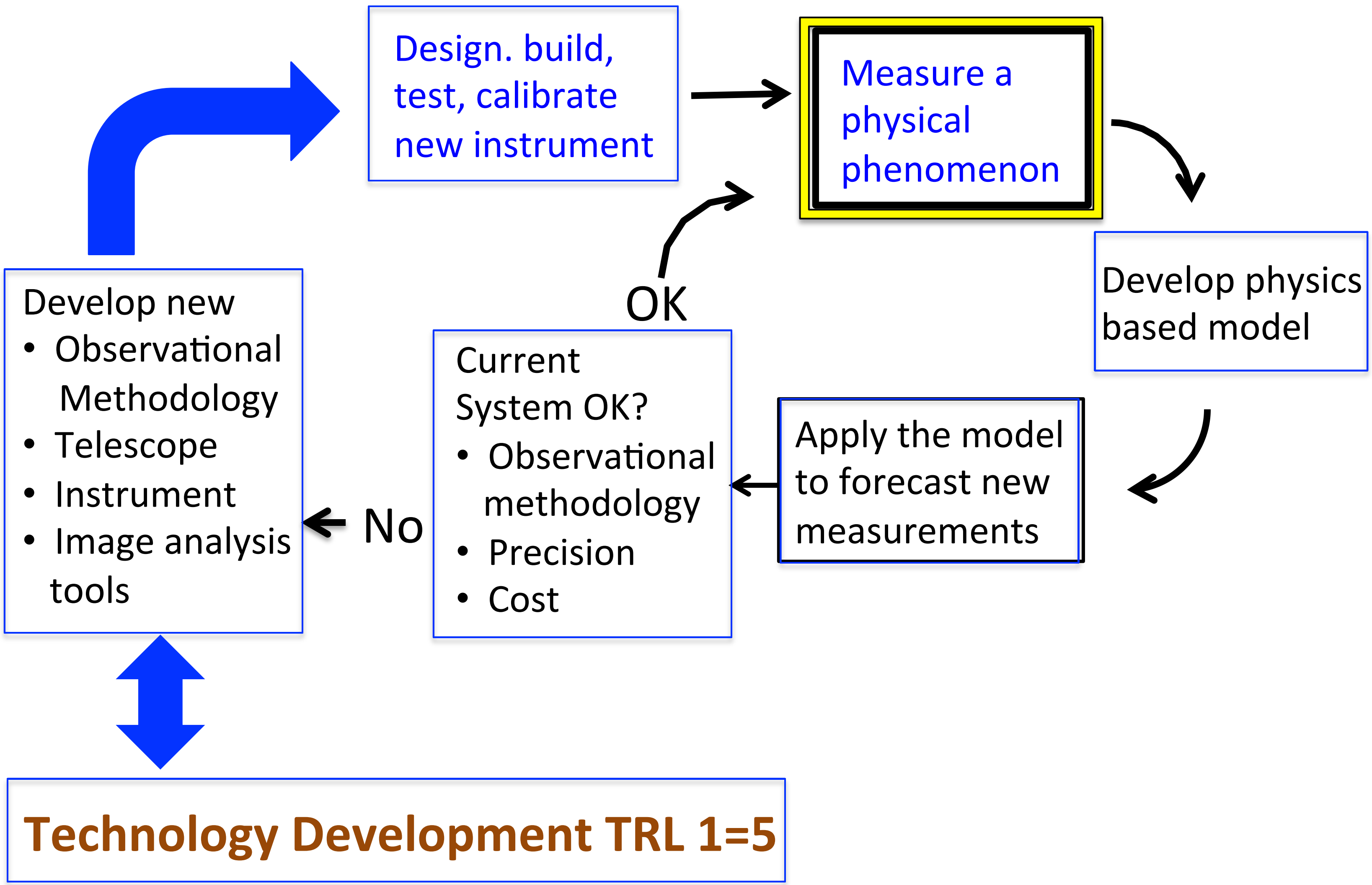
Class outline

- The challenges of space optics - **Today**
- Derive Etendu, throughput, transmittance
  - Power to the focal plane
- Geometric aberrations: thermal, structural, metrology, tolerancing:: **correctable by A/O**
- Scalar wave image formation **1 March**
- Vector-wave image formation: polarization aberrations:: ***not*** **correctable by A/O ~1 March**
- **Hubble trouble ~ 3 March**

Space Science Imaging System Engineering contains:



The scientific method
“engineering meets science”



What can we measure?

- Intensity as a function of
  - A single point $I = f(x_0, y_0)$
  - An image $I = f(x,y)$
  - Wavelength $I = f(x,y;\lambda)$ or $I = f(x,y;\sigma)$
  - Time $I = f(x,y;\lambda;t)$
  - Polarization $I = f\{I,Q,U,V;(x,y;\lambda;t)\}$
  - The total number of measurables (degrees of freedom) is: $7+n$ where *n* is the number of spectral channels

This information needs to fit into a 2-d display changing with time => the instrument!

What are optics for remote sensing?

- Optical science
  - Study of the generation, propagation, imaging, measurement and analysis of electromagnetic radiation from 300 nm to ~40 micron wavelength
- Optical engineering
  - Understand requirements, identify system approach, design, specify, test components integrate, align, test and calibrate an optical system to a fixed cost.
- Optics Technology
  - Technology development to enable new scientific or engineering measurements

Analysis tools

- Trigonometry – ray trace
  - Image location, size, orientation, geometric aberration
- Scalar waves – complex variables
  - Diffraction, interferometry, image formation & quality
- Vector waves – polarization – matrix algebra
  - image formation & quality
- Photons – Signal-to-noise
  - Do not "exist" until the detection process!
- Statistics – partial coherence - correlated fluctuations
  - Interferometry and image formation: **where your science is!**
- ~~Quantum mechanics – generation & absorption of light~~

Tools for optical science and engineering

Tools	Image Location	Image Size	Image Orientation	Image Intensity	Image Quality	Physical Properties of the Source
Ray Trace	YES	YES	YES	YES	NO	NO
Scalar Diffraction	NO	NO	NO	NO	YES	NO
Vector Diffraction	NO	NO	NO	YES	YES	YES
Radiometry	NO	NO	NO	YES	YES	YES
Statistical Theory	NO	NO	NO	YES	YES	YES
Quantum Theory	NO	NO	NO	YES	YES	YES

Select the tool that applies to the problem you are working

- **In general follow these steps** =>

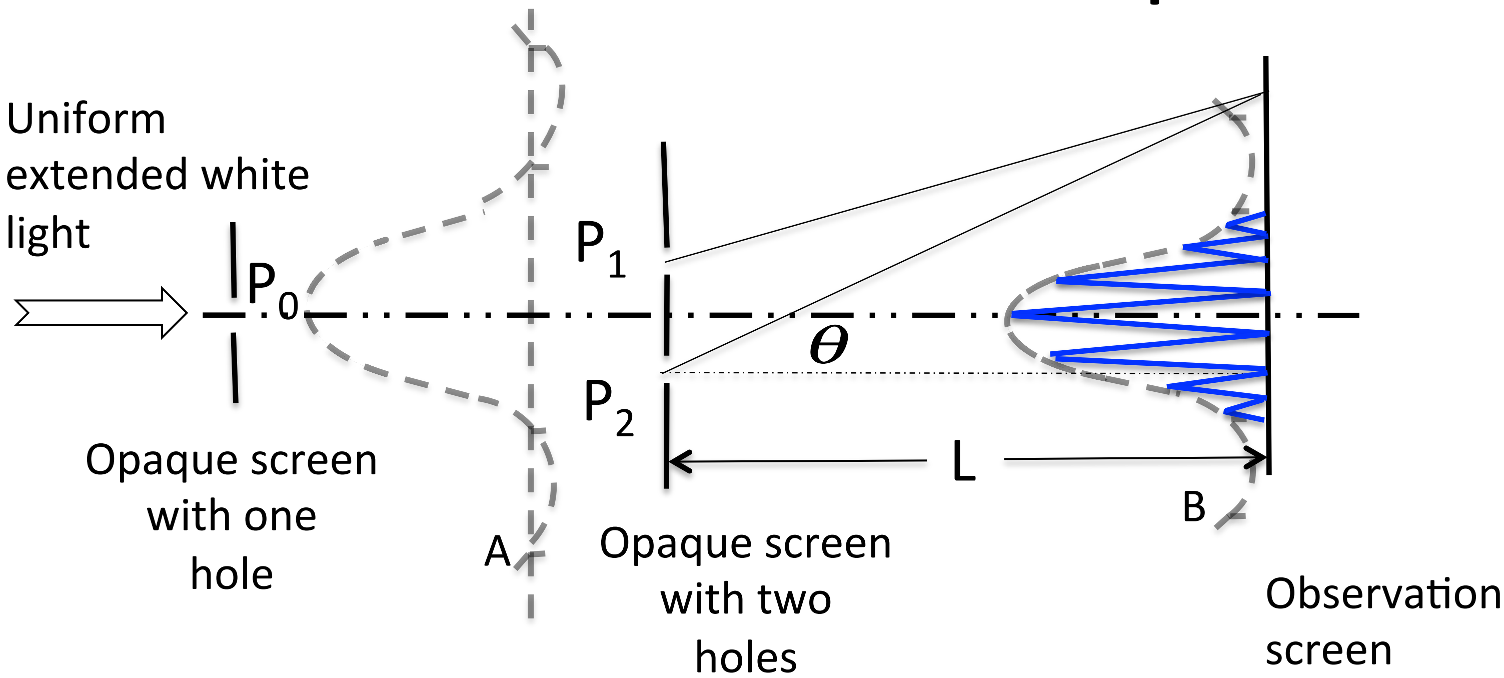
1. First order design
   - **image location, size, orientation**
   - **radiometry (through-put or etendu & transmittance)**
2. **Geometric aberration ray trace (estimate image quality)**
3. Diffraction with scalar waves (estimate image quality)
4. Vector propagation (polarization aberrations & image quality)
5. Statistical optics (the role of partially coherent waveforms in image quality)

- **Covered by Hect's Optics & inadequate in Hect's Optics**

Image formation process
modeled by
statistical optics

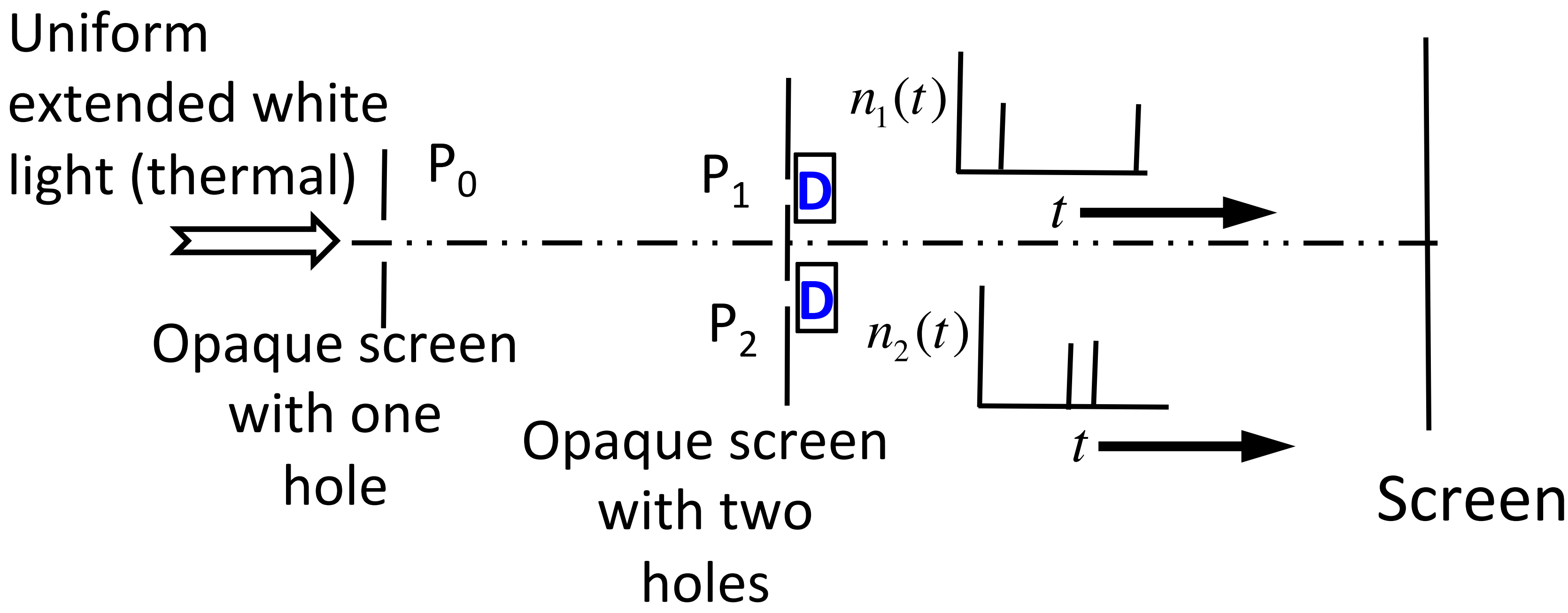
See Born & Wolf *Principles of Optics* Chapter 10
& J. Goodman's *Statistical optics*
for mathematical formalism

Reminder of the double slit experiment



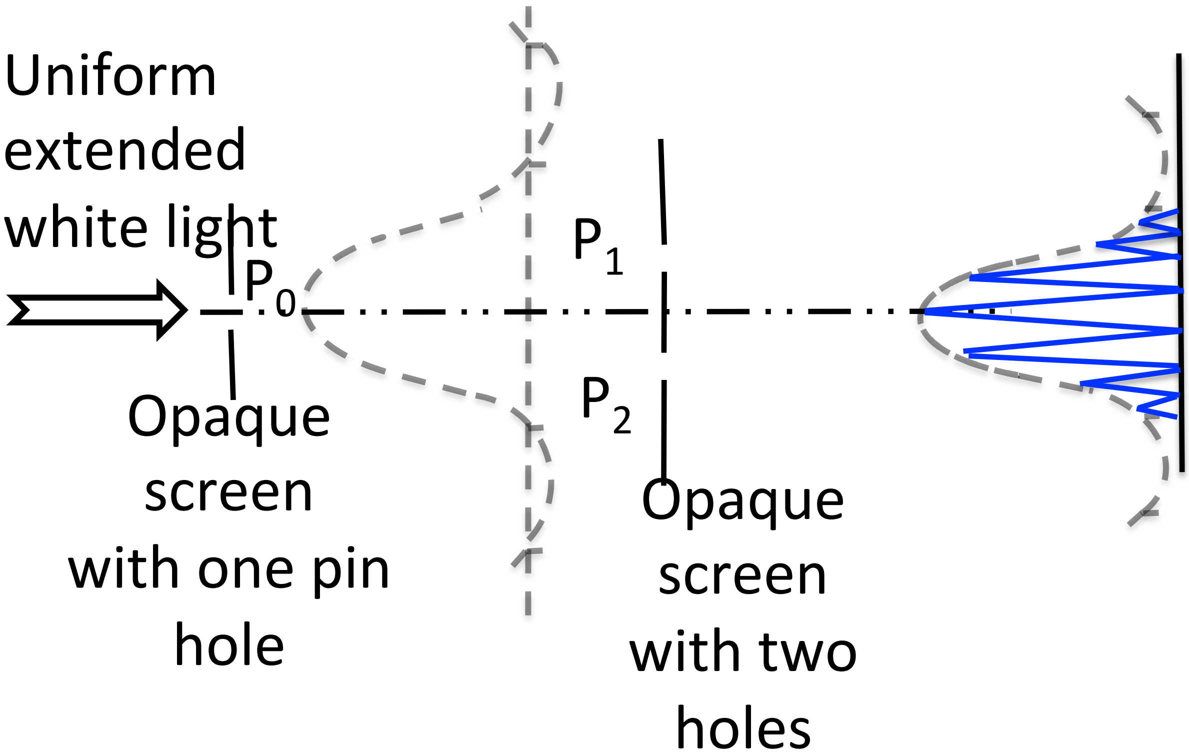
- Curve B is the diffraction pattern from holes P1 and P2
  - Spacing of the fringes underneath curve B is related to the separation of the holes P_1 and P_2
  - Visibility (contrast) of these fringes underneath curve B is given by the degree of correlation (coherence) of the fluctuating electromagnetic fields between points P_1 and P_2.

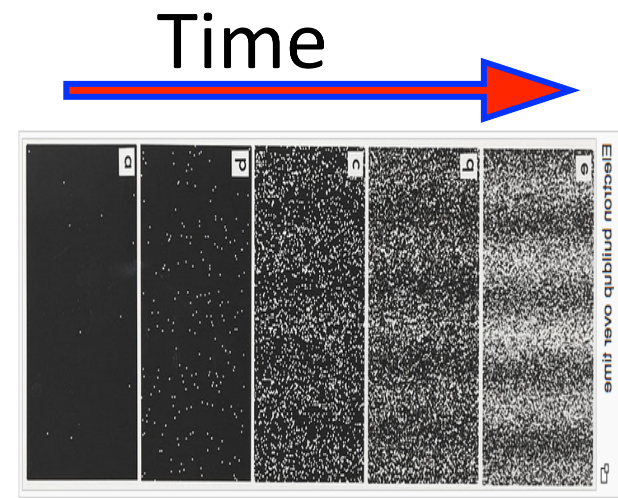
Wave-Particle Duality of Light: Photon counting



- **D** are 2 identical detectors
- Photons are counted as a function of time
- **Note** the photon arrivals are not simultaneous
- If we remove the detectors D and let light fall on a screen interference fringes will be seen.

Wave-Particle Duality of Light: Interference





- **The fringe envelope is the Probability Density Distribution (PDD) of the arrival of photons**
- The fringe pattern evolves during the integration time

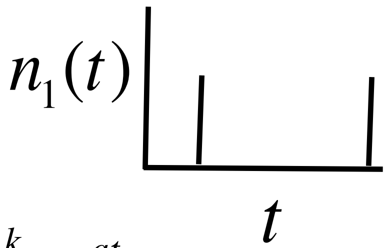
Wave-Particle Duality of Light: Photon counting

- Assume radiation can be represented as a stationary ergodic ensemble of a stochastic process
- The image is the statistical probability density distribution for the photon arrivals.
- For the case shown;
  - 3,000 photons the image is not distinguishable from noise
  - 12,000 we an get an idea of what the image is
  - 280,000 photons the image is clear

Image	Number of Photons
a	$3x10^3$
b	$1.2x10^4$
c	$9.3x10^4$
d	$7.6x10^5$
e	$3.6x10^6$
f	$2.8x10^7$

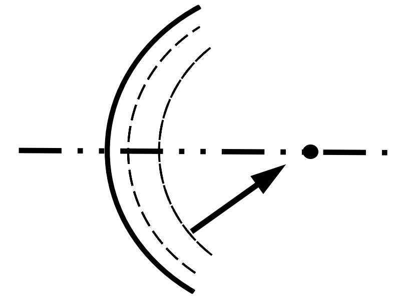
Which tool to use for design?

Photons



Or

Waves



$$P(k;r) = \frac{(a\tau)^k e^{-at}}{k!};\ \ k \text{ is the}$$

number of photons that arrive in time τ & a is a constant.

$$I(x,y) = k(x,y) \cdot t$$

$$W(x_i, y_j) = A(x_i, y_j) e^{-i\phi(x_i, y_j)}$$

$$I(x,y) = \sum_{j=1}^{N} \sum_{i=1}^{M} \left| W(x_i, y_j) \right|^2$$

- **Waves relate directly to engineering parameters that affect the shape of the PDD & we understand how to control that shape**

Optics for space vs. ground

	Ground Observatories	**Space Observatories**
Wavelength coverage	400 nm to 50 μm with absorption windows	γ-ray to long-wave radio waves
Scattered light for coronagraphs	Atmosphere limited to $>10^{-8}$	Unknown, limited by technology; probably $<10^{-15}$ contrast
Angular resolution	2×10^{-4} arcsec (500-m @ 500 nm)	Unknown; may be $<10^{-7}$ arcsec (10-km baseline)
Thermal environment	~230 to 310 K	Extreme: ~20 K with sunshade
Gravity	1-g; The vector changes during the night.	0-g
Accessibility	Easy-to-fix hardware	Telescope inaccessible after launch
Operation cost	Keck ~24 M/year	~10 times as much

Instrument function

- Remember the optical system is continuous ***complex*** to the detector ***intensity***
- Instruments operate on - or manipulate the complex amplitude & phase wavefront at the telescope focus to reimage an “analyzed” wavefront on the focal plane for detection.
  - Devices that perform this analysis are: prisms, gratings, interferometers (FTS), polarizer's (I,Q,U,V)
  - Detectors only see Intensity
- Need science measurement driven innovative instruments to open new windows….
  - Imaging spectrometers
  - Scanners
  - Imaging photopolarimeters

Integrated modeling & test beds for optical systems

- Need to accurately predict instrument performance as a function of multidisciplinary design variables
  - Computer models to link thermal, materials, structural, optical and control system
  - Essential to quantifying both subsystem and system-level cross-disciplinary trades in terms of optical performance metrics
- Hardware test beds for to reduce mission risk
  - Technology development
  - Device/subsystem validation

How do we create a working space telescope?

- Need to be organized!
- For a system to work all of its parts must work together
- Space optical systems require a team
  - Two people work for 500 years OR
  - 100 people for 10 years
- Everybody cannot just work on what they are interested in
  - Leaves gaps
- The role of the technical manager is to organize the effort so that most team members are working on what interests them – **but some uninteresting work must get done**

Science Mission Directorate (SMD) Process

- The space science community
  - astrophysicists
  - earth & planetary atmospheres, oceans
  - earth & planetary geologists & botanists
- Prioritize science measurement objectives
- Engineers assess the technology to make these measurements and the risk of success
- Instrument scientists & optics technologists
  - identify new technology needs
  - develop the needed technology
- NASA groups these science measurement objectives into missions

Develop requirements to communicate to other team members & sponsor

- **Science**
  - "Determine the scope of global warming"
- **Science measurement objectives**
  - "Measure the annual abundance of CO_2 to an accuracy of 0.1%"
- **Functional requirements (constraints on the instrument & system)**
  - "the needed signal to noise is 60:1, global measurements, $5 \text{ to } 16.\ \mu$, resolution $0.1\ cm^{-1}$..."

Develop requirements to communicate to other team members & sponsor

- **Create a System architecture**
  - "Telescope with spectrometer, low earth orbit, down link capacity……. "
- **Develop a point design**
  - "Grating or Fourier transform spectrometer, spectral resolution, $A\Omega$ ..??"
- **Assess feasibility develop and apply models**
- **Is new technology needed? If yes then . . .**
  - Define clearly functions needed
  - Prepare call for proposals
  - Win contract & start research & development

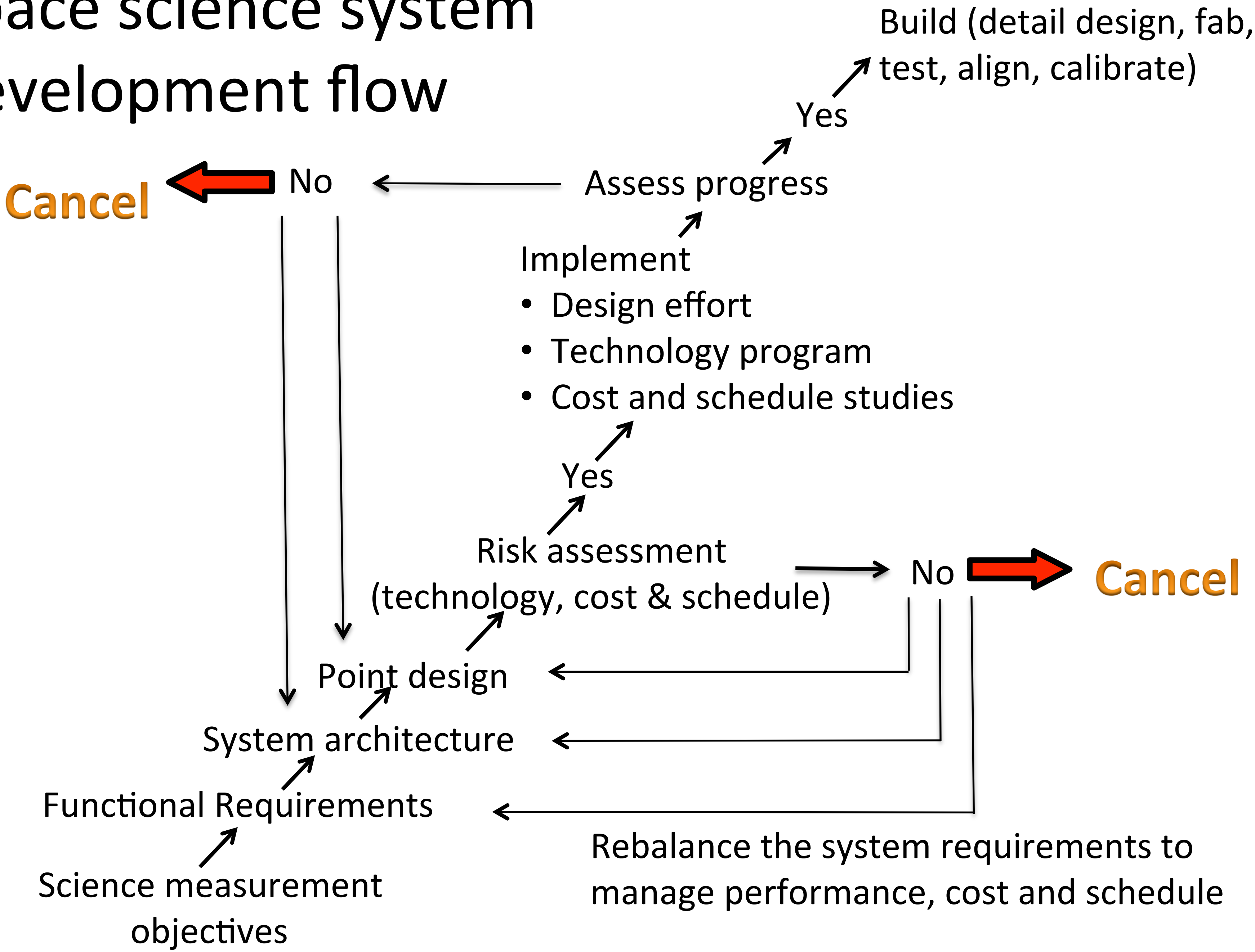
Develop requirements communicate to other team members & sponsor

- Need commitments from individuals to complete tasks
- Write contracts based on
  - Functional requirements
  - Engineering specifications
  - Software control, data analysis

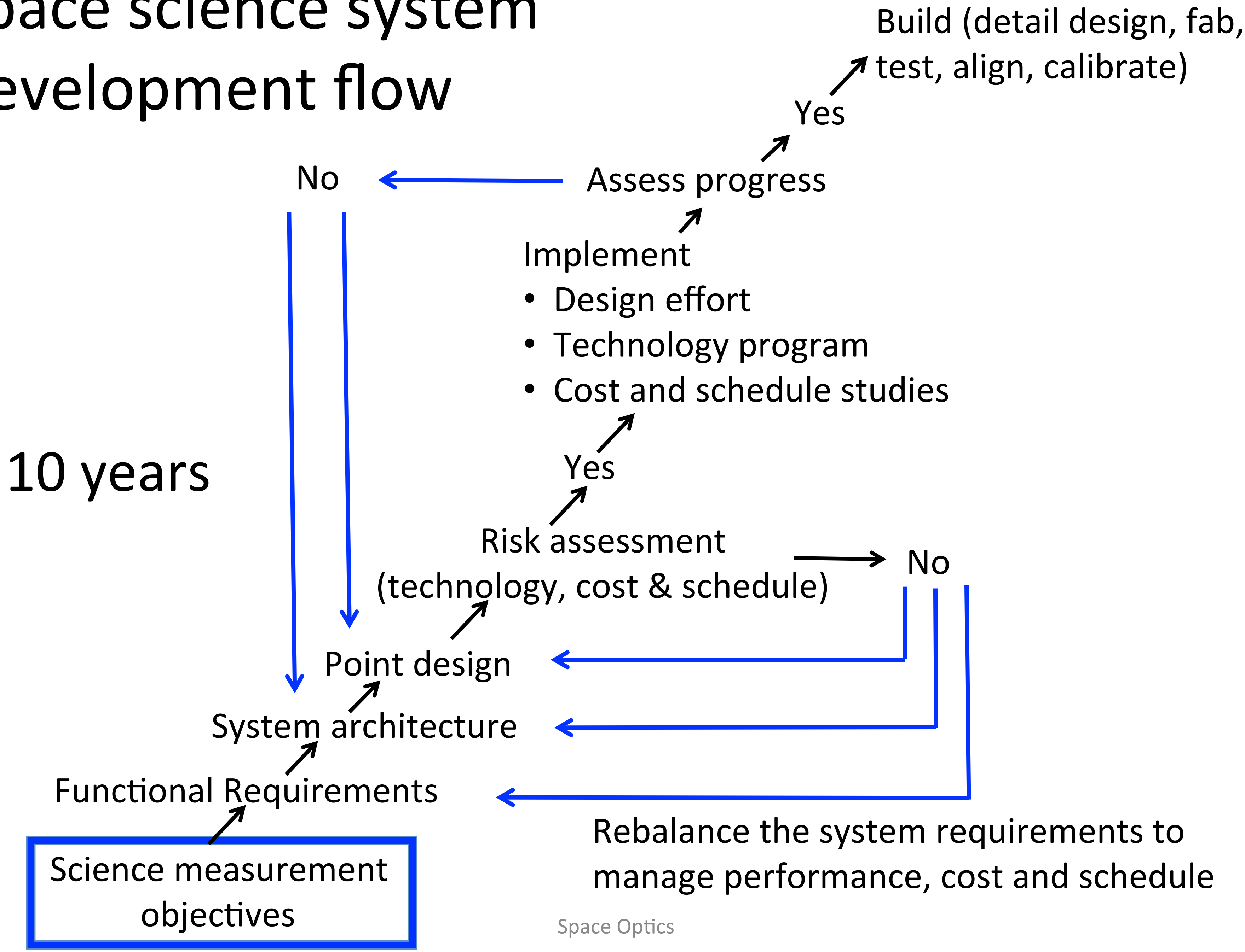
Functional requirements

- **Yes**
  - Measure the R=70 spectra between 400 and 600 nm of an exoplanet with a SNR>5
- **No**
  - Use a 1-meter telescope with a 600 lines/mm grating and the Falcon 6 rocket fairing launched from Wallops?
- **Identify clearly what your functional requirements are, then look at what is available?**
- **Engineering requirements & specifications are derived from your science measurement functional requirements**
- **Scientists negotiate requirements with engineers**

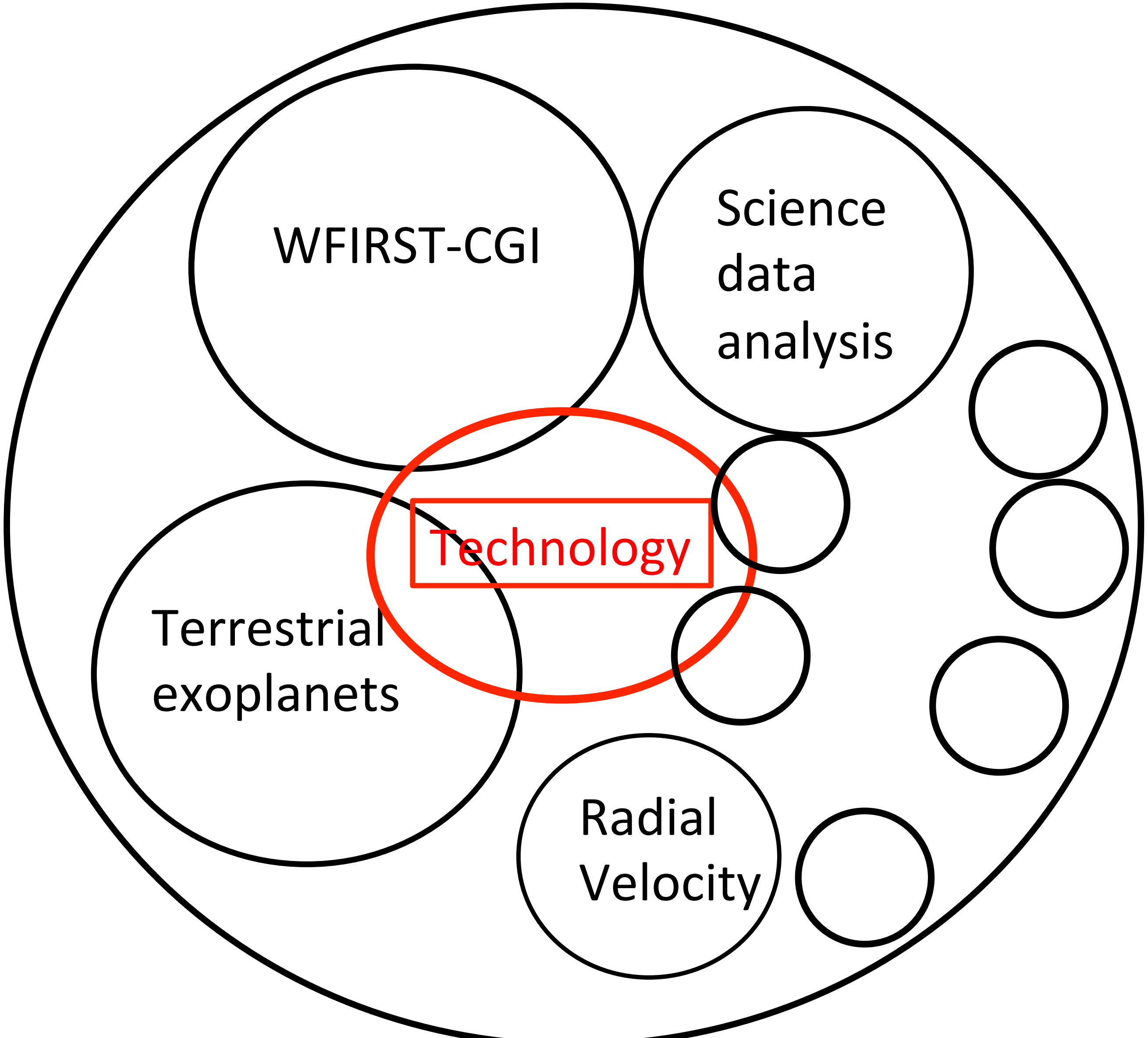
Space science system development flow



Space science system development flow



program, project, task, technology

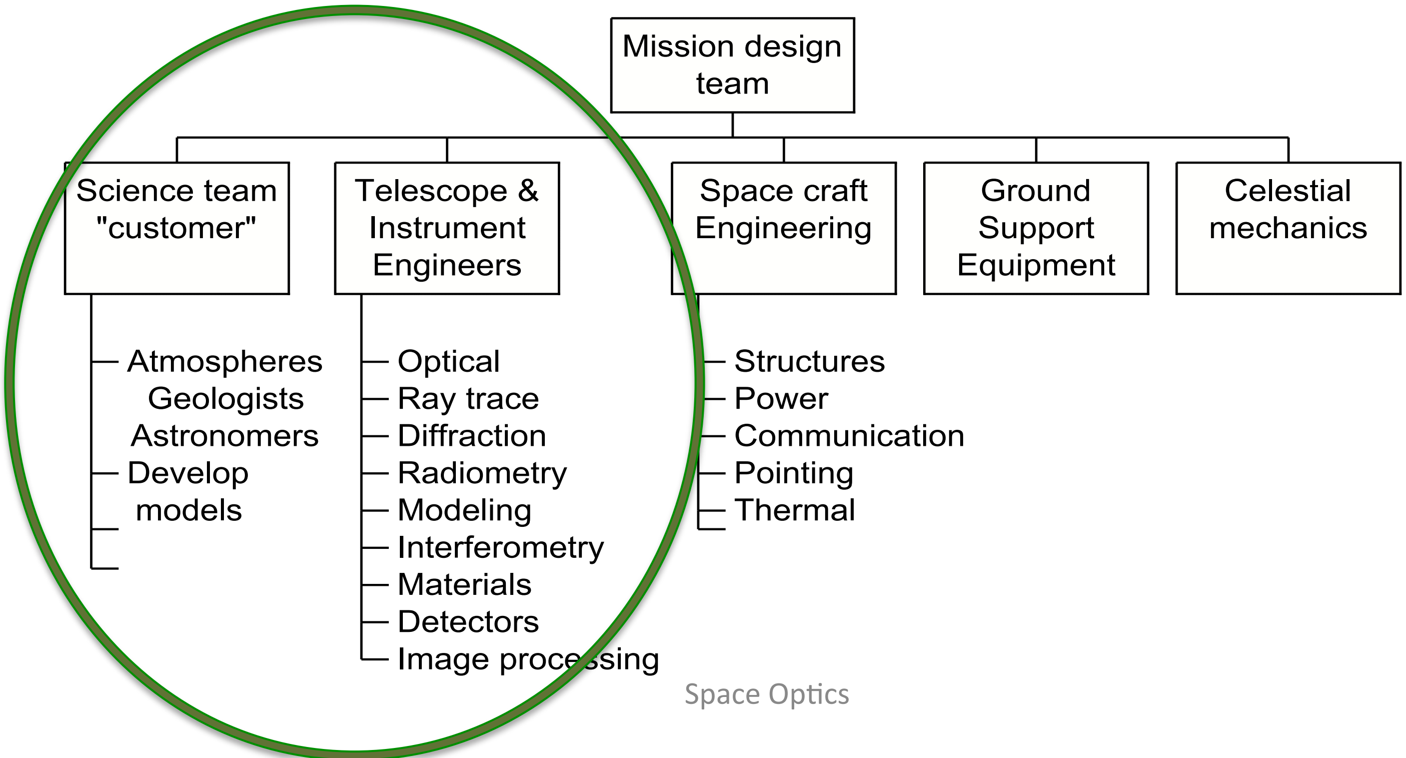


Language is important
Program development

- A program contains:
  - Science advocacy
  - **Funding advocacy**
  - **Mission development – instrument vision**
  - **Technology development**
  - **Project – fabrication & test of flight hardware**
    - **project move through time within**
    - **Cost, schedule and performance**
  - **Public awareness**

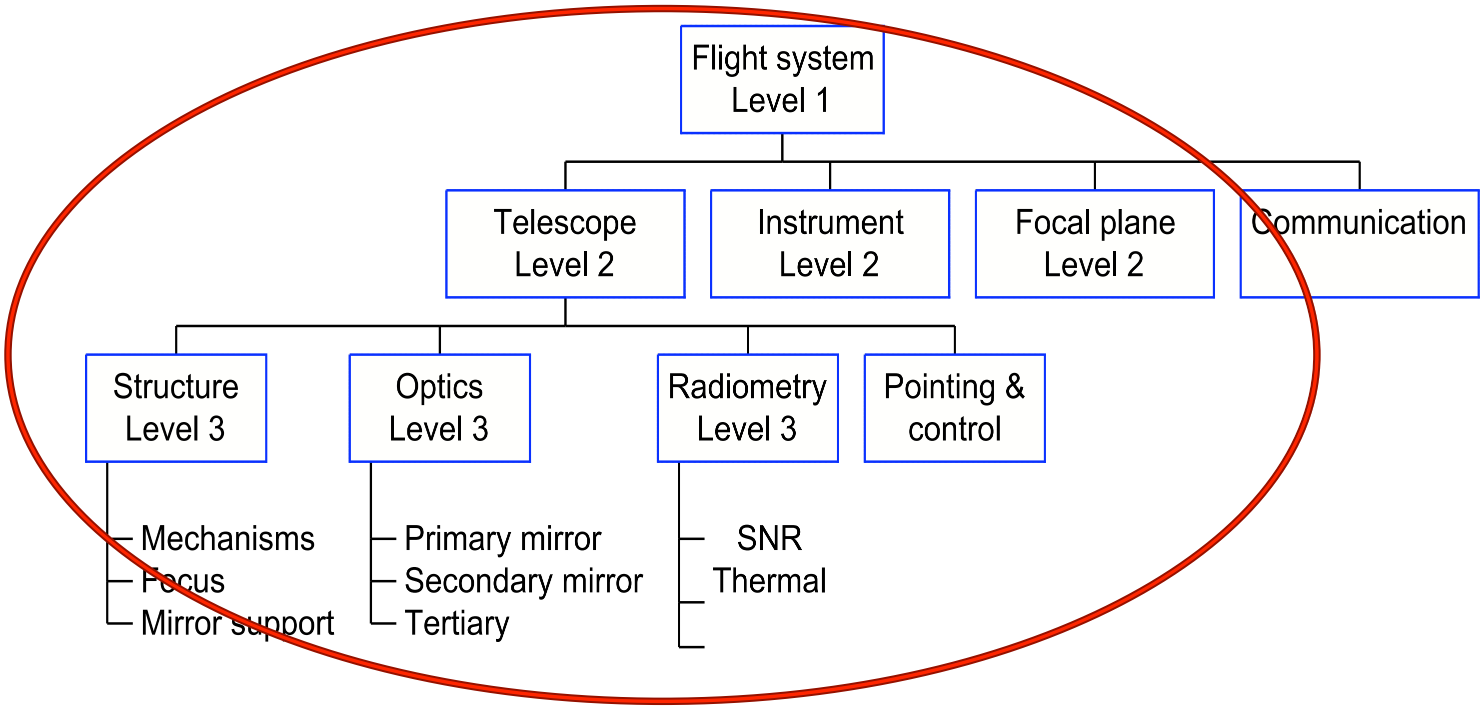
Mission development

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



Where do we start?

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



Technology before project

- With ~100 engineers charging $\$2x10^{+6}$ per month a project which is manufacturing the instrument cannot stop, **pay engineers to NOT work** and wait for technology to be developed.
- If the technology to design, build, integrate, align, test and calibrate the optical system is not "off the shelf" then a technology development program is needed to make the technology "ready for flight" **BEFORE the project receives approval to start**.
- Communicate the readiness of your technology using the technology readiness level scale (TRL)

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Optics technology priorities

- New precision materials & structures to enable
  - Low cost figuring
  - Low-mass, large area deployable mirrors
  - Precision is insensitive to temperature: metering structures – athermalization & optics metrology & control
- Includes
  - Optical finishing, coatings, materials science,
  - The deployment of highly reflecting, polarization controlled, uniform, precision optical surface
- Optical sieves, membrane telescopes and large area nano-structure optical elements (8 to 40 meters)

Detectors, focal planes, on-board signal processing

- Convert photons to electrons or other forms of energy
  - Large format, very low background & noise
  - Thermal infrared, Sub millimeter - Cryo-coolers
  - X-ray & UV
- Large area, low noise
- Low noise space qualified preamplifiers

Top technology categories

- 2017-2022 (needed for missions before 2022)
  - High contrast exoplanet technologies
  - Ultra-stable large aperture UV/optical telescopes
  - Quantum optical interferometry (atomic interferometers)
  - Spectrometers for mineralogy
  - Sample handling
  - Extreme environment technologies

Look in-depth at two technology areas: Mirror System & Optical Components

- Optical metrology & wavefront sensing and control
  - Correct telescopes to diffraction limited performance after construction to reduce cost
  - Enables light weight large aperture telescopes and instruments (e.g. JWST)
- Coronagraphs to control scattered light in telescopes and instruments
  - Solar astronomy 10^{-7}
  - Exoplanet research 10^{-12}

Optical metrology & structures

- Technology necessary to hold the optical components of the telescope properly separated and in focus
- Latches, hinges, bonding science, dynamics, materials
- Metrology: lasers, sensors, actuators
- In some cases these optical components may be 10's of meters apart and robotically deploy to a precision less than a millimeter, and self align to less than a wavelength of light.
- Formation flying mirror sats: virtual structures

Optical metrology & wavefront sensing & control

- Classically:
  - Telescopes use mass to achieve the needed stiffness for $\lambda / 40$ surface error (12 nm in the visible).
- Today:
  - Large classical telescopes too large to launch!
  - Too massive and too large volume: therefore we use optical metrology, wavefront sensing & control and actuators to get the "stiffness" needed.
  - Replace mass with lightweight sensors, actuators and software

Space telescope system architectures

- 12 to 20 meter telescope
- JWST type only larger & more complex
  - Unassisted deployment
  - Maybe low risk since JWST experience
  - Dead-end technology
- Evolvable space telescope (EST)
  - Robotic assembly in space
  - Higher risk, new
  - Technology for telescopes of unlimited aperture

Space telescope system architectures

- Thought process
- Space telescope system engineering
  - Design concept
  - Architecture trades
  - Decisions today map to billions of $ tomorrow

Background

- 21st century space astronomy needs twelve to twenty meter class space telescopes
- Requirements
  - Cost less than JWST
  - Performance to 100 nm UV wavelength
  - Coronagraph for imaging spectrometry @ 10^{-11}
  - Polarization preserving (0.01%)
  - ~4-arc minute FOV (or larger)

$$N = \left[\frac{FOV}{1.2\lambda / d} \right]^2 = 8.4 \cdot 10^8 \approx 4 \text{ giga-pixels}\Big|_{\text{nyquist}}$$

How to

- Reduce cost
  - Minimize # of reflections (precision mechanical structures)
  - Implement the Evolvable Space Telescope (EST)
  - Prime focus
- Increase UV-Vis performance
  - Innovative optical design (imagers & spectrometers) – wide FOV with fewer reflections
  - Polarization preserving configurations & coatings

How important is mirror count? Cost to recover mirror losses

- To fit our optical instruments into the telescopes of today, designers use lots of fold mirrors which absorb and scatter valuable radiation.
- Calculate the cost of light lost because of reflections.
  - Reflection losses reduce aperture
  - Cost to recover aperture to compensate losses

How important is mirror count?
Cost to recover mirror losses

Unnecessary reflections are expensive

A_e = the effective aperture

d_e = diameter of the effective aperture

A_T = telescope aperture

d_T = telescope diameter

τ = transmittance or reflectance

$$A_e = \tau A_T$$

$$\pi \frac{d_e^2}{4} = \tau \cdot \pi \frac{d_T^2}{4}$$

$$d_e = d_T \sqrt{\tau}$$

Reflection losses reduce the effective aperture of a telescope

# of normal incidence reflections to detector	Tau for R=0.95	A 10-m aperture is effectively	A 2.4-m aperture is effectively
1	0.95	9.7	2.3
4	0.81	8.8	2.1
8	0.66	7.8	1.9
12	0.54	6.9	1.7
16	0.44	6.1	1.5
20	0.36	6.0	1.4
24	0.29	4.8	1.1
28	0.24	4.2	1

Assume a 10 meter telescope can be built for $3B. What is the cost to recover the losses ?

# of normal incidence reflections to detector	Tau for R=0.95	Increase the 10m diameter to maintain SNR	Mission cost assuming cost=d^2.0
1	0.95	10.3	3.2
4	0.81	11.1	3.7
8	0.66	12.3	4.5
12	0.54	13.6	5.6
16	0.44	15.1	6.8
20	0.36	16.7	8.4
24	0.29	18.5	10.3
28	0.24	20.5	12.6

Eight reflections cost > $1B

Survey of cost models for space telescopes, P. Stahl (2010) OE **49**, 053005

Process we go through to create a new telescope architecture

- Create the concept
- Conceive an evolvable space telescope (EST)

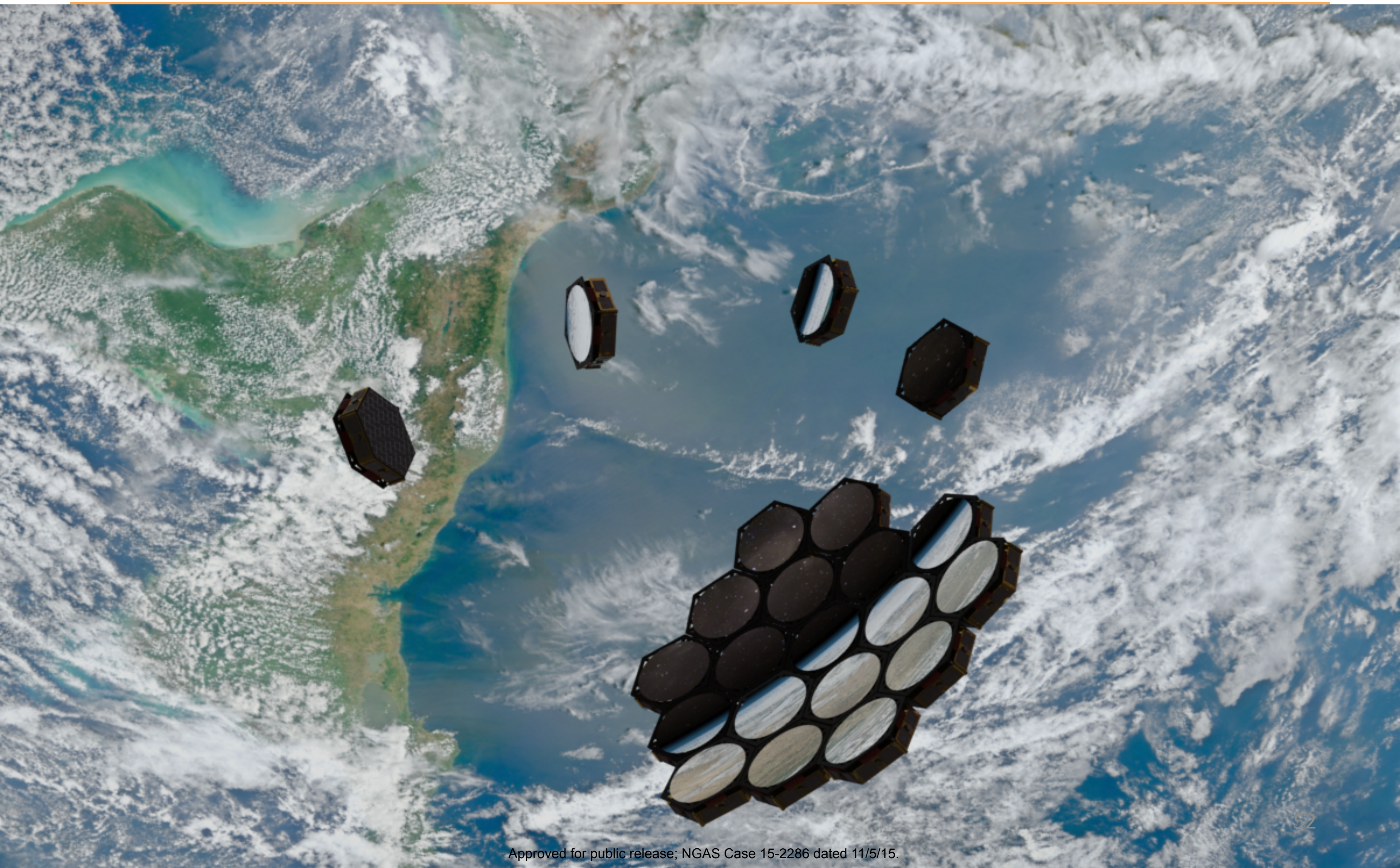
EST Plan

- By launching the telescope in segments and reuse in-space structural elements =>
- Many of the constraints on
  - Mass,
  - Deployment mechanisms
  - Packaging
  - **are removed**

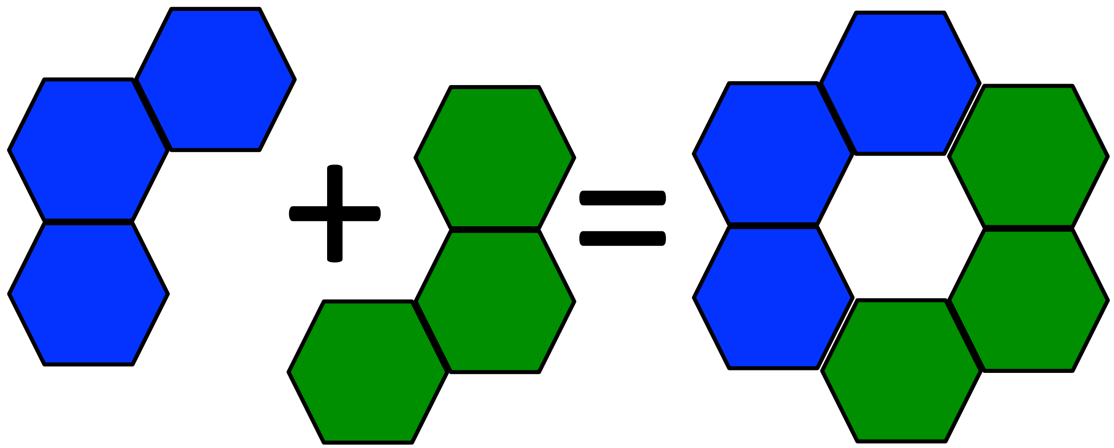
New paradigm to break cost curve

- Partition the telescope into segments
- Launch segments separately
- In space assembly in stages
- Choose stages so each one is astronomically productive
- Today discuss
  - An architecture to do this
  - Optical design & issues
- MacEwen: infrastructure
- Lillie: on-orbit assembly & servicing

The Evolvable Space Telescope Vision



Phase 1 and 2 of EST
4-m class segments



Φ_1 6x12-m Φ_1' 6x12-m Φ_2 12-m

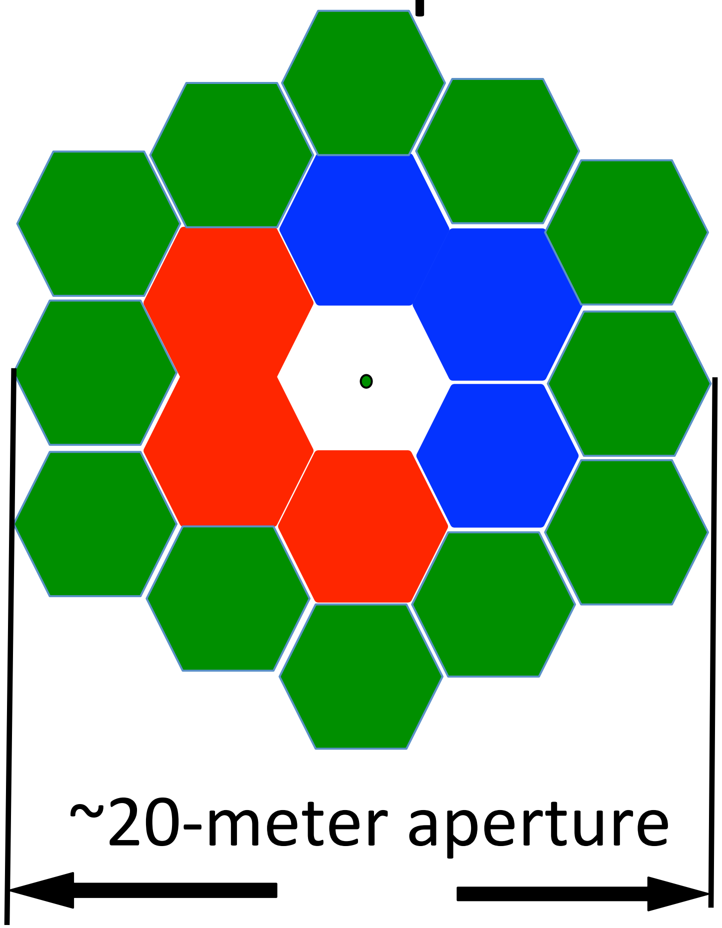
Off-axis segmented + **Off-axis segmented** = **Filled 12-meter**

Evolvable Space Telescope (EST)

1. **Stage 1**: **First, build, launch, and conduct high value science with a fully functional three 4m segment telescope complete with instruments.**
2. **Stage 2: Some years later add a mirror, instrument, and service package to the in-space Stage 1 telescope to create an 8 – 12 meter aperture.**
3. **Stage 3**: **Some years after that add to the in-space Stage 2 telescope, more mirror segments, to make a 14 – 20 meter aperture with new instruments and additional support systems.**

- <u>Science data is obtained continuously beginning with Stage 1 commissioning with only HST-like servicing gaps in the science return</u>

UVOIR concept built using EST processes & technology



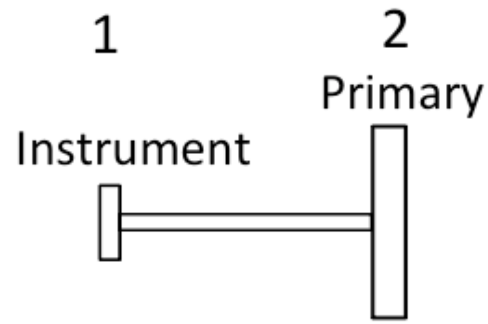
Phases to a 20-meter

1. 3 segments
2. 3 more segments
3. 12 more segments added at edge

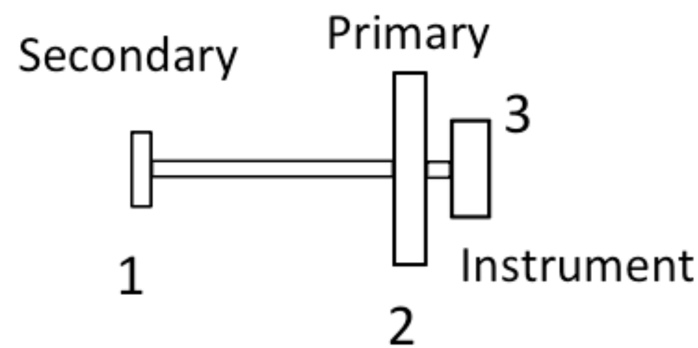
Is Prime focus an advantage? . . . .

Pointing stability is a big issue
Prime focus may be more stable

Prime focus telescope is a 2 body problem



Cassegrain telescope is a 3 body problem

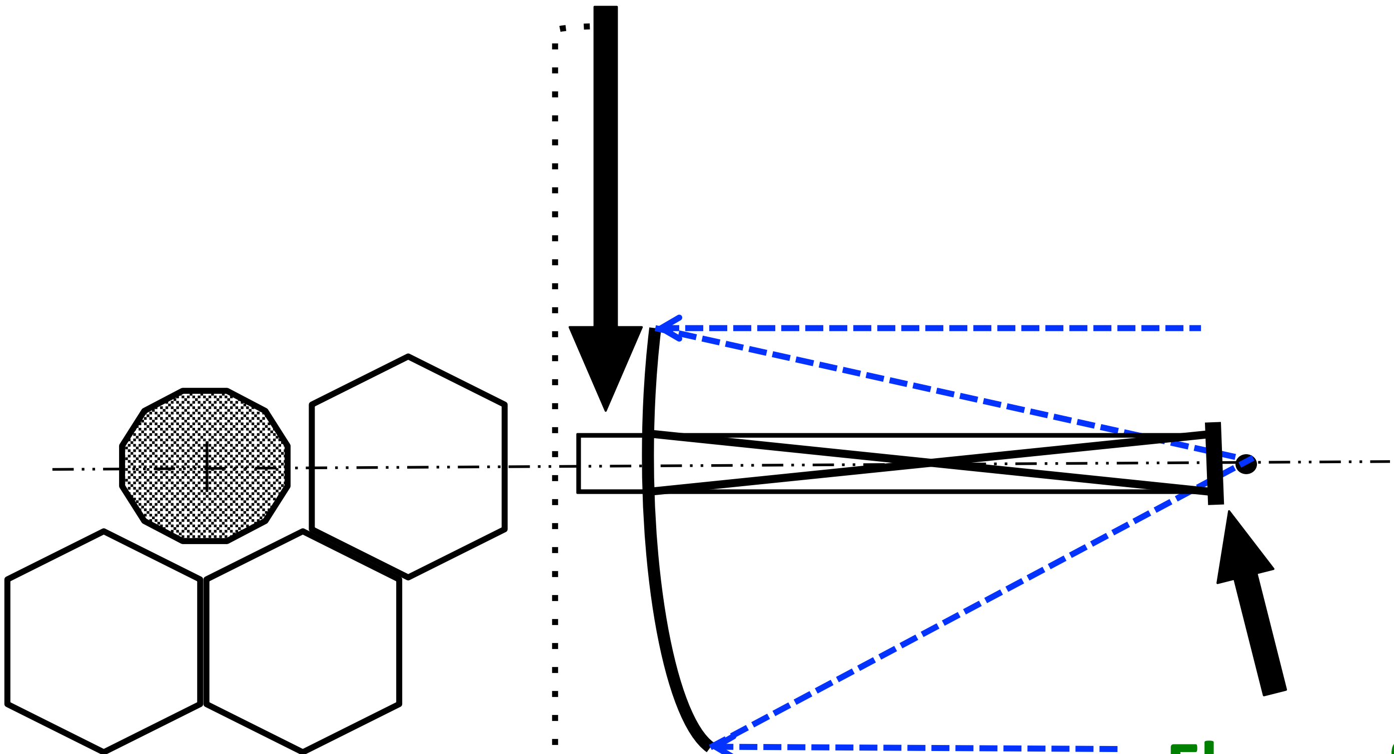


The thermal & vibration structural errors in a Cassegrain telescope are twice (2x) that for a prime focus system

Prime focus 6 x 12 m EST

Metering structure

Between vertex of the primary & the flange



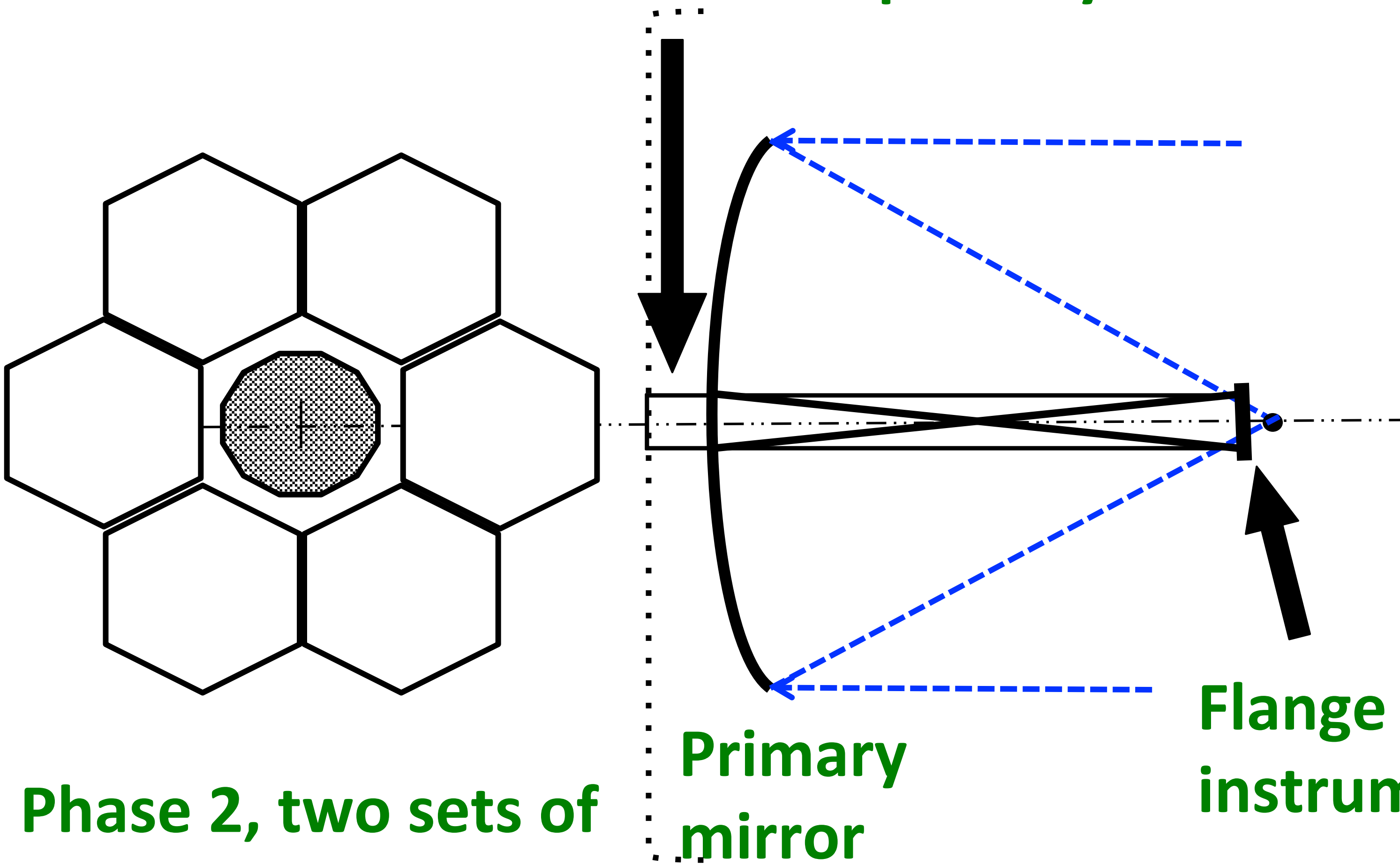
Phase 1, three segments

Primary mirror

Flange for docking instruments or Cassegrain 2nd ary

Prime focus 12-m EST

Metering structure
Between vertex of the primary & the flange

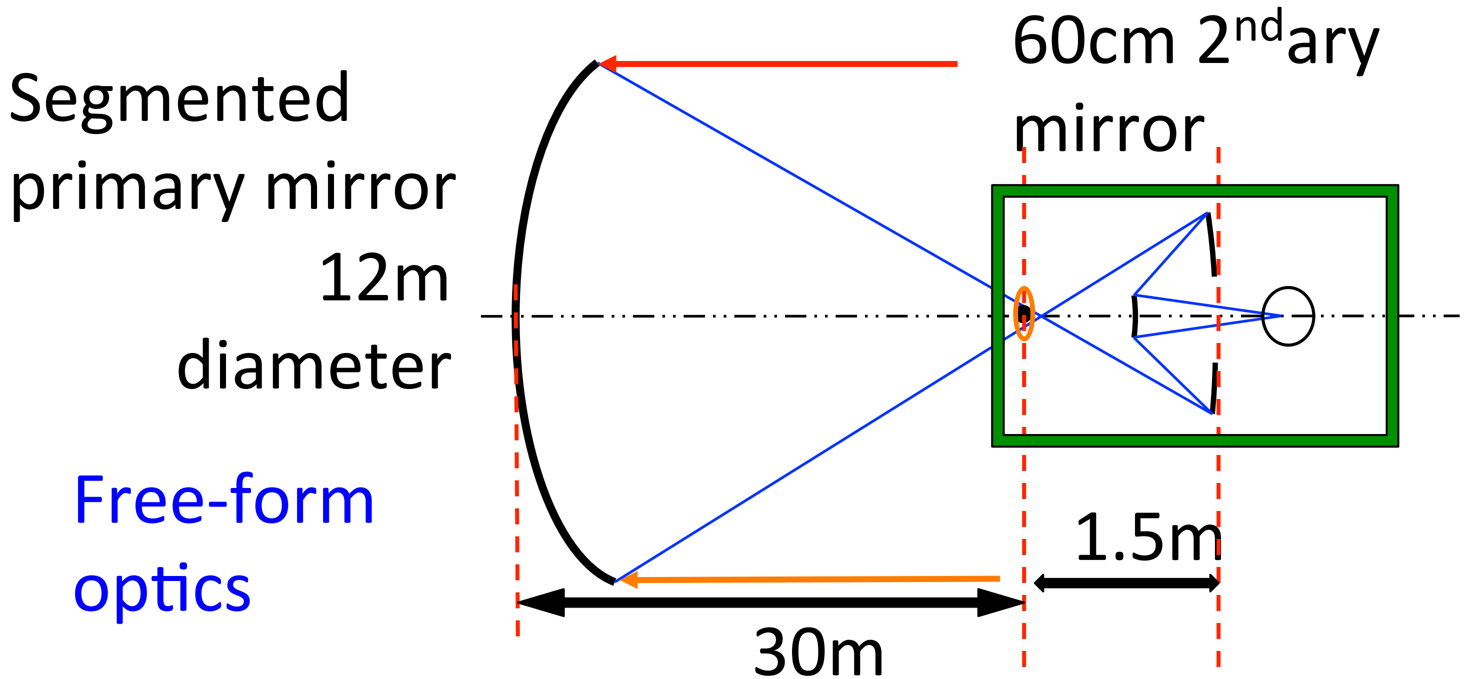


Primary mirror

Flange for docking instruments

Phase 2, two sets of Three segments=6.

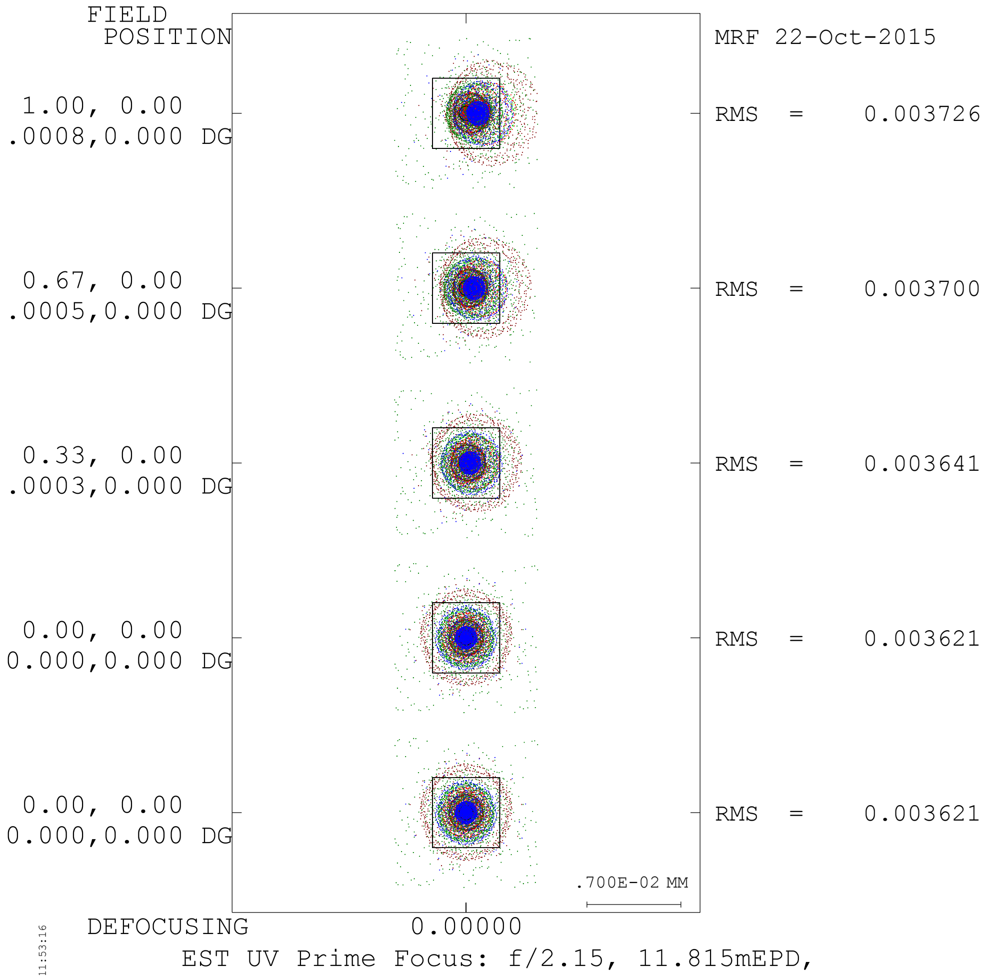
Concept for prime focus UVOIR imager



- Low polarization (no fold mirrors)
- High transmittance (few reflections)
- UV transmitting refractive correctors
- Wide field

Ray-trace quick look at single reflection filled aperture

- 2 Corrector glasses: LiF & CaF_2 @ f/2.15
- Wavelength range: 150-250 nm
- Spot diagrams over 7.8 arc sec FOV

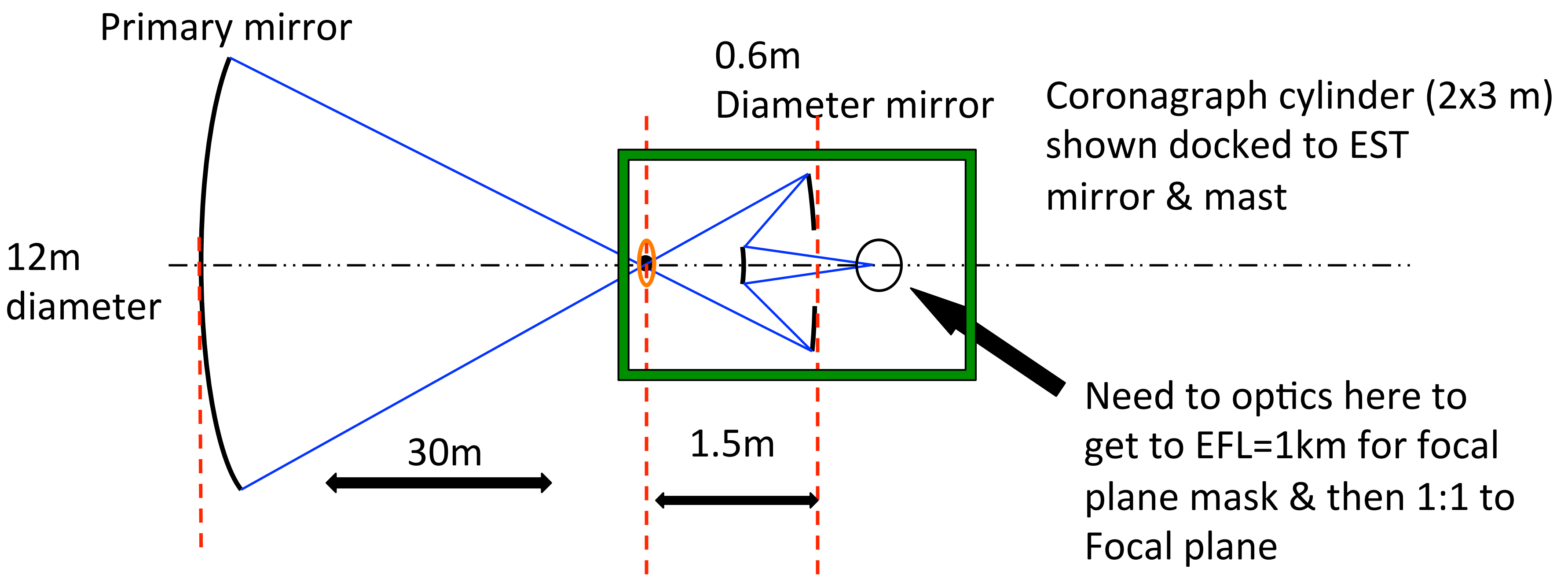


5 micron pixels

Lyot coronagraph system for prime focus EST

System minification
is 20:1
Drawing below is not to scale

- Segmented active secondary
0.6 meters diameter
To image 1:1 the primary segments
- Solid tertiary
- Refractive correctors
- Stop at prime focus controls scattered light



Breckinridge, Lam & Chipman (2015) Polarization aberrations in astronomical telescopes PASP **127**, 445 = > fold mirrors are bad for coronagraphs => EST gives potential to build a Lyot coronagraph with no fold mirrors – only powered optical elements

Lyot coronagraph system for prime focus 6x12-m EST

Pupil =>

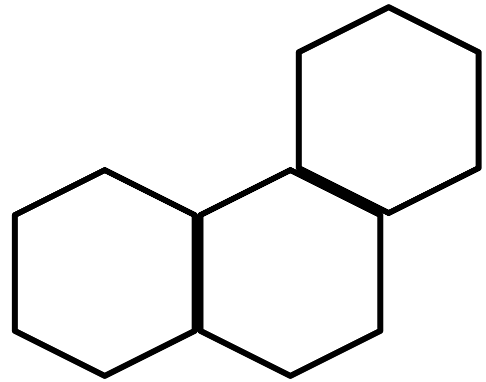
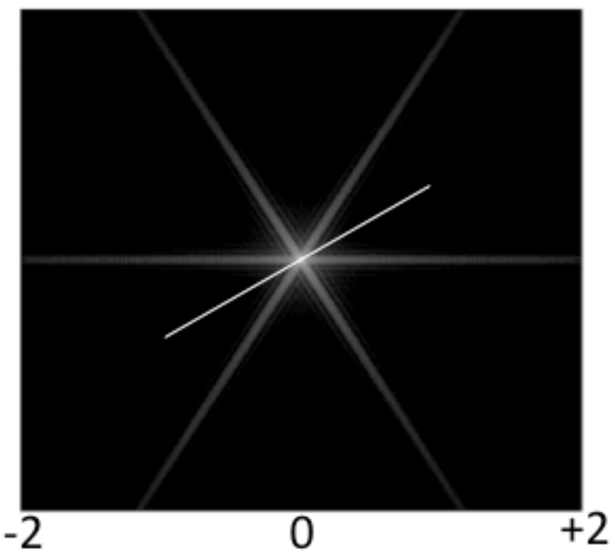
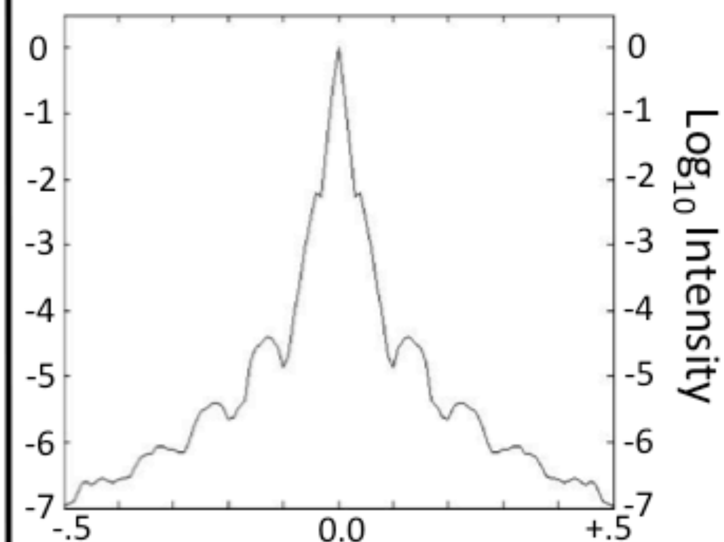


Image plane =>



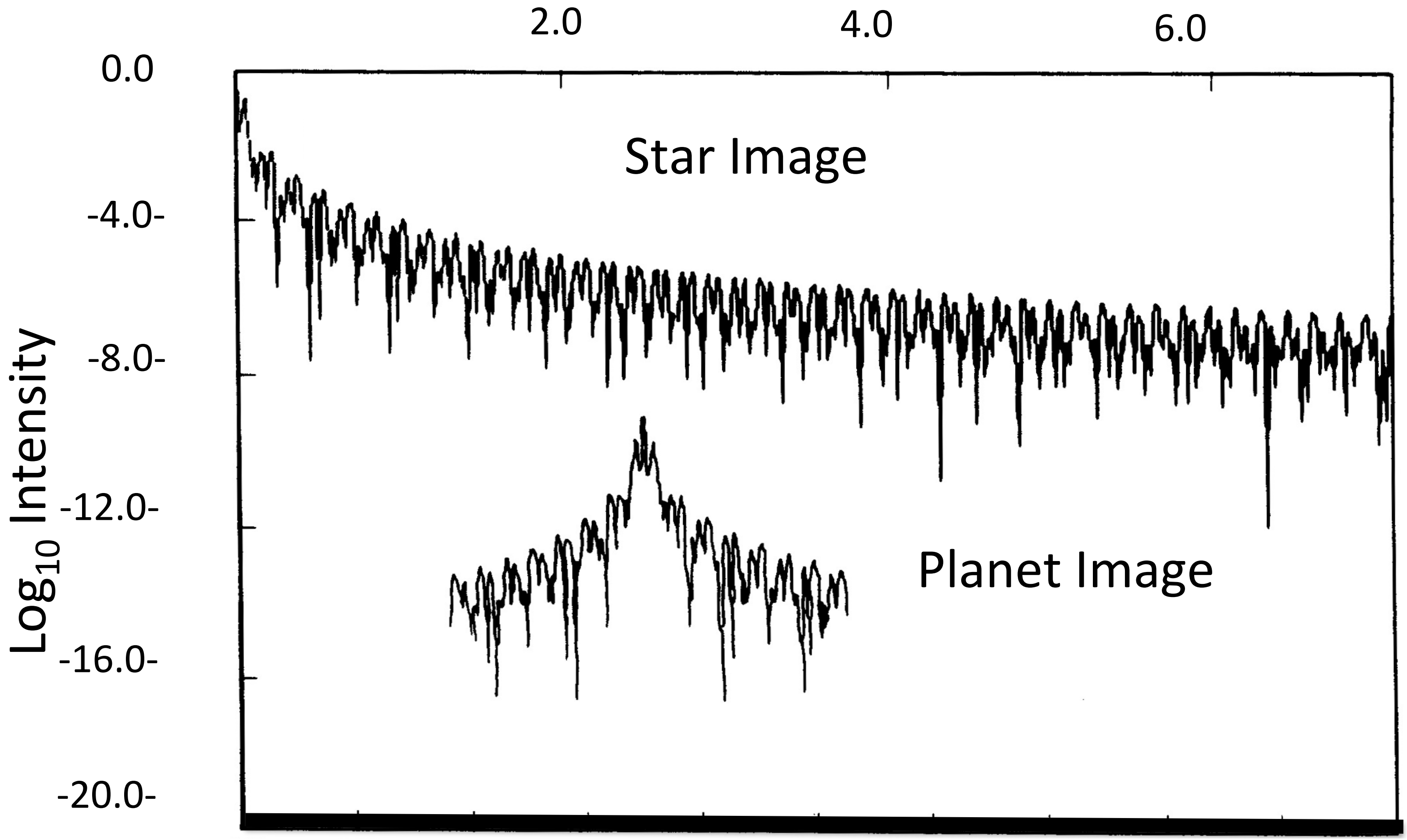


Prime focus advantages over Cassegrain

- Science applications
  - UV imaging spectroscopy (75 to 250 nm)
  - High contrast exoplanet coronagraphy ($C_T \approx 10^{-11}$)
  - Deep field imaging & spectroscopy astrophysics $(m_V \approx 35,\ \text{for 12-m})$
- Prime focus design advantages
  - Low scattered light – less complicated to baffle than Cassegrain
  - One metal/dielectric reflection to UV focal plane
  - One metal/dielectric reflection to a coronagraph mask
  - Thermally induced structural distortion: ½ Cassegrain
  - Two-reflections to an A/O in an imager
  - Minimum polarization aberrations
  - Fewer sources of polarization anisotropy

Coronagraphy

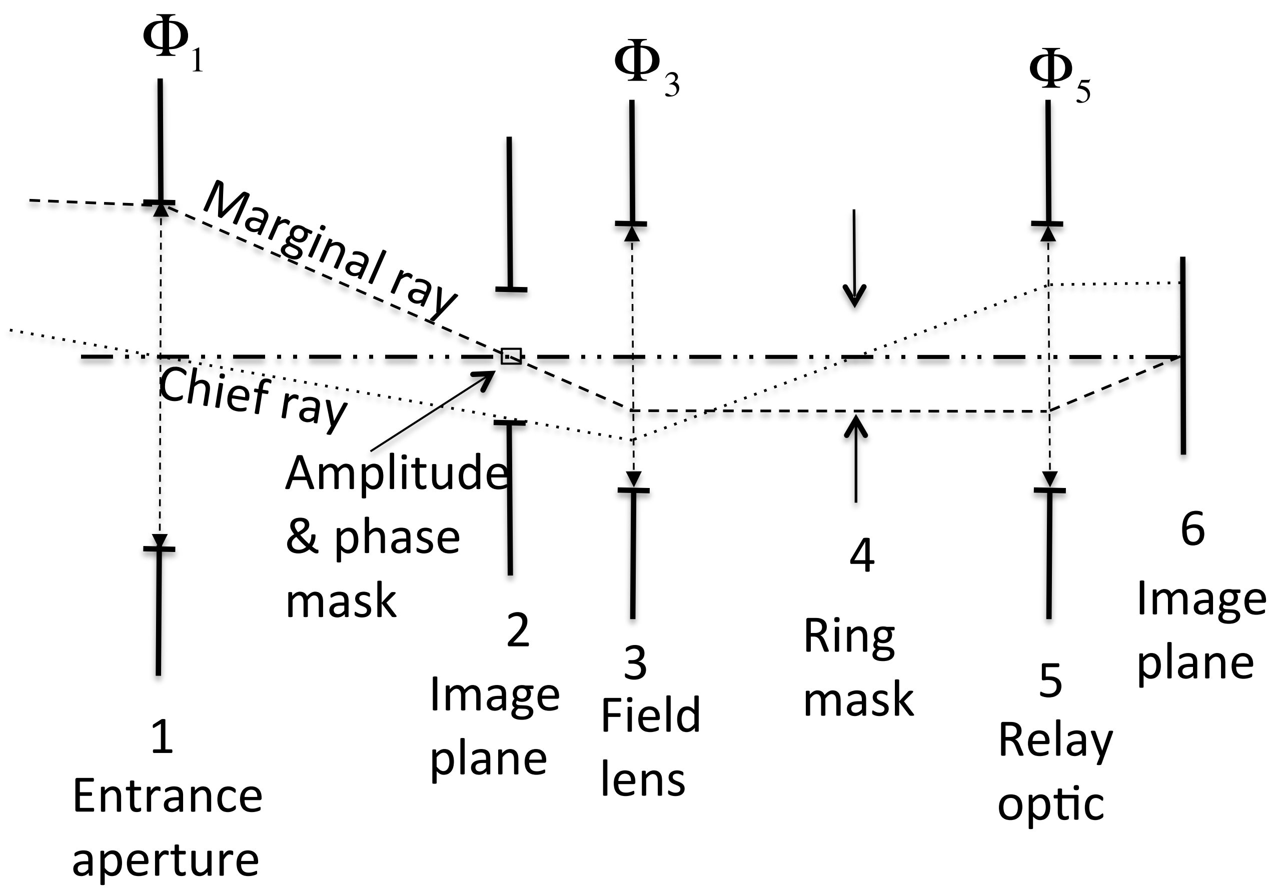
Exoplanets, which shine in light reflected from their star are much fainter than the star



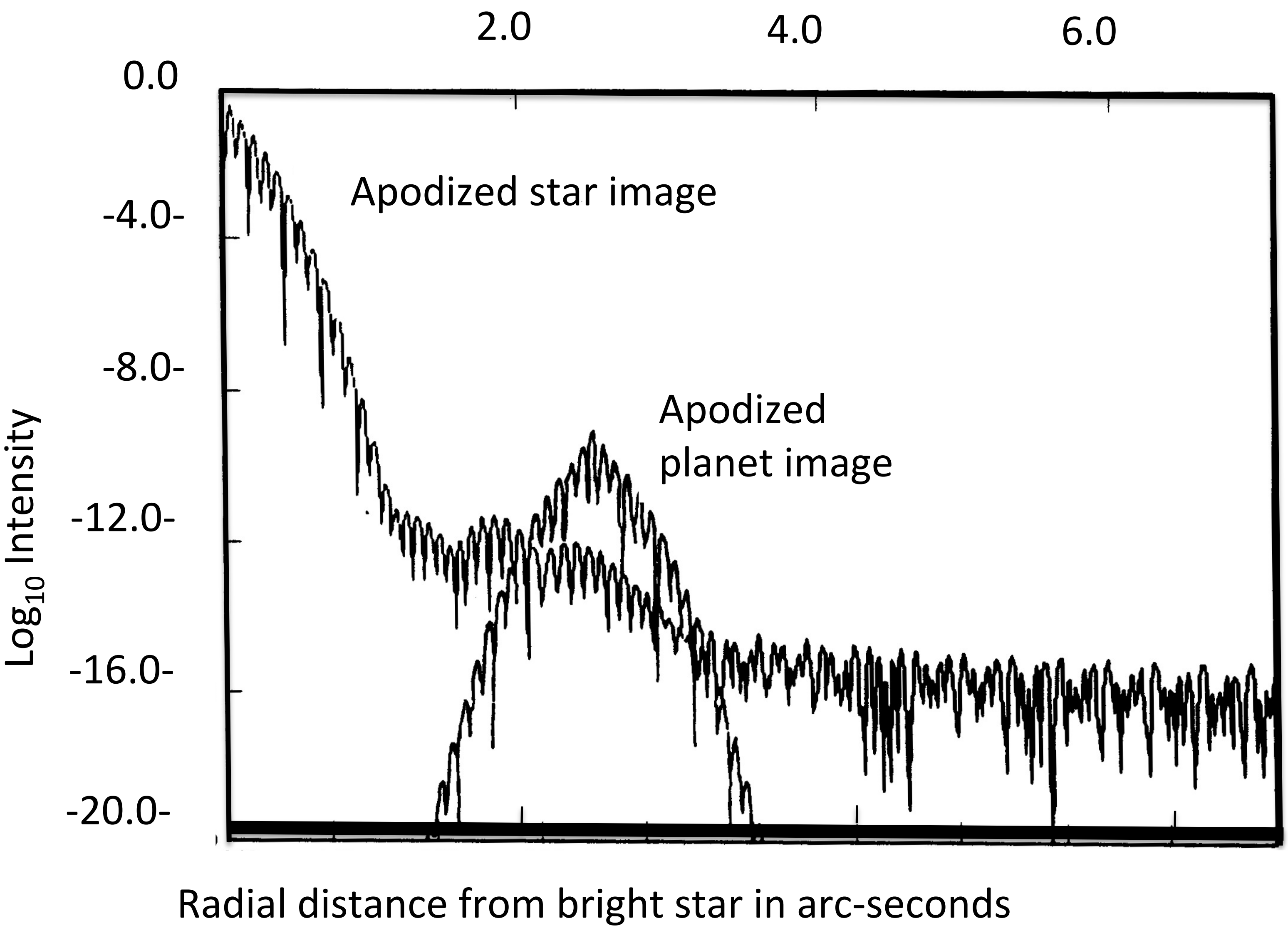
Radial distance from bright star in arc-seconds

Coronagraphy

Measure a very faint object in the presence of a very bright one.
solar research 10^{-8} & exoplanet research 10^{-12}



Apodization reveals exo planet



Thank you

Class outline

- The challenges of space optics
- Derive étendu, throughput, transmittance
  - Power to the focal plane
- Geometric aberrations: thermal, structural, metrology, tolerancing & A/O
- Scalar wave image formation
- Vector-wave image formation: polarization aberrations
- Hubble trouble

Space Optics (2)
AstrOpt2016
Derive Etendu $A\Omega$.

J. B. Breckinridge

Adjunct professor

Caltech & College of Optical Sciences

Transmittance, throughput, & vignetting

- How bright is my image?
- Can I record it?
- Parameters that describe the ability of the optical system to transmit power
- What is the diameter of my optical elements?
- Can they be fabricated or just designed!

Kirchoff's Laws

If a body of mass is at thermal equilibrium with its surrounding environment, conservation of energy requires that

$$\Phi_{incident} = \Phi_{absorbed} + \Phi_{reflected} + \Phi_{transmitted}$$

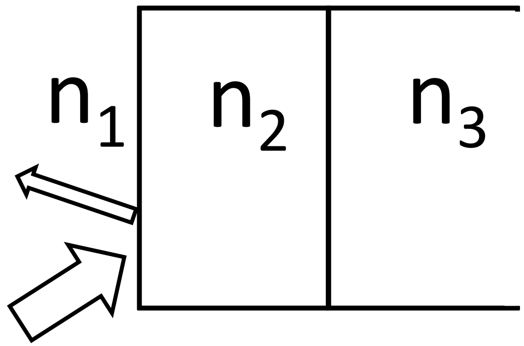
By dividing both sides by $\Phi_{incident}$, we write $\boldsymbol{\alpha + r + t = 1}$, where α is absorbtance, r is reflectance, and t is transmittance. For an opaque body where there is no transmittance ($t = 0$), the radiation is either absorbed or reflected. Therefore,

$$\text{watts absorbed} = \alpha \cdot E \cdot \text{area} = \varepsilon \cdot M \cdot \text{area} = \text{watts radiated.}$$

Minimize reflectance loss to maximize transmittance

- Antireflection coat has limitations

$$R_i(\lambda) = \frac{I_{Reflected}(\lambda)}{I_{Incident}(\lambda)}$$



If $n_2(\lambda) = \sqrt{n_1(\lambda) n_3(\lambda)}$

Then reflectance is zero & transmittance is maximized

Often a physical material with just the right $n_2(\lambda)$ does not exist

Power at the focal plane is determined by

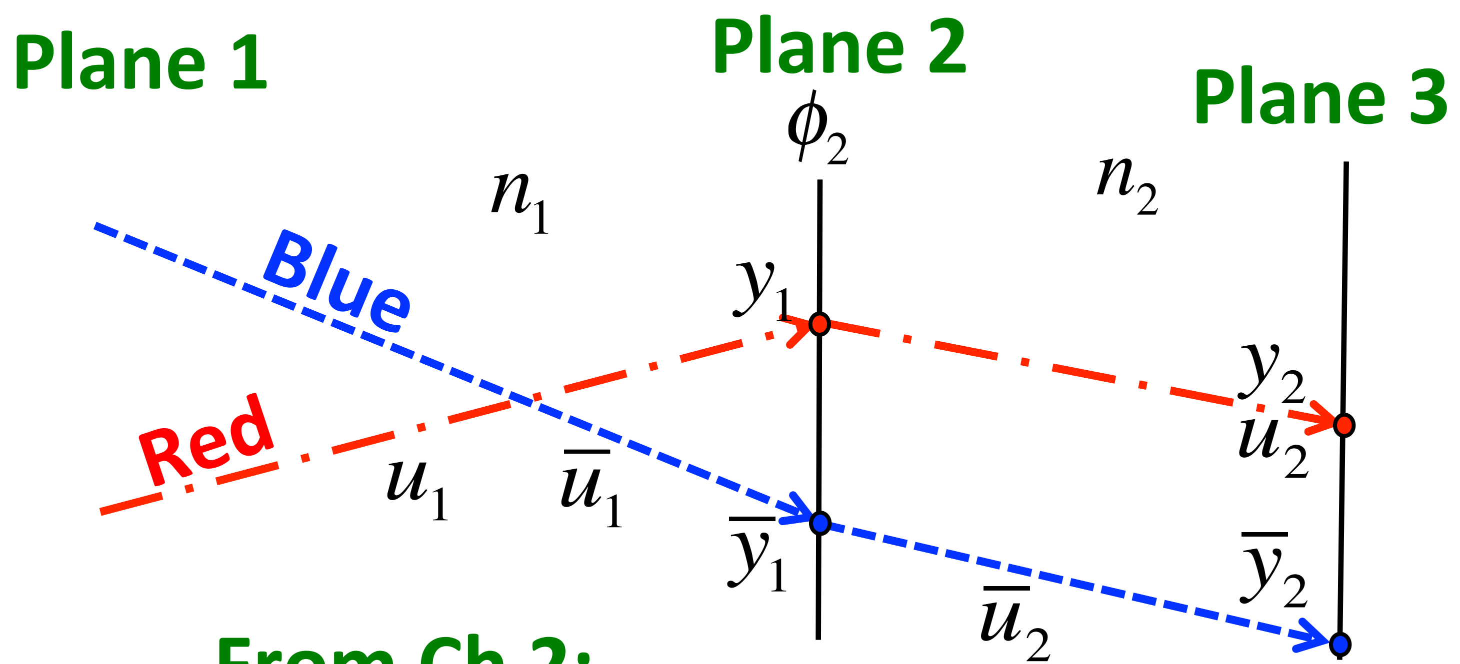
- Transmittance
- **Etendu or "through-put"**
- Polarization (discussed later)

Étendú or throughput [pp103]

- Calculated using tools of 1st order optics
- Expresses the geometric ability of an optical system to pass radiation from object space to image space
- Ray trace can indicate an excellent image but if no light gets through the system, there is no image – SNR=0.0!
- Consider 2 general rays, pass them through the optical system, then look at pupil and image planes

Étendú or throughput

Consider 2 general rays



From Ch 2:

$$n_2 u_2 = n_1 u_1 - y_1 \phi_2$$

$$n_2 \bar{u}_2 = n_1 \bar{u}_1 - \bar{y}_1 \phi_2$$

Étendú or throughput

Consider 2 general rays

$$n_2 u_2 = n_1 u_1 - y_1 \phi_2$$

$$n_2 \bar{u}_2 = n_1 \bar{u}_1 - \bar{y}_1 \phi_2$$

Recall that: $\phi_2 = (n_1 - n_2) C_2 = \dfrac{(n_1 - n_2)}{R_2}$

The optical power is the same for both rays

$$\frac{(n_2 u_2 - n_1 u_1)}{y_1} = \phi_2 = \frac{(n_2 \bar{u}_2 - n_1 \bar{u}_1)}{\bar{y}_1}$$

Re-group the terms

Then we discover that there is an invariant between any two planes in the optical system

Invariant on refraction

$$n_1 \bar{u}_1 y_1 - n_1 u_1 \bar{y}_1 = n_2 \bar{u}_2 y_1 - n_2 u_2 \bar{y}_1 = H$$

Étendú, Helmholtz, LaGrange Invariant

$$n_1\left(u_1\bar{y}_1 - \bar{u}_1 y_1\right) = n_2\left(\bar{u}_2 y_2 - u_2\bar{y}_2\right) = \mathrm{H}$$

Rewrite this equation with the object plane on the LHS

$$y_1 = 0$$

And and the pupil plane on the right hand side

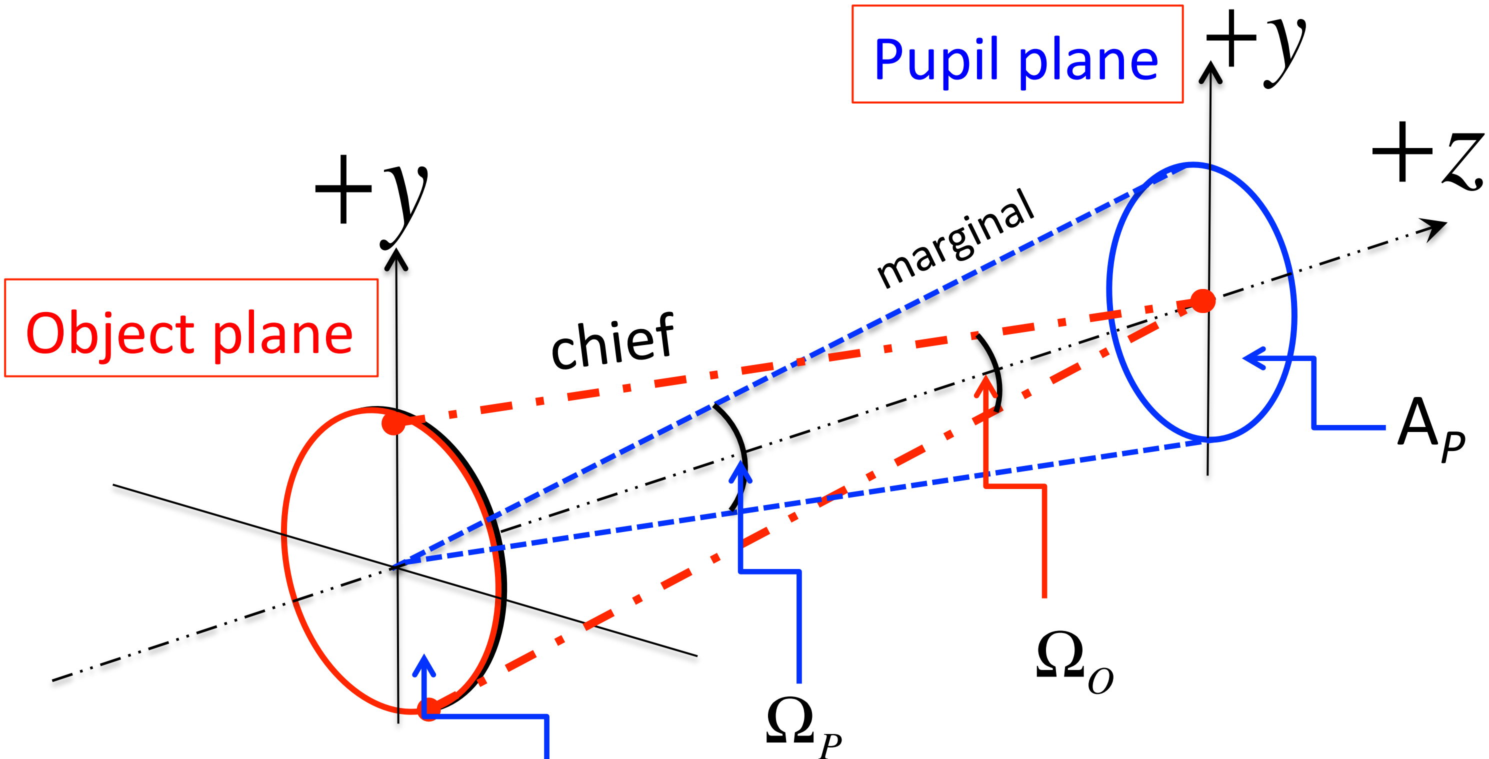
$$\bar{y}_2 = 0$$

Then

$$n u \bar{y}_1 = n \bar{u} y_2 = \mathrm{H}$$

H has units of angle × distance, e.g., radians × centimeters.

Area solid angle product



$$A_O \Omega_P = A_P \Omega_O$$

Confusion?

- Transmittance, transmission, transmissivity - **dimensionless**
- Throughput, etendu, Optical Invariant

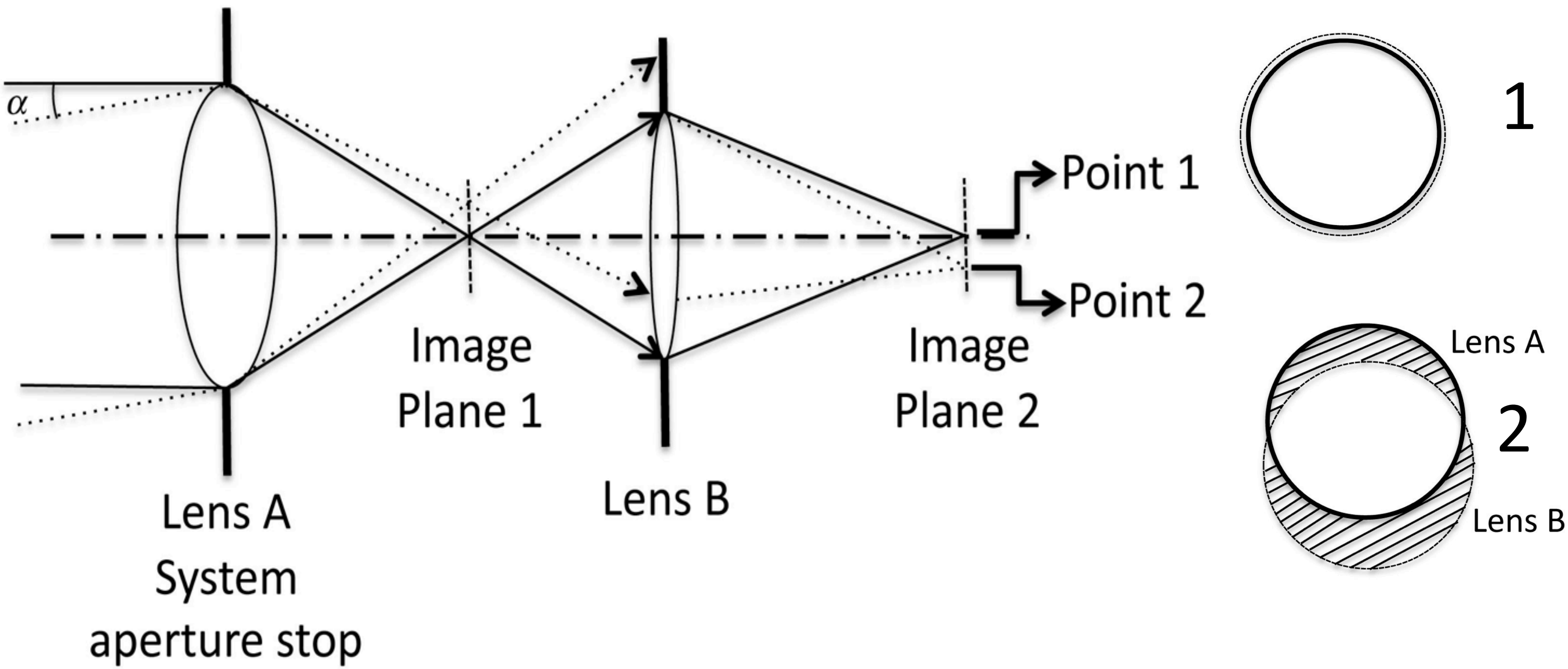
- Units of solid angle × Area, when calculating optical system capacity to transmit radiative power

- Units of radians × length for optical ray trace design

Useful relationships

$$\Omega = \frac{\pi}{4\left(f\#\right)^2}$$

Vignetting: Étendú is not conserved at field points



For no vignetting, the radius of the *k*th surface must be

$$R_k \geq |y_k| + |\bar{y}_k|.$$

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Geometric aberrations

J. B. Breckinridge
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