Optical systems for space-based scientific remote sensing

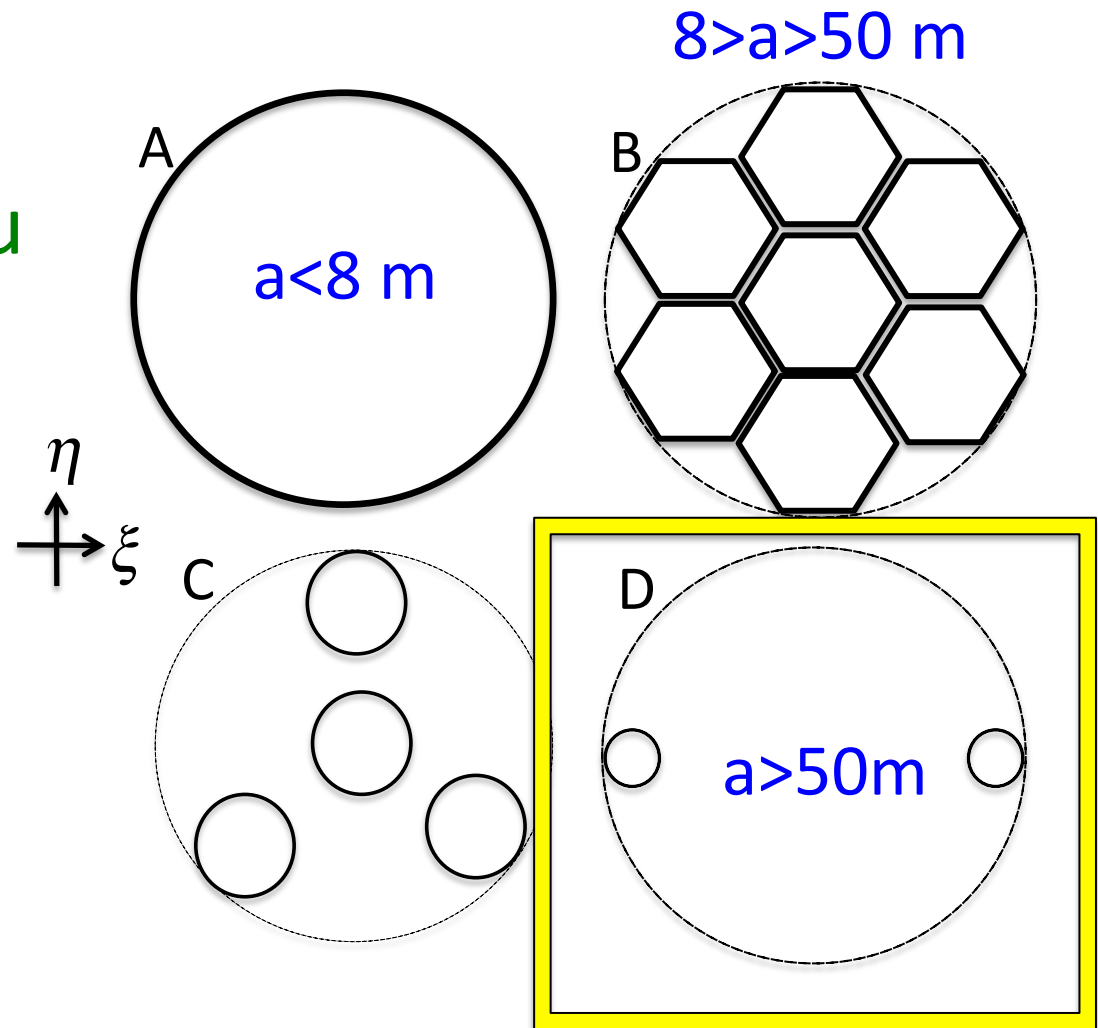University of Arizona

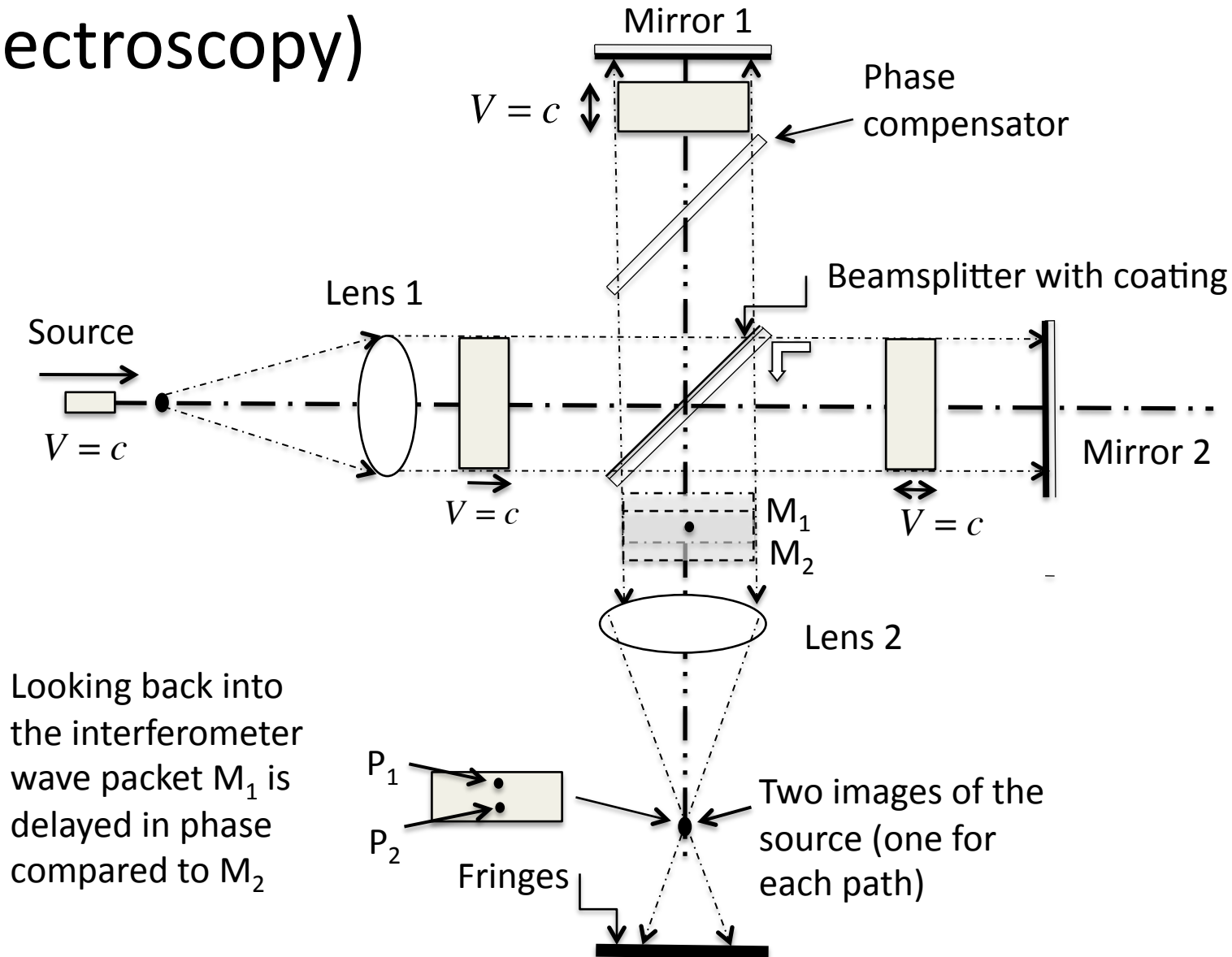January 28, 2014

Dr. James Breckinridge

Pasadena, CA.

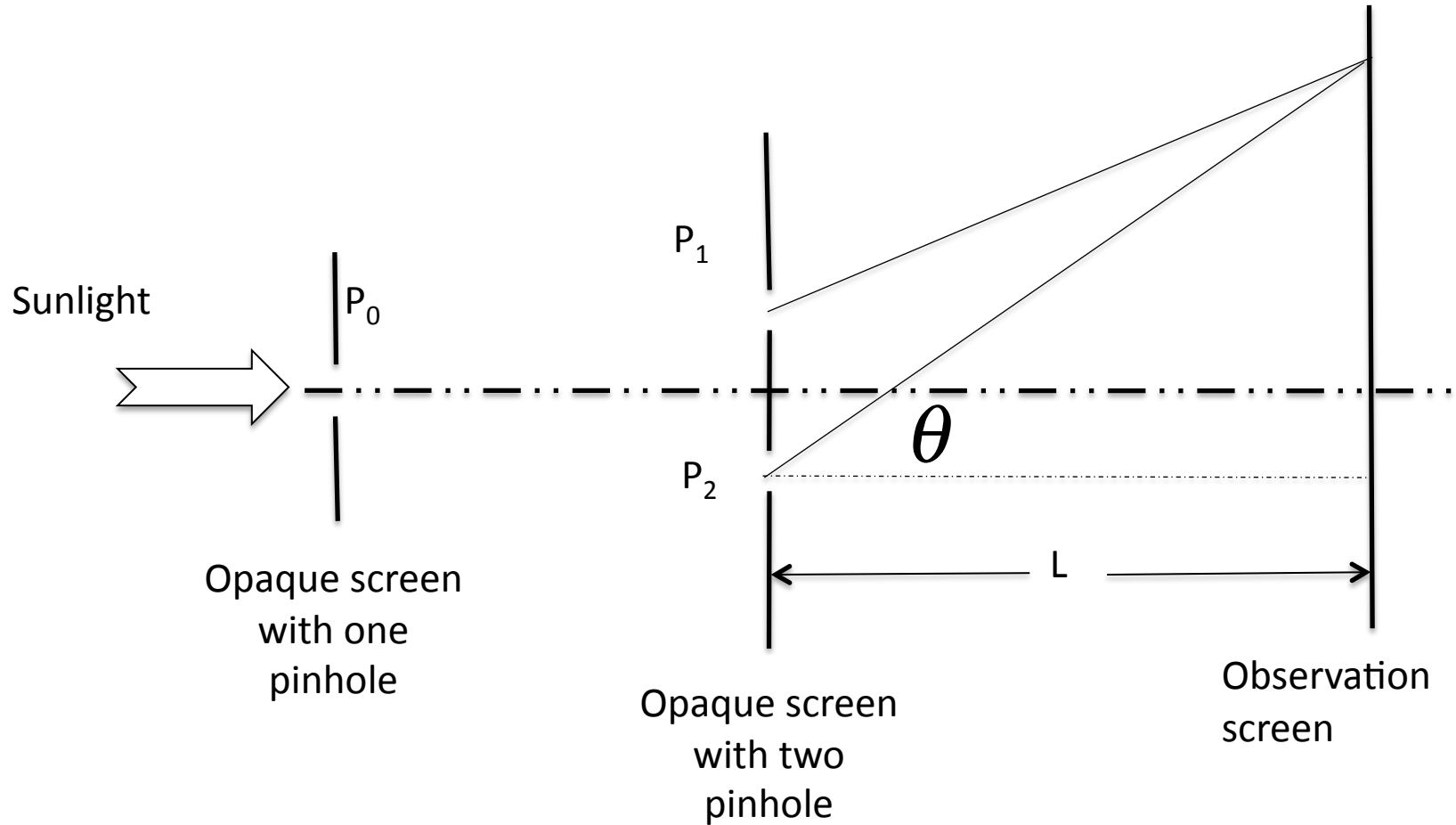jbreckin@optics.arizona.edu

interferometer aperture

- What kind of aperture are you going to build?

- Angular resolution is more important than power at the image plane

A a<8 m

B 8>a>50 m

C

D a>50m

η

ξ

Temporal frequency interferometry (Spectroscopy)

Mirror 1

Phase compensator

$V = c$

Beamsplitter with coating

Lens 1

Source

$V = c$

$V = c$

M_1
M_2

$V = c$

Mirror 2

Lens 2

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

P_1

P_2

Fringes

Two images of the source (one for each path)

Spatial frequency interferometry: Young's double slit experiment

Sunlight

P_0

P_1

P_2

θ

L

Opaque screen with one pinhole

Opaque screen with two pinhole

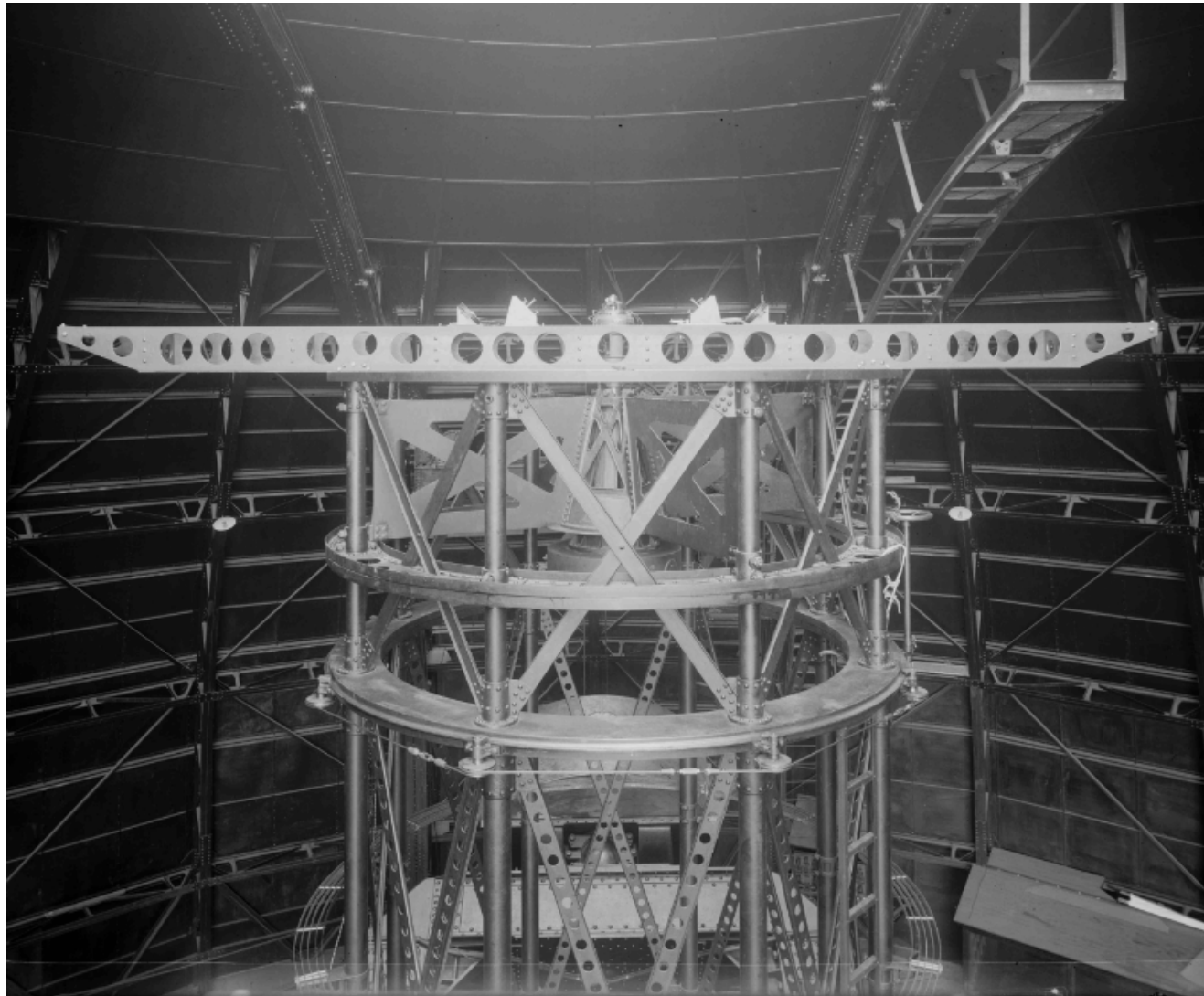Observation screen

Fizeau Interferometer

He took Young's **WHITE-LIGHT** double slit experiment and used its principles for astronomy recognized we could measure star dia.
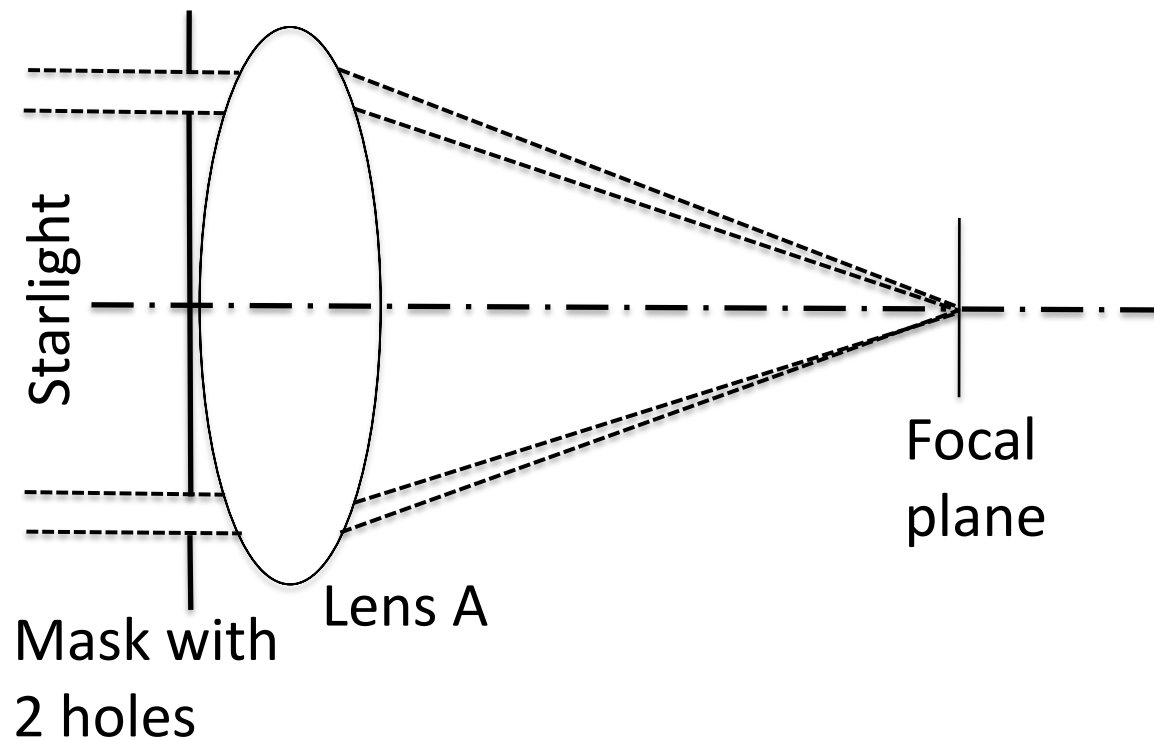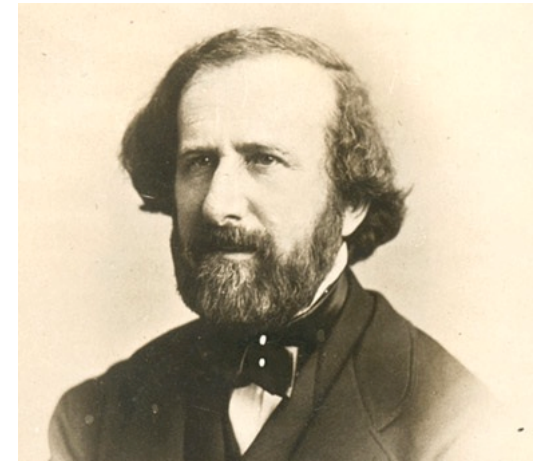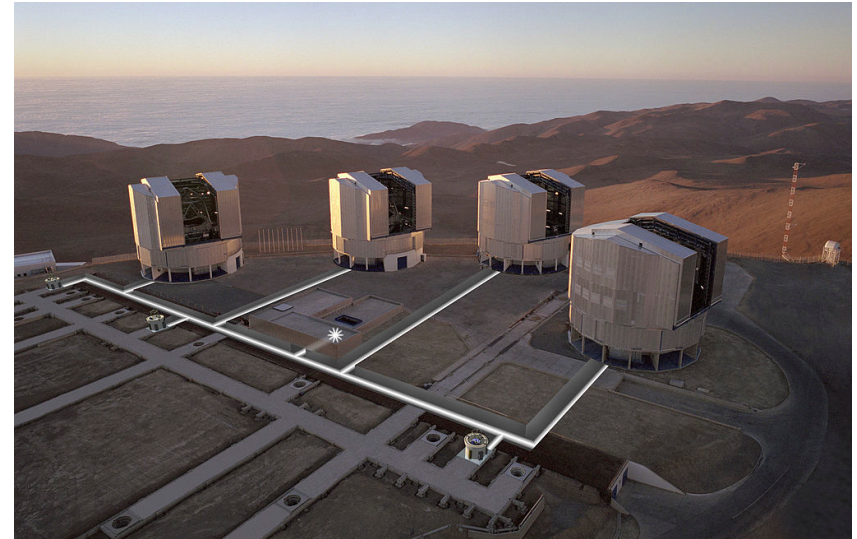
Michelson's Interferometer @ 100-inch

Interferometer

- ESO very large telescope interferometer (VLTI) – Paranal Chile

- Navy prototype optical interferometer (NPOI) – Flagstaff, AZ

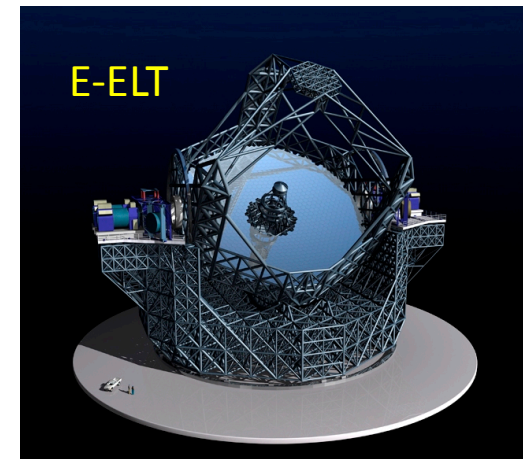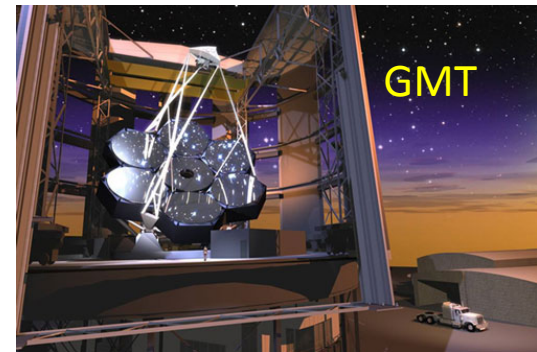- Center for high angle resolution astronomy (CHARA)

Era of ELTs (2016 -)

A new generation of 20-42m ELTs is being designed:

• Thirty Meter Telescope (www.tmt.org)   - Caltech, UC, Canada + poss. Japan   - 30m f/1 primary via 492 ⊠ 1.4m segments   - $80M design underway (2004-2009)   - $760M construction cost (FY2006)   - major fund-raising already underway

TMT

• Giant Magellan Telescope (www.gmto.org)   - Carnegie, Harvard, Arizona, Texas,   Australia + others   - 21m f/0.7 primary via 6 ⊠ 8.2m segments   - funds for $50M design study being raised

GMT

• European ELT (www.eso.org/projects/e-elt)   - 42m f/1 primary with 900+ ⊠1.4m segments   - 5 mirror design   - 57M Euros design underway (2007-)

E-ELT

How will these AO-designed ELTs affect ground-space synergy and space astronomy?
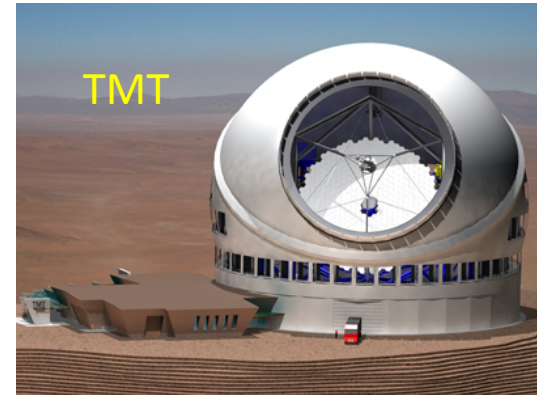
Space science system development flow

Build (detail design, fab, test, align, calibrate)

Yes

Assess progress ← No

Implement
- Design effort
- Technology program
- Cost and schedule studies

Yes

Risk assessment (technology, cost & schedule) → No

Point design

System architecture

Functional Requirements

Science measurement objectives

Rebalance the system requirements to manage performance, cost and schedule

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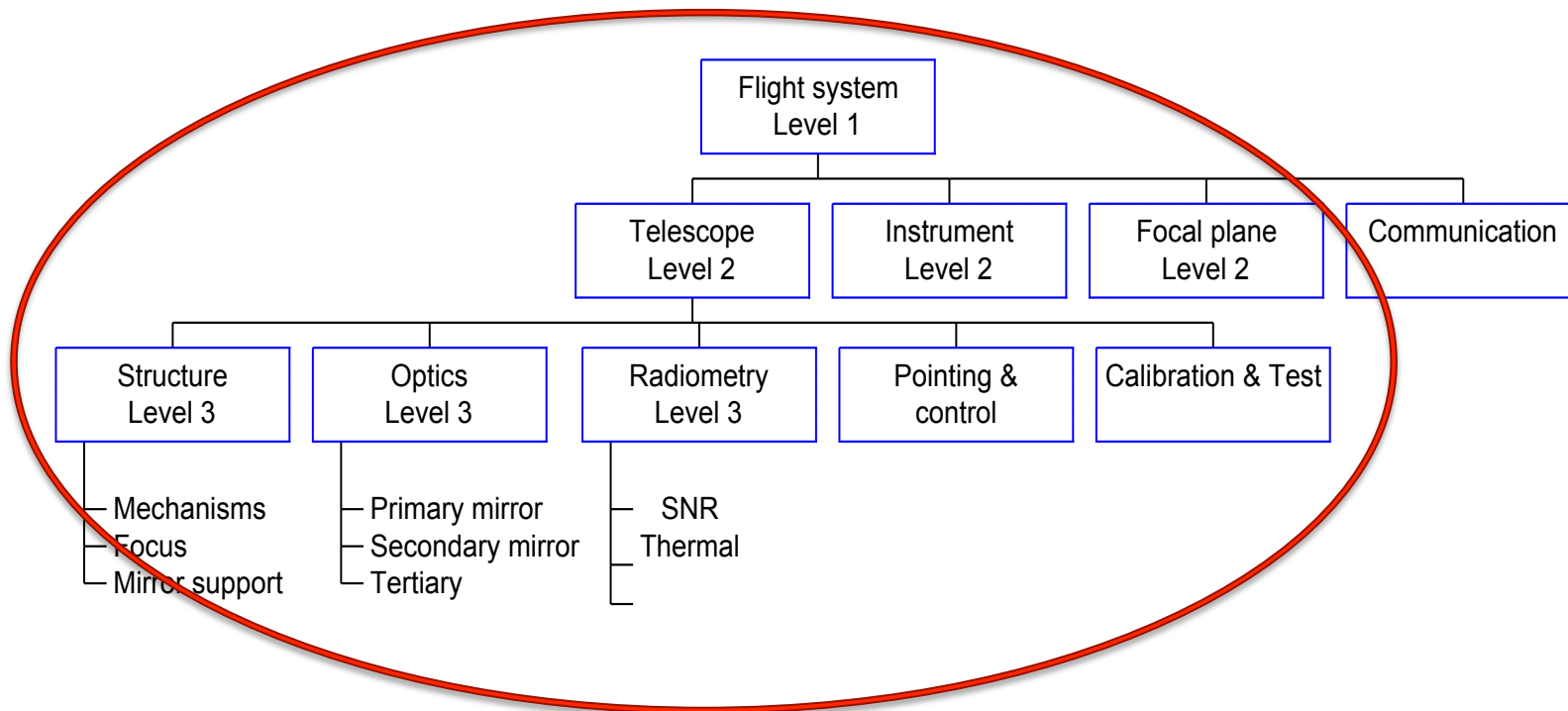
- Create a work-breakdown structure (WBS)
- Assign personnel to jobs in the WBS you know they can do – or accept responsibility to do
- Create a work plan with schedule, cost and performance
  - Develop a list of tasks that need to be done
  - Negotiate with your team who is going to do which task
 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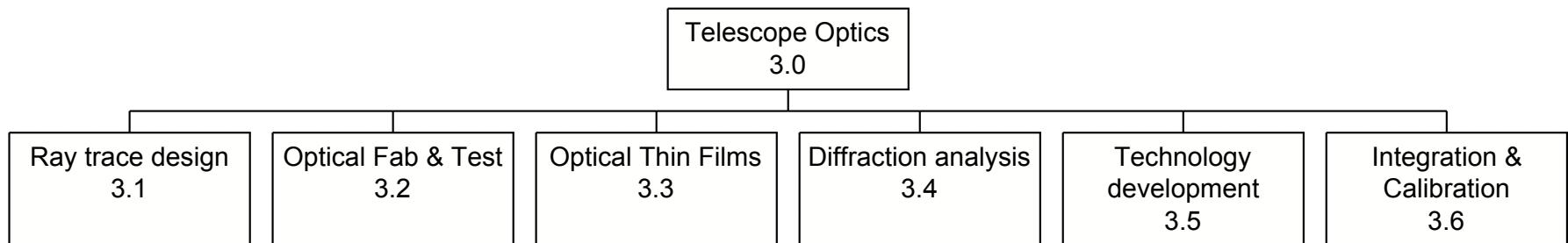
What is a work break down structure?

- 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

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.

```
                          Flight system
                            Level 1
        ┌──────────────────────┼──────────────┬──────────────┐
   Telescope            Instrument        Focal plane    Communication
    Level 2               Level 2           Level 2
 ┌──────┬──────────┬──────────────┬──────────────┐
Structure   Optics      Radiometry    Pointing &    Calibration & Test
 Level 3    Level 3       Level 3       control

├ Mechanisms   ├ Primary mirror    ├  SNR
├ Focus        ├ Secondary mirror  ├ Thermal
└ Mirror support └ Tertiary
```

Example WBS

```
                        ┌─────────────────┐
                        │ Telescope Optics│
                        │      3.0        │
                        └────────┬────────┘
     ┌──────────┬──────────┬─────┴─────┬──────────┬──────────┐
┌─────────┐ ┌─────────┐ ┌─────────┐ ┌─────────┐ ┌─────────┐ ┌─────────┐
│Ray trace│ │Optical  │ │Optical  │ │Diffract.│ │Technology│ │Integr. &│
│design   │ │Fab &Test│ │Thin Film│ │analysis │ │develop.  │ │Calibrat.│
│  3.1    │ │  3.2    │ │  3.3    │ │  3.4    │ │  3.5     │ │  3.6    │
└─────────┘ └─────────┘ └─────────┘ └─────────┘ └─────────┘ └─────────┘
```

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

Tuesday, January 28, 2013

- 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 29, 2013

- 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

Thursday January 30, 2013

- Science in the noise

- Hubble space telescope
  - How the error occurred
  - Findings of the failure board
  - Hunt for the optical prescription
  - Approaches to the "optical repair"
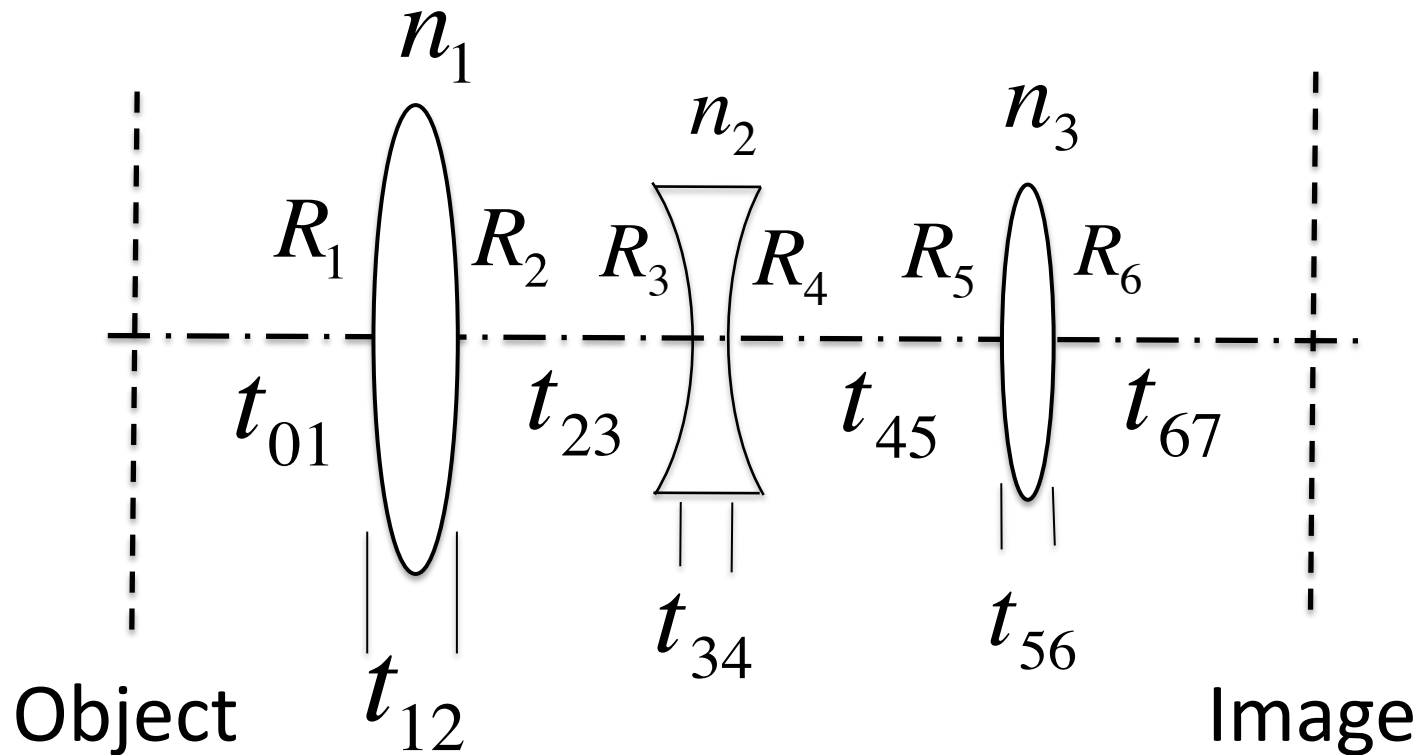 - Fix for the NASA/JPL Wide Field & Planetary Camera
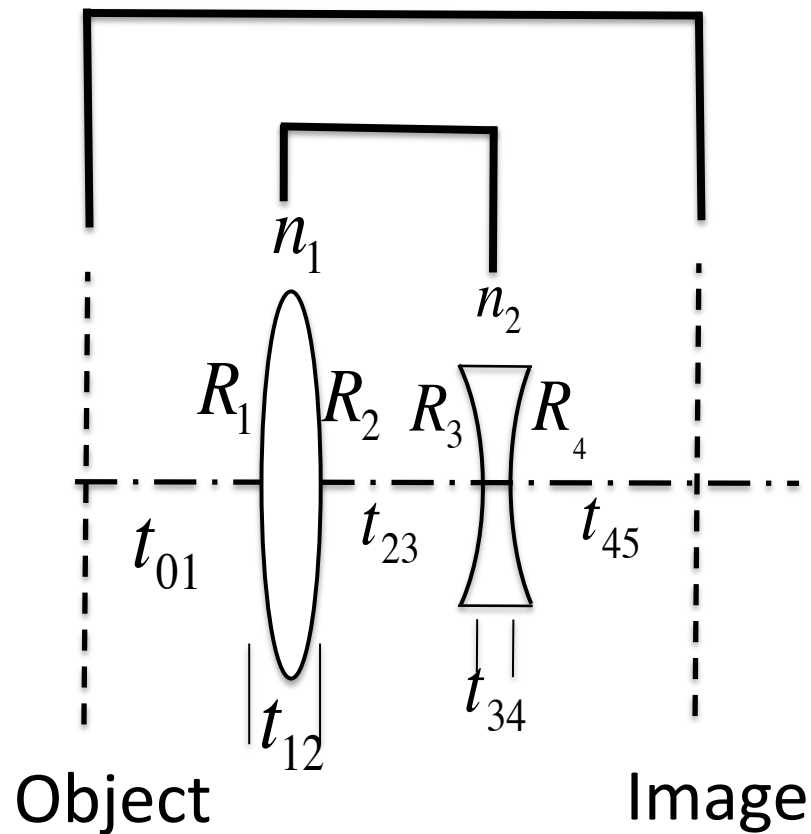
Triplet has 19 degrees of freedom

8 Surface curvatures (including object and image)
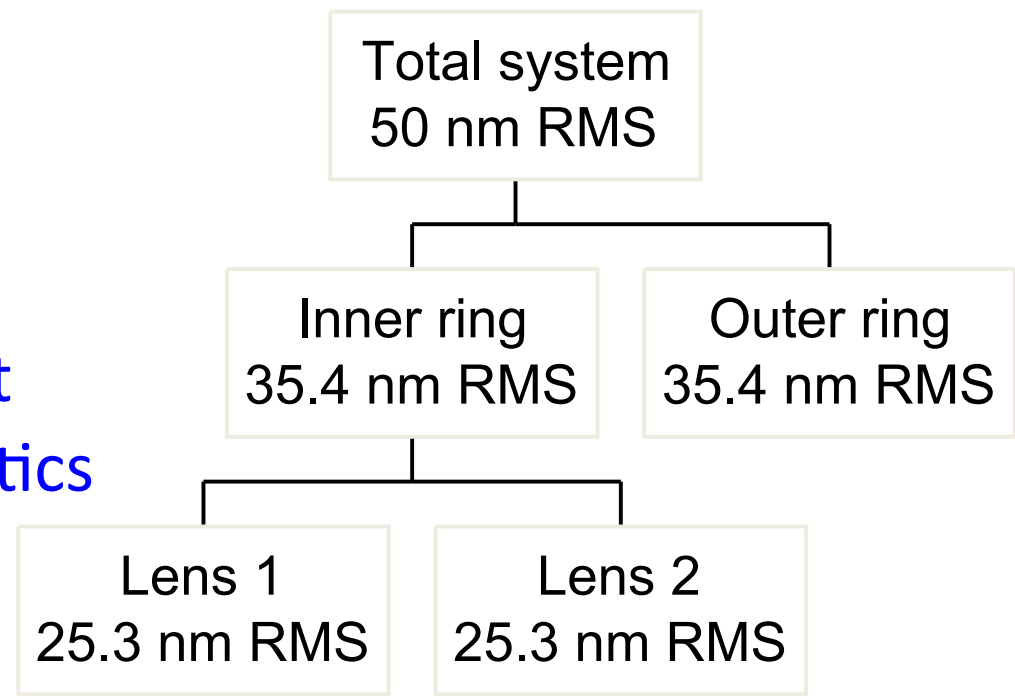
7 Spacings

3 Indices of refraction

1 Entrance stop location

RMS Wavefront specification

But this assumes wavefront errors obey Gaussian statistics And that is not always the case

Total system 50 nm RMS

Inner ring 35.4 nm RMS

Outer ring 35.4 nm RMS

Lens 1 25.3 nm RMS

Lens 2 25.3 nm RMS

Work flow

Preliminary design review

Detail ray trace

Detail focal plane engineering

Tolerance analysis

Mechanical Design

Pointing & Tracking & SNR

Test and validation plan

Specify subsystems
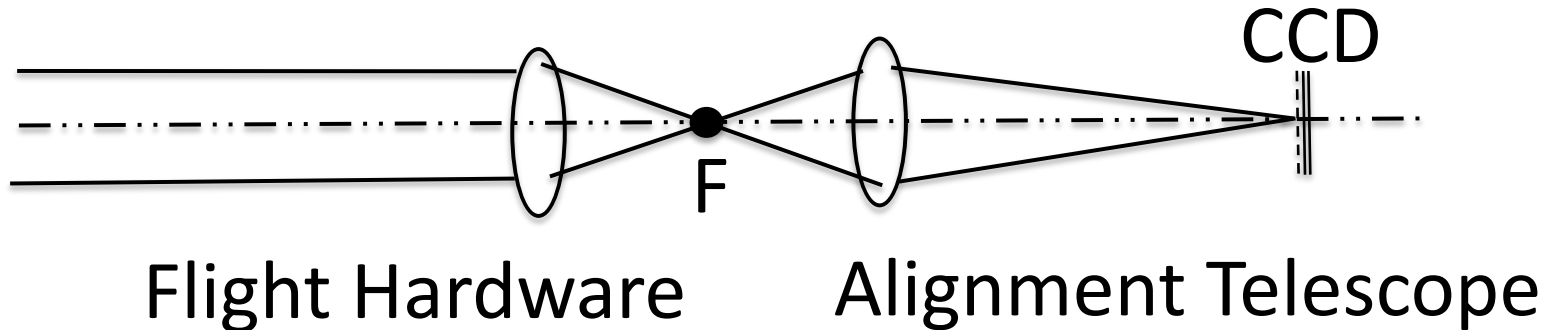
Critical design review

20

Challenges

- Better is the evil of good enough
- Haste makes waste (focus test example)
  - Usually do not build hardware with a focus knob
- You plan the job assuming the A team will do the work then wind up executing the job with the B or C team!
- Cabling, handling equipment
- Ground support equipment (GSE)
  - Communications with satellite
  - Calibration equipment
  - End to end verification at Launch pad

Haste makes waste

- Space craft and instruments take time to outgas to vacuum of space. Turn them on to soon, power supplies arc and the satellite electronics burns up

- Cryogenic telescopes burn thru cryogen unless careful
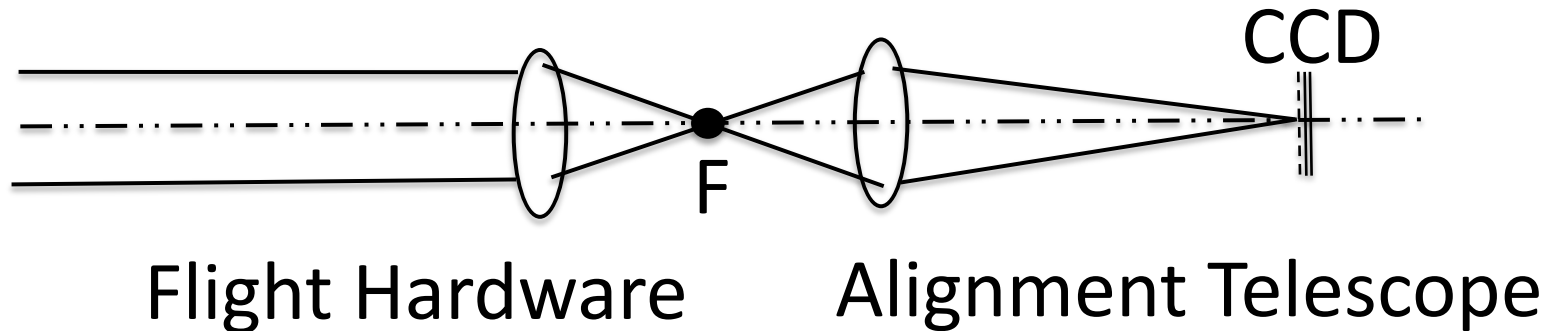
- Careless alignment tests –

Haste makes waste!

Objective is to measure the physical position of focus (F)
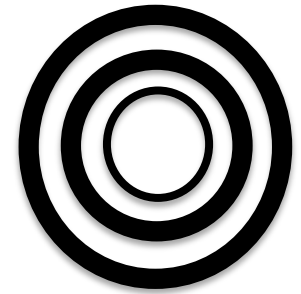
CCD

F

Flight Hardware

Alignment Telescope

The engineer set up the measurement and discovered that the CCD saturated.
There were no neutral density filters available in time to complete the measurement.

23

Haste makes waste!

CCD

F

Flight Hardware   Alignment Telescope

The optical engineer built a mask and placed it over the entrance aperture of the alignment telescope to reduce the intensity on the CCD
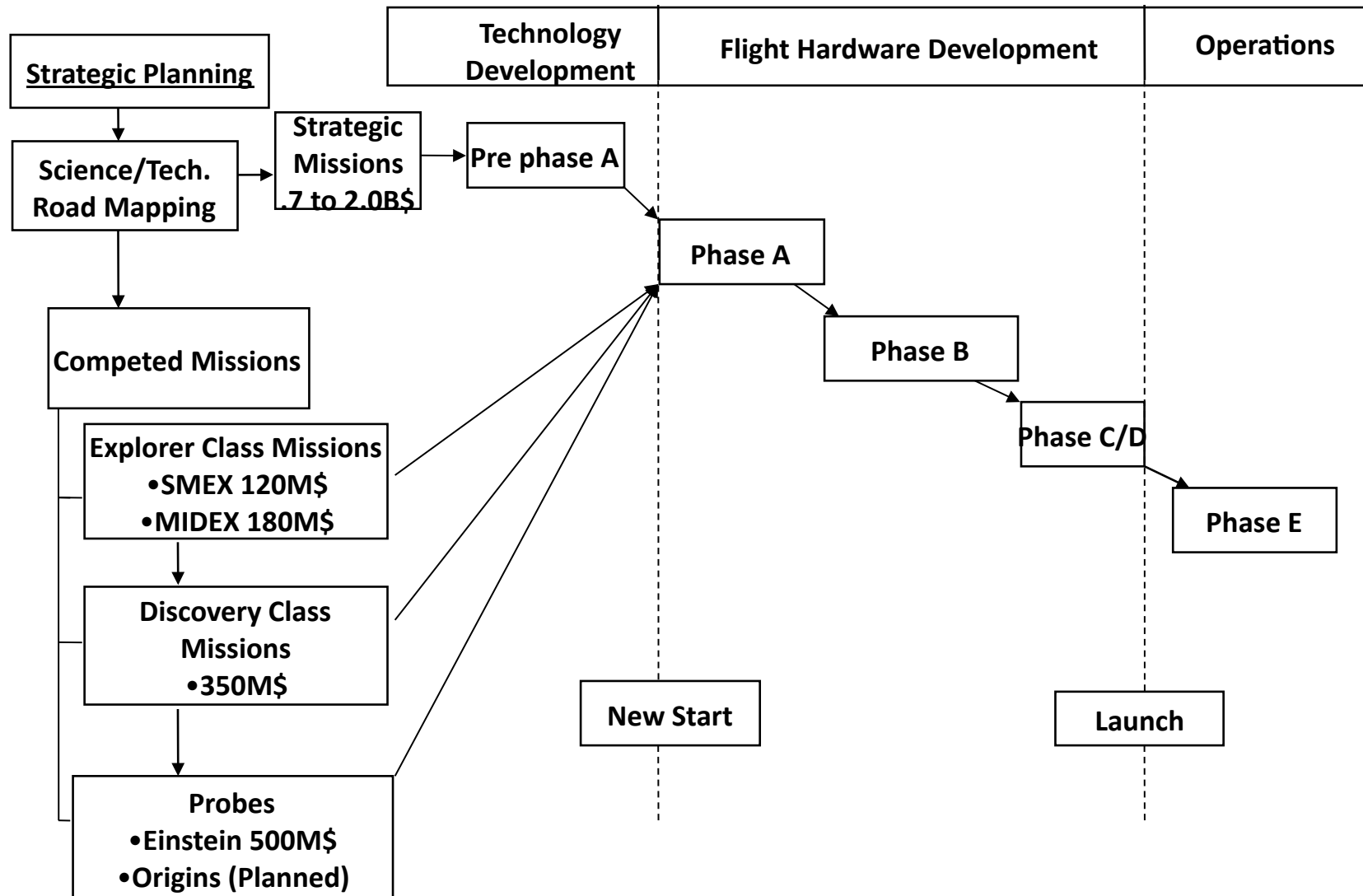
His apparatus measured <u>a</u> focal position F and recorded all of his data. He then went to bed – it was 3:00 AM!.

At 7:00 AM the flight hardware was shipped to the Cape

A week later the engineer reduced his data and announced the hardware was in error

The NASA road to success

Technology Development	Flight Hardware Development	Operations

Strategic Planning

Science/Tech. Road Mapping

Strategic Missions .7 to 2.0B$

Pre phase A

Phase A

Competed Missions

Explorer Class Missions
•SMEX 120M$
•MIDEX 180M$

Discovery Class Missions
•350M$

Probes
•Einstein 500M$
•Origins (Planned)

Phase B

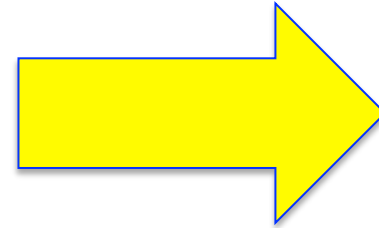Phase C/D

Phase E

New Start

Launch

<10 Years

The road to successful strategic ($1B) missions

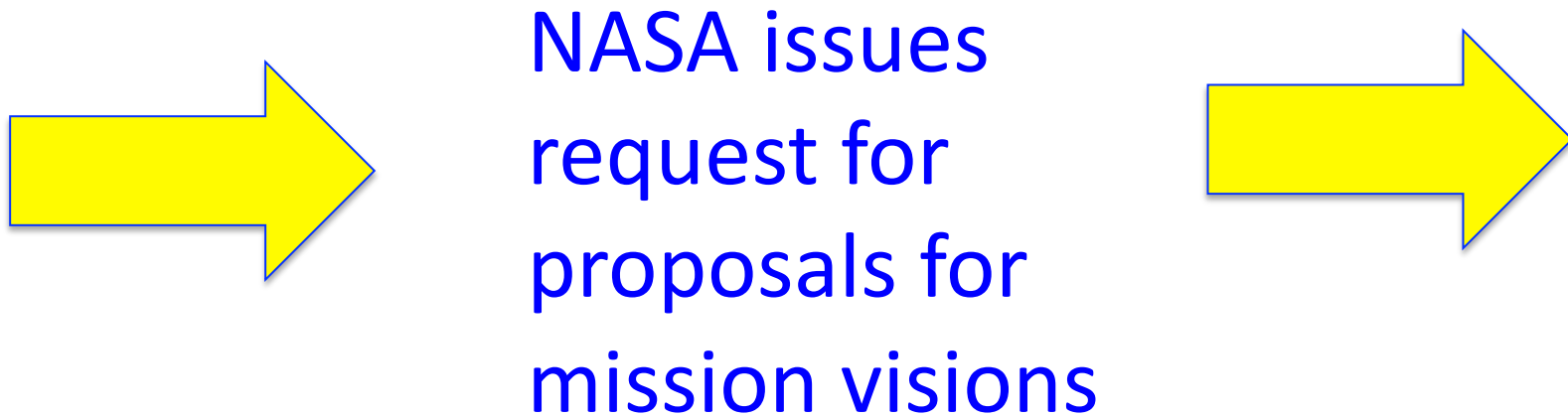Strategic
Planning

Where is science going?

Can the science be done from the ground?

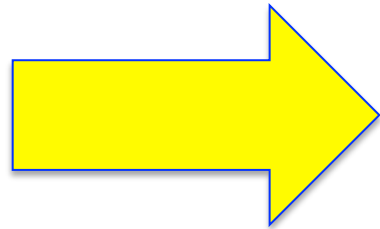Compatible with the mission of the agency?

Telescope & Instrument ideas?

Support by the National Academy of Science?

The road to successful strategic missions

NASA issues request for proposals for mission visions

Multiple science measurement objectives
within a single vision mission
to satisfy as many communities as possible
[Build advocacy]

The road to successful strategic missions

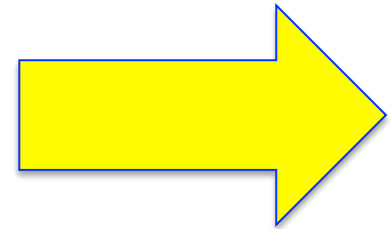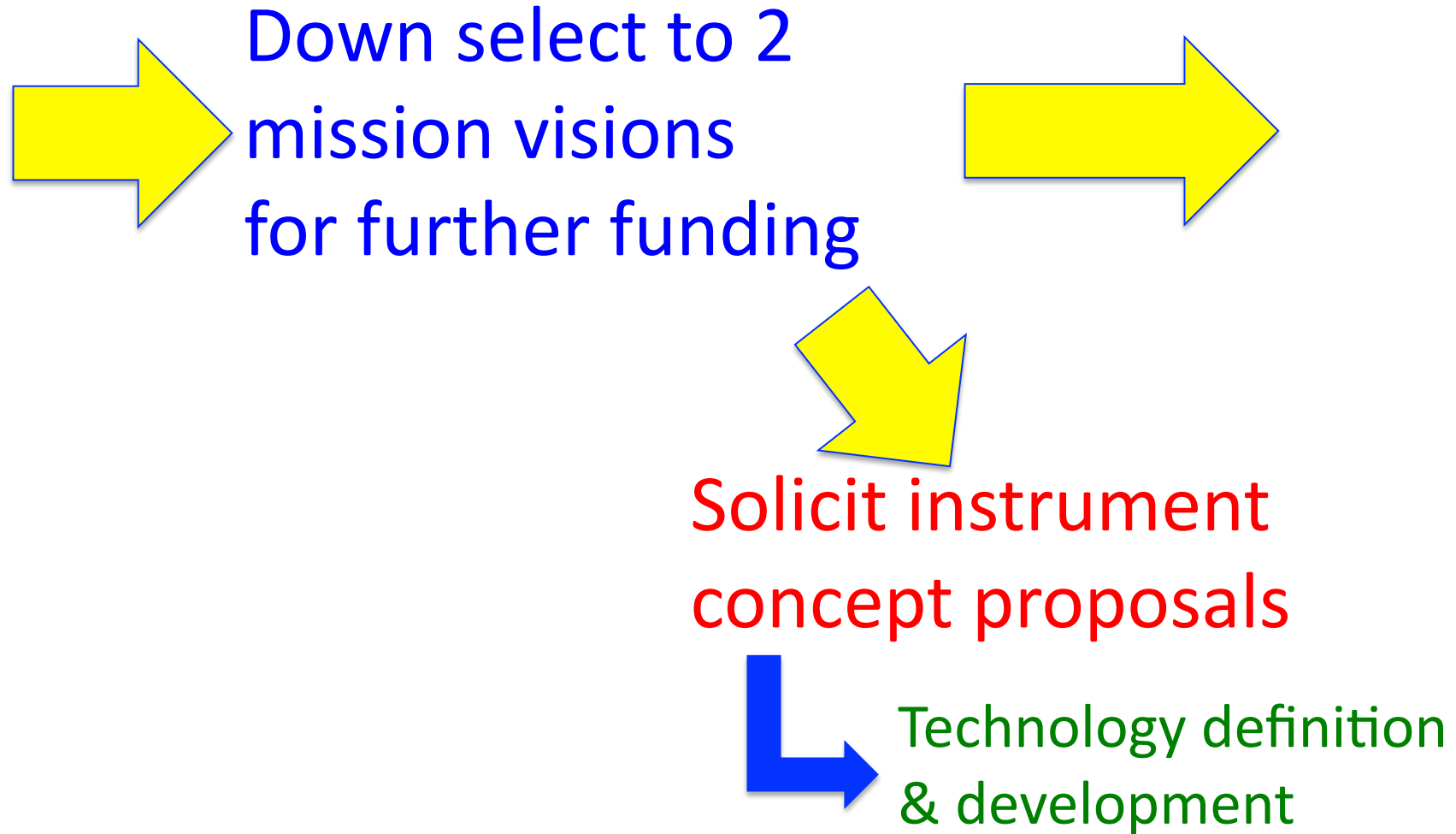3 to 6 selected to study for 18 months

$200 to 600K per study

Multiple science measurement objectives
within a single vision mission
to satisfy as many communities as possible
[Build advocacy]

The road to success

Down select to 2
mission visions
for further funding

Solicit instrument
concept proposals

Technology definition
& development

The road to success

- It is now a race to see which team can retire the risk of failure the quickest without sacrificing the quality of the science

- Sometimes new technology is needed

- How do we quantify technical maturity and thus risk to the sponsor?

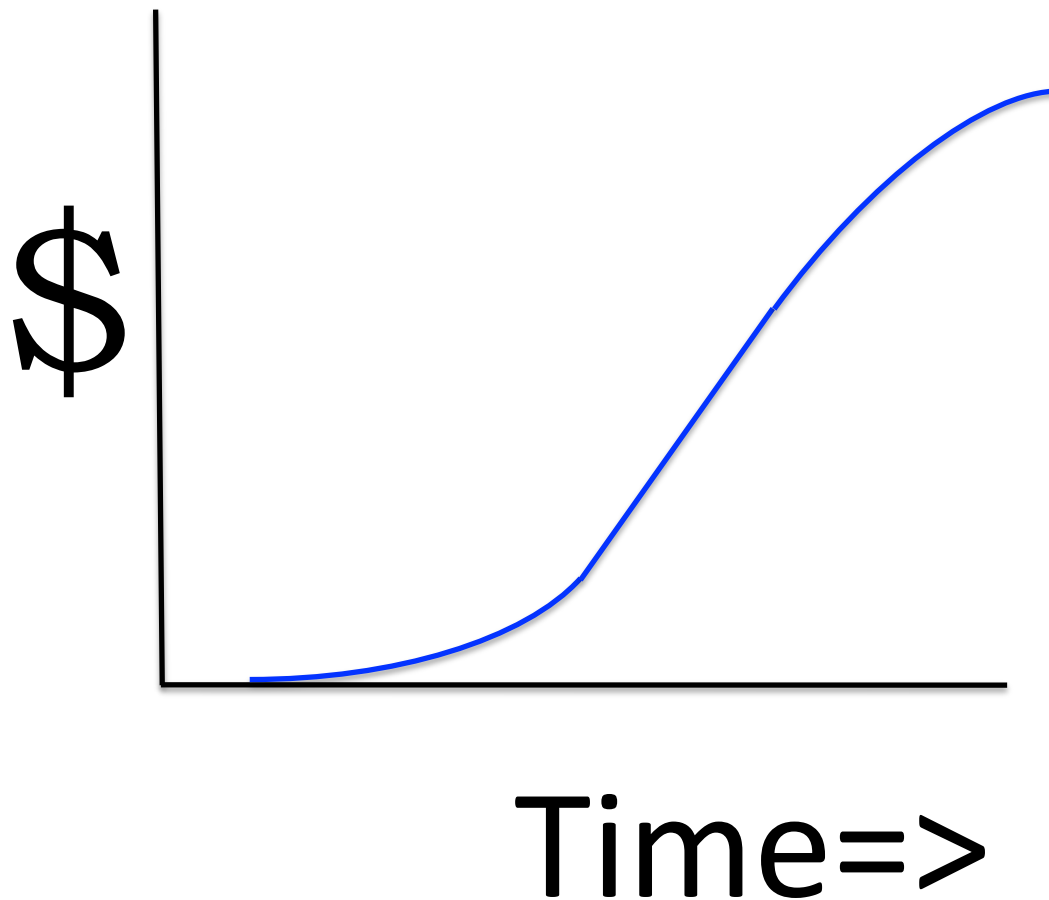- Is the sponsor "technical"?

Less expensive science missions

- Explorer ($150M)

- Midex ($120M)

- SMEX ($180M)

- Discovery ($350M)

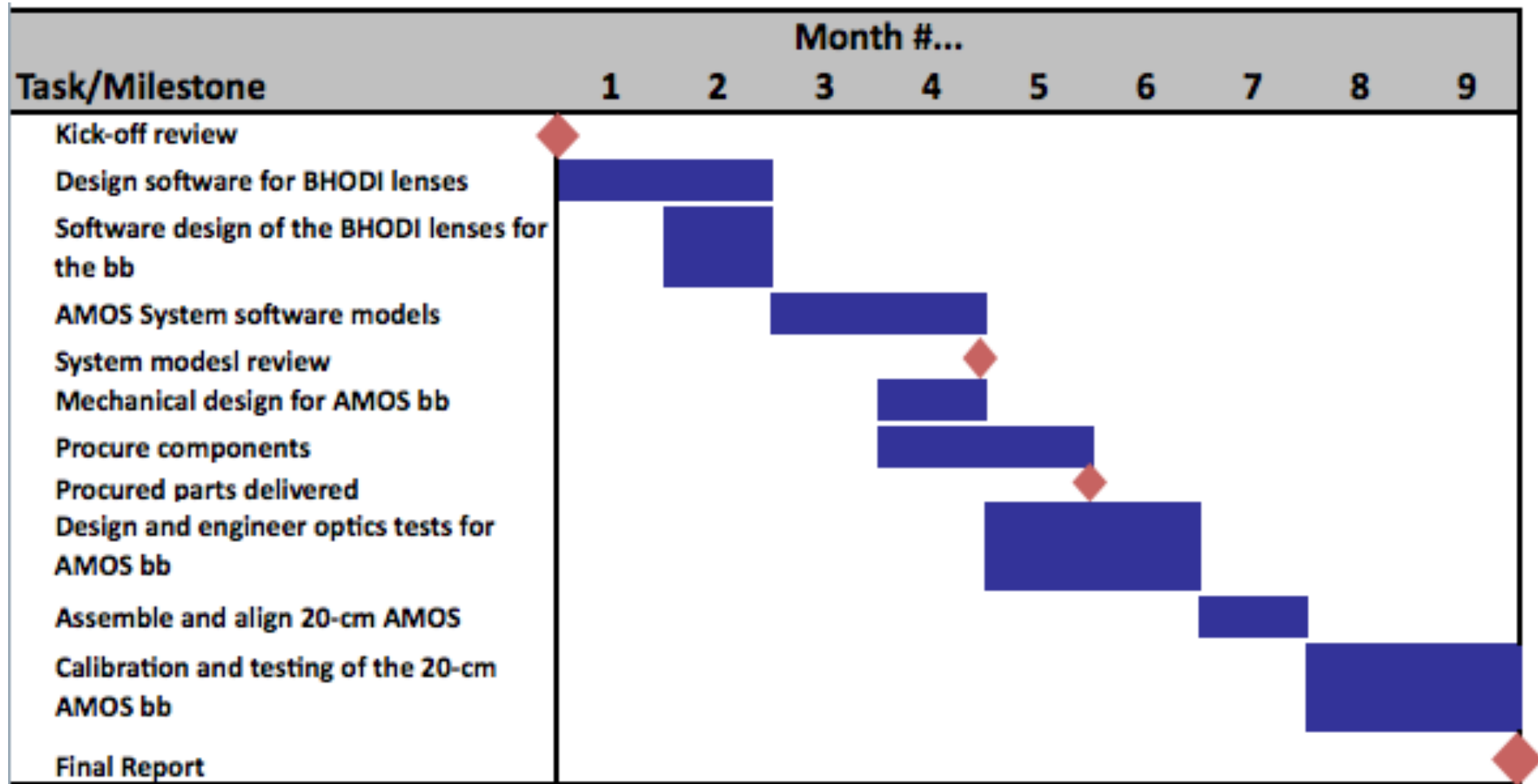| TRL #	Definition	Description	Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental-proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Documented analytical/experimental results validating predictions of key parameters.

TRL #	Definition	Description	Criteria
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/ component breadboard is built and operated to demonstrate basic functionality and critical test environments	Documented test performance demonstrating agreement with analytical predictions.
5	Component and/or breadboard validation in relevant environment.	Invention begins, practical application is identified but is speculative.	Documented description of the application/concept that addresses feasibility and benefit.
6	System/sub-system model or prototype demonstration in an operational environment. .	A high fidelity system/ component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment	Documented test performance demonstrating agreement with analytical predictions.

TRL #	Definition	Description	Criteria
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment	Documented test performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	Documented description of the application/concept that addresses feasibility and benefit.
9	Actual system proven through a successful mission operations/	The final product is successfully operated in an actual mission.	Documented mission operational results

Project "S" curve

$ (vertical axis)

Time=> (horizontal axis)

Schedule example

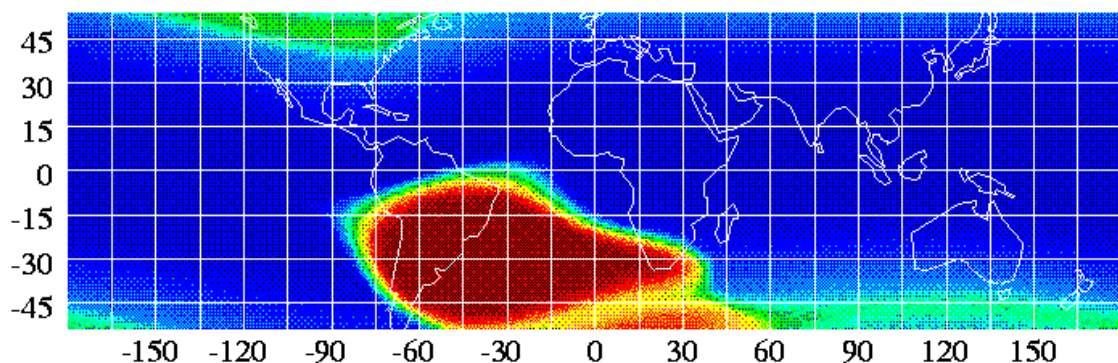| Task/Milestone	Month #...								
	1	2	3	4	5	6	7	8	9
Kick-off review	◆								
Design software for BHODI lenses	■	■							
Software design of the BHODI lenses for the bb		■							
AMOS System software models			■	■					
System modesl review				◆					
Mechanical design for AMOS bb				■					
Procure components				■	■				
Procured parts delivered					◆				
Design and engineer optics tests for AMOS bb					■	■			
Assemble and align 20-cm AMOS							■		
Calibration and testing of the 20-cm AMOS bb								■	■
Final Report									◆

Radiation damage

- Some glasses in the glass table will turn brown and then black (Voyager example)
  - Scattered light increase sometimes
- Changes mechanical properties on materials
  - Young's modulus, coefficient of expansion, etc.
- Some glass and filters will fluoresce light & blind detectors
- Gamma rays penetrate and leave track on detectors
- Radiation damage to electronics – space harden
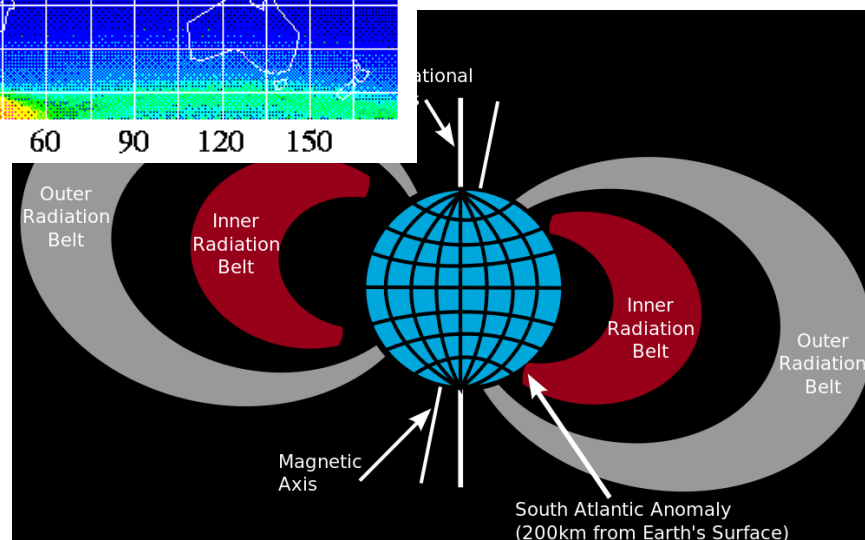
South Atlantic Anomaly

Where the inner van Allen belt dips down to 200km

Increased flux of energetic particles which exposes satellites to higher than usual levels of radiation.
Non concentricity of the of the earth with its magnetic dipole.

HST stops its exposure
The ISS special shielding

Thermal control

- Why control temperature in optical systems?
  - Optical systems are seldom used at the temperature they were built
  - nm tolerances => thermal control
  - How accurate? Will it affect your wavefront?
- Temperature changes because
  - Convection
    - Redistributes temperature
    - Atmospheric turbulence
  - Conduction
  - Radiative transfer

Thermal control

- Thermal infrared science
  - IRAS & Spitzer
  - Star and planetary formation from cold gas
  - Cosmology
- Ground systems
  - light bucket
  - diffraction limited then need A/O]
- Space systems
    - Sun, earth & moon
- Thermal noise in detectors

Why control temperature?

The depth of focus using a $\lambda/4\lambda$ criterion is given by $dz = \pm 2(F\#)^2 \cdot \lambda$

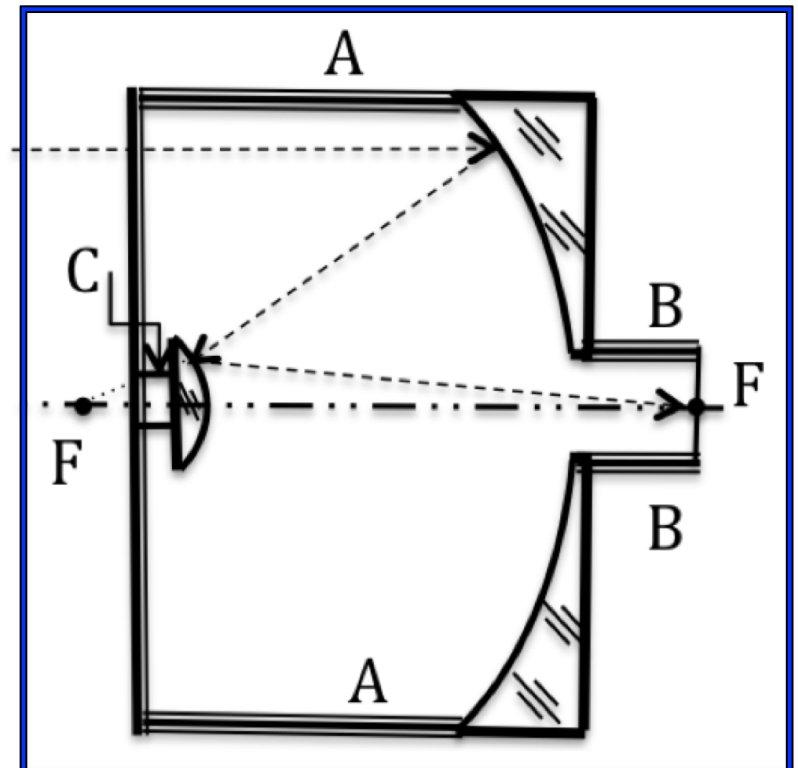For $\lambda = 500$-nm and a 1/20 wave criterion at $F\# = 2$, we find:

$dz = 0.8\mu$. Aluminum is $22 \times 10^{-6} \dfrac{m}{mK^0}$

If A = 200 mm, then a 1 degree K ΔT changes the spacing rod length by 4.4μ which is $>0.8\mu$.

If we select the coefficient of expansion X_C and X_A such that the lengths A and C are related as

$\dfrac{A}{C} = \dfrac{x_C}{x_A}$

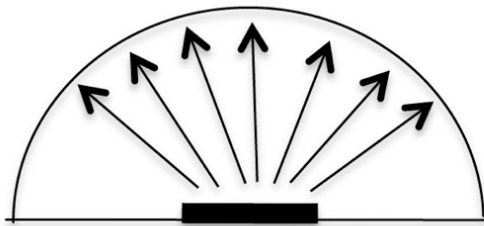then we say the telescope is athermalized, but . . . .

41

Thermal control

- Athermalized telescopes require that the entire structure be at the same temperature, that is, no gradients isothermal.
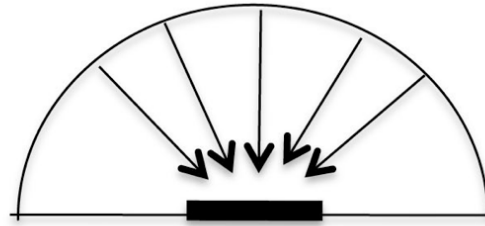
- But this is never the case.

Material	Linear temperature expansion coefficient $10^{-6}\dfrac{m}{mK^0}$
Aluminum	22.2
Invar	1.5
Pyrex	4.0
Quartz	0.59
Zerodur* (Schott)	0.02
Silicon Carbide	2.77

* 0 to 50 degrees C

Definitions

Exitance

Irradiance

Intensity
(point source)

Radiometry nomenclature

Name	Symbol	Definition	Units
Energy	Q		joule, J
Flux	Φ	$\dfrac{\partial Q}{\partial t}$	watt, W
Flux density		$\dfrac{\partial \Phi}{\partial A}$	
Exitance	M	$\dfrac{\partial \Phi}{\partial A}$	$\dfrac{\text{watts}}{\text{m}^2}$
Incidence	E	$\dfrac{\partial \Phi}{\partial A}$	$\dfrac{\text{watts}}{\text{m}^2}$
Intensity	I, J	$\dfrac{\partial \Phi}{\partial \Omega}$	$\dfrac{\text{watts}}{\text{sr}}$
Radiance	L	$\dfrac{\partial \Phi}{\partial A \cdot \cos\theta \cdot \partial \Omega}$	$\dfrac{\text{watts}}{\text{m}^2 \text{sr}}$

How many photons from a 0 magnitude star are incident on a telescope in space?

αLyr (Vega)

is m_V = 0.0 and it's irradiance at the top of the atmosphere 500 to 700 nm is

$$\approx 2 \cdot 10^6 \left[\frac{\text{photons}}{\text{sec} \cdot \text{cm}^2} \right]$$

Hayes, Latham and Hayes, (1975) "Measurement of the monochromatic flux from Vega in the near Infrared", *Astroph. J* 197, 587-592

Signal to noise ratio

$$E_{m=0} \approx 2 \cdot 10^6 \left[\frac{\text{photons}}{\text{sec} \cdot \text{cm}^2} \right]$$

Photons obey Poisson statistics. Assume we detect each photon that arrives then the maximum possible SNR from a 1 cm^2 telescope over a 1 second integration time is given by

$$SNR = \frac{N}{\sqrt{N}} = \frac{2 \cdot 10^6}{\left(\sqrt{2}\right) \cdot 10^3} = 1.4 \cdot 10^3$$

$$\frac{I_1}{I_2} = \left(2.512\right)^{m_1 - m_2} \quad \text{or} \quad m_2 - m_1 = 2.5 \log\left[\frac{b_1}{b_2} \right]$$
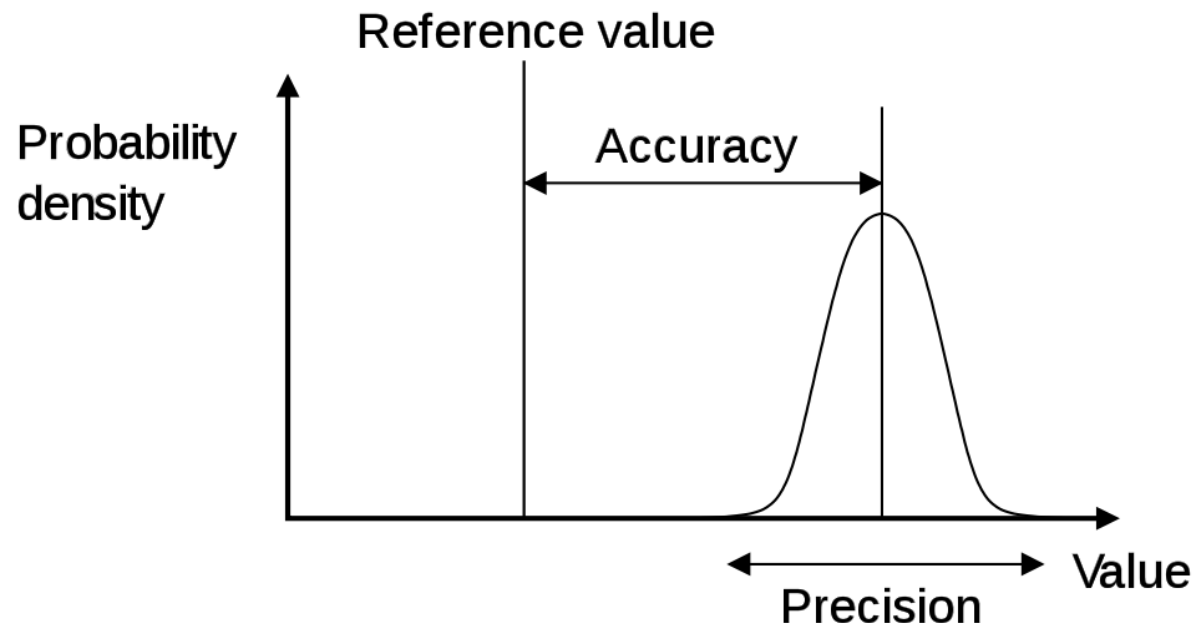
But the detector adds noise of its own

Coming closer to answering the question:
Example of a science measurement requirement
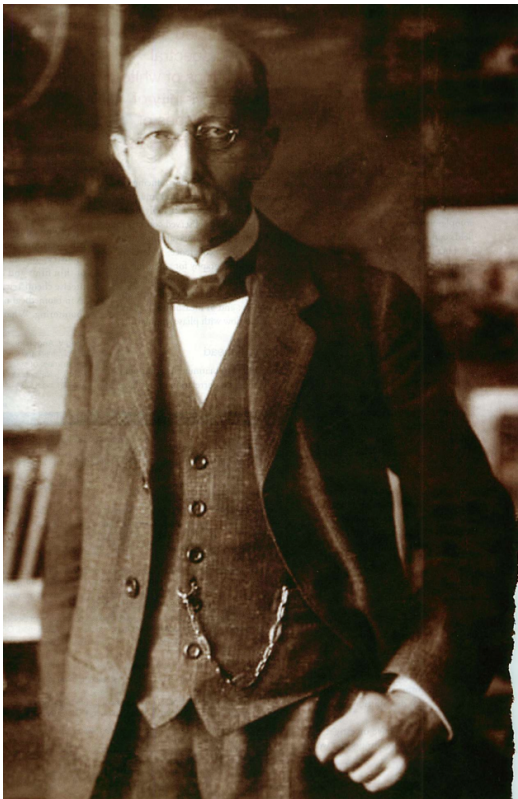
- ## Mission studies
  - ### Science measurement requirement
    - *Measure the central intensity of an absorption line at 483.56 nm in the spectrum of a 14th magnitude star with 5% accuracy at the 95% confidence level*

Thermal signal and background
Planck's equation

$$M_\lambda = \frac{2\pi hc^2}{\lambda^5 \left[\exp\left(hc / \lambda kT \right) - 1 \right]},$$

h = Planck's constant = 6.625×10^{-34} J × sec,
c = velocity of light = 2.9979×10^8 m/sec,
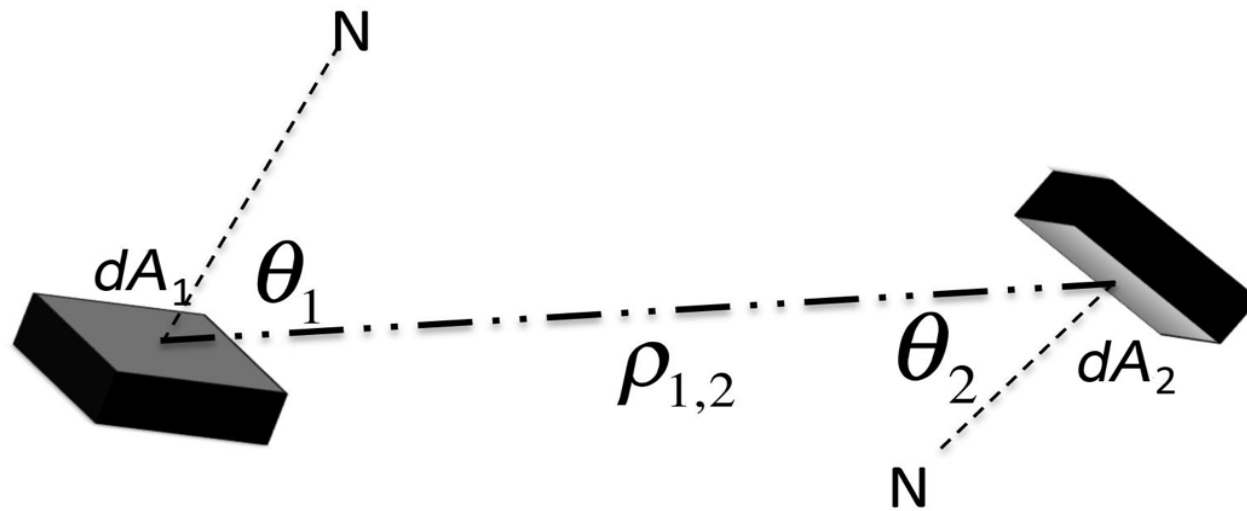k = Boltzmann's constant = 1.3805×10^{-23} J/ Kelvin,
T = absolute temperature in units of Kelvin,
λ = wavelength in meters,

$$M_\lambda \text{ has units of } \frac{\text{Watts}}{\text{Meter}^2 \cdot \text{Meter}}$$

Fundamental equation of radiative transfer

$$d\Phi_{1-2} = \frac{\left[L_1(\theta,\phi) - L_2(\theta,\phi) \right] \cdot \left(dA_1 \cos\theta \right)_1 \cdot \left(dA_2 \cos\theta_2 \right)}{\rho_{1,2}^2}$$

Power to the focal plane!

Transmittance

Throughput (etendu)

Absorption

Emission

Reflectance

Transmission

Launch Vibration Qualification

- Must know the power spectrum (x,y,z) of the vibration – units are usually g's
- Mount the instrument on a vibration table to simulate its location on the spacecraft
- Sine sweep
- Continuous sine wave
- Open it up and locate the pieces!
- Redesign and reshake

Inconsistent optical <u>system</u> engineering

- Better is the evil of "good enough"
- Examples:
  - Focal plane MTF does not match telescope resolution
  - Pointing and tracking requirement is given as .1 arc-seconds. Science needs <5 arc seconds and telescope resolution is 10 arc-seconds
  - The $A\Omega$ of the telescope does not match the instrument

Vacuum?

- Do you build your instrument to run in the vacuum of space, or do you build a chamber around it?
  - Windows (Kepler story)

The Real (Optical) Solution

Before the repair   After the repair

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

Thursday Jan 29, 2012

- Science in the noise

- Hubble Space Telescope
  - Prescription retrieval
  - How it happed
  - How we fixed it