Lecture 3

Optical systems for space-based scientific remote sensing

University of Arizona
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Tuesday, January 29, 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 31, 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

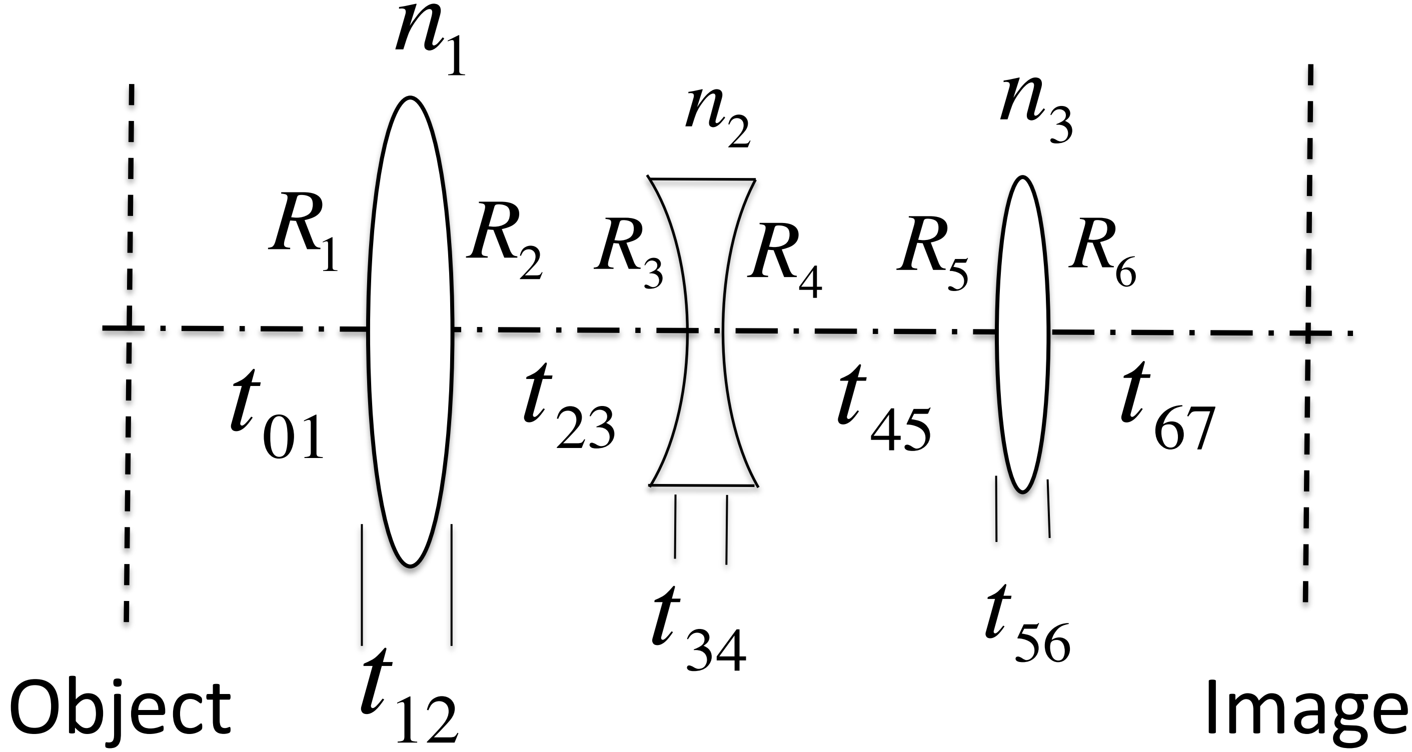
Triplet has 19 degrees of freedom

8 Surface curvatures (including object and image)

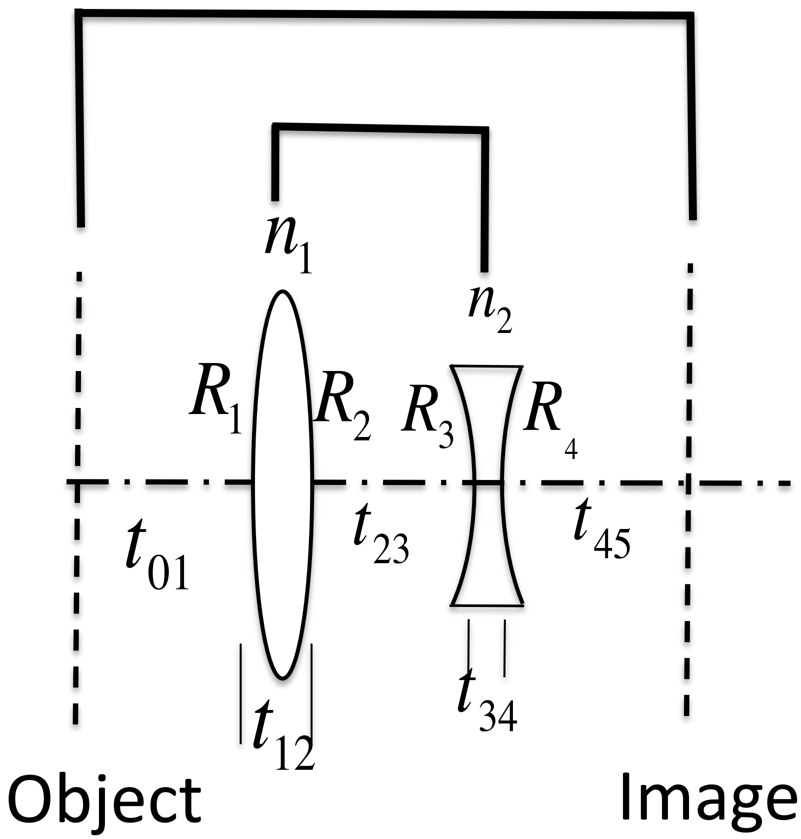
7 Spacings

3 Indices of refraction

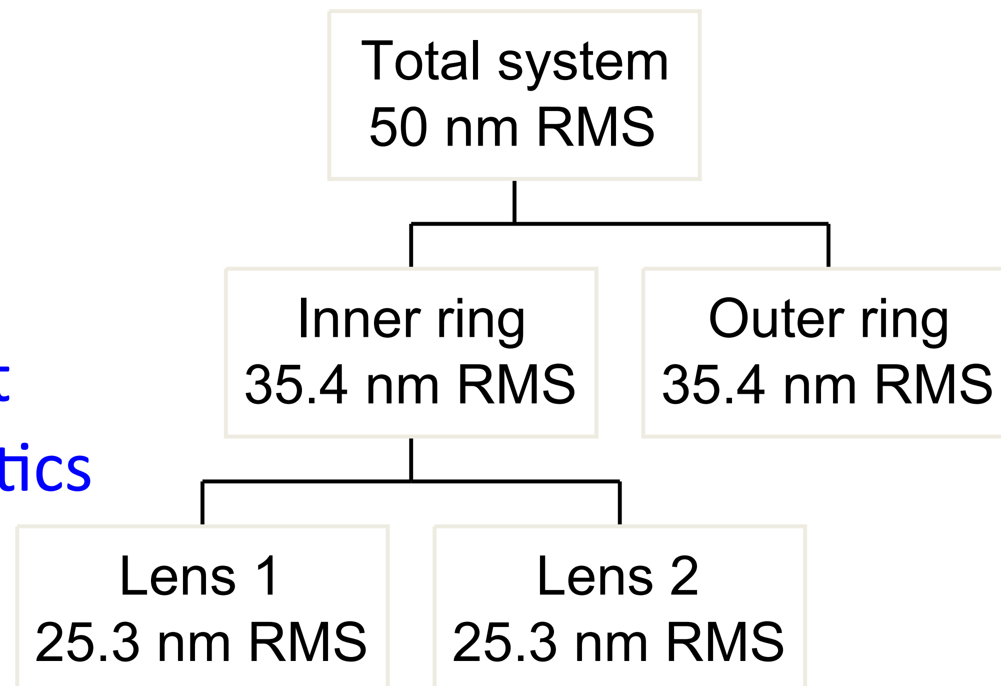
1 Entrance stop location



RMS Wavefront specification



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



Work flow

Design approach

Optical system engineering

Thin Films & Scattrd Light

Fabrication

Ray trace concept

Focal plane

Radiometry SNR

Mechanical Mechanisms structures

Sensitivity analysis

Long Lead Procurements Optics & focal Plane? →

Preliminary design review

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

Challenges

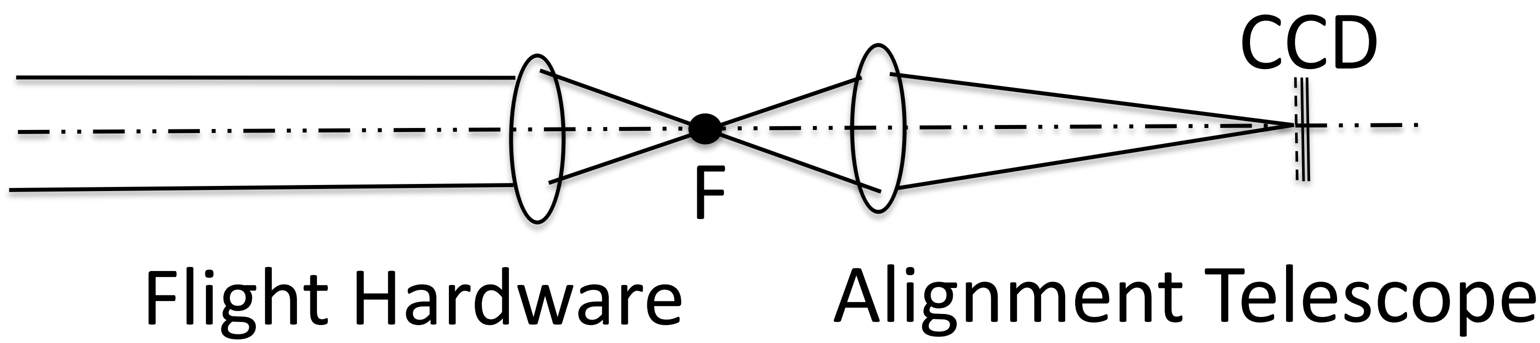
- Better is the evil of good enough
- Haste makes waste (focus test example)
  - Usually do not build hardware with a focus knob
- You plan the job assuming the A team will do the work then wind up executing the job with the B or C team!
- Cabling, handling equipment
- Ground support equipment (GSE)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

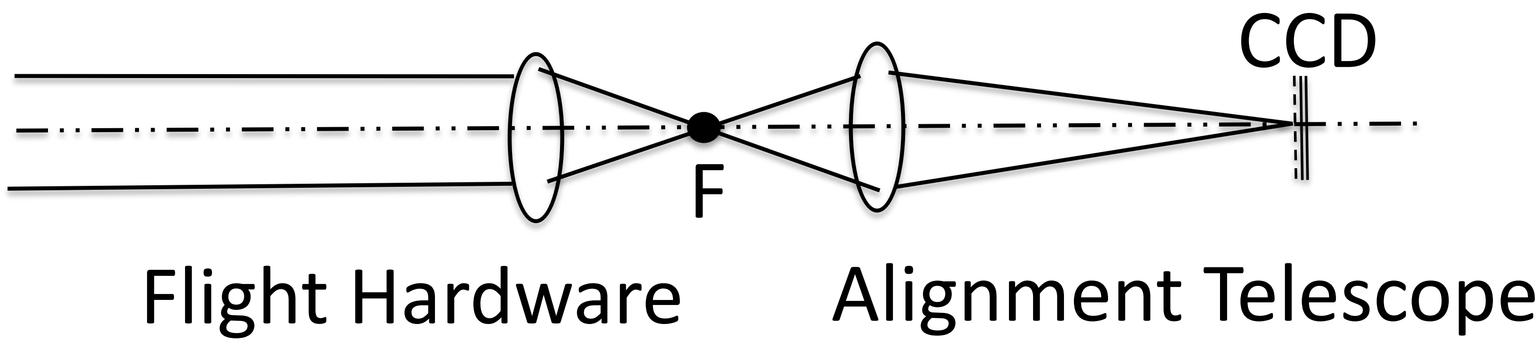
Haste makes waste!

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

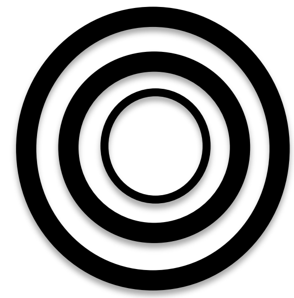


The engineer set up the measurement and discovered that the CCD saturated.
There were no neutral density filters available in time to complete the measurement.

Haste makes waste!



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 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

5 to 10 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

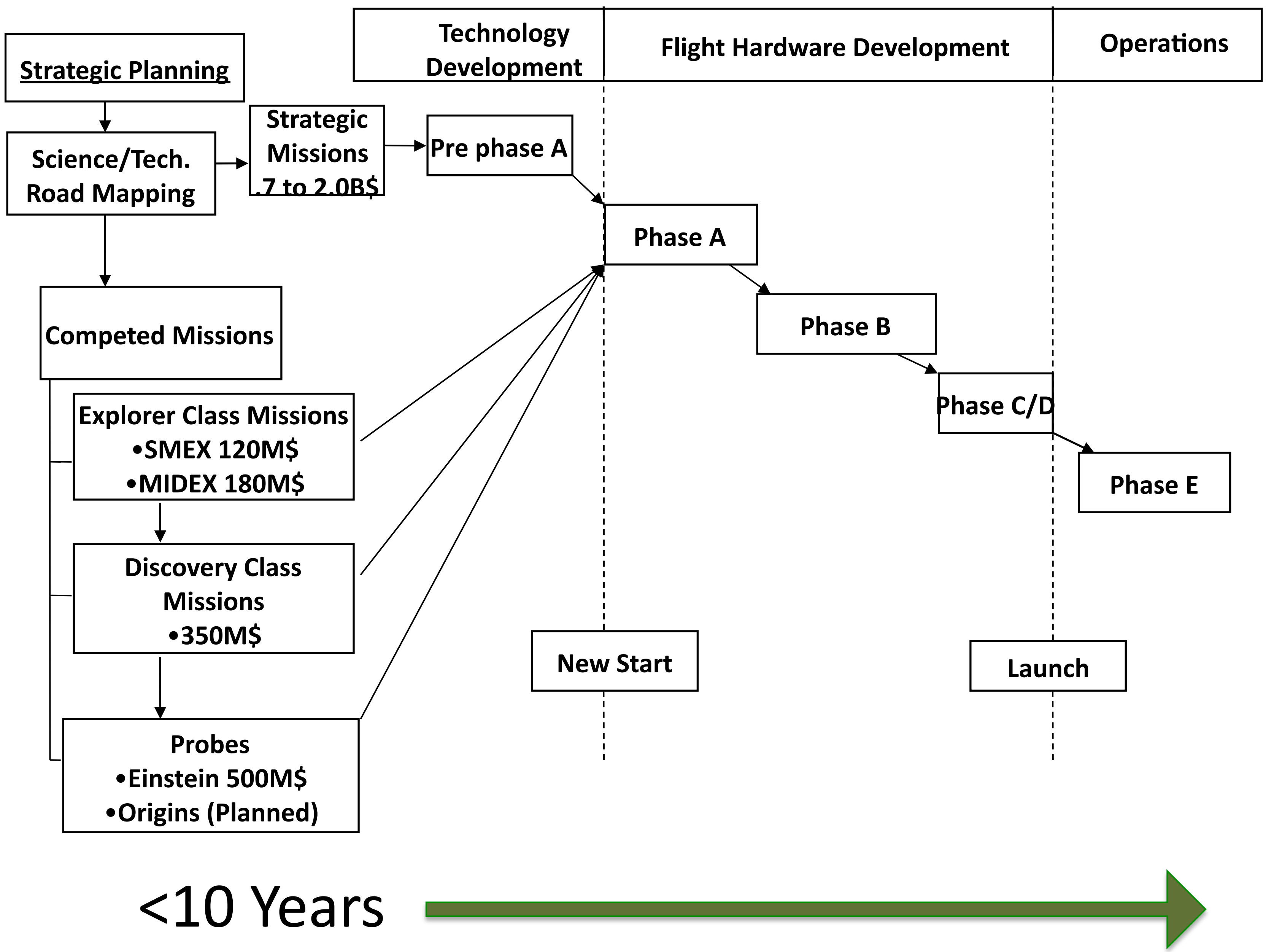
Solicit instrument
concept proposals

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?

The NASA road to success



Less expensive science missions

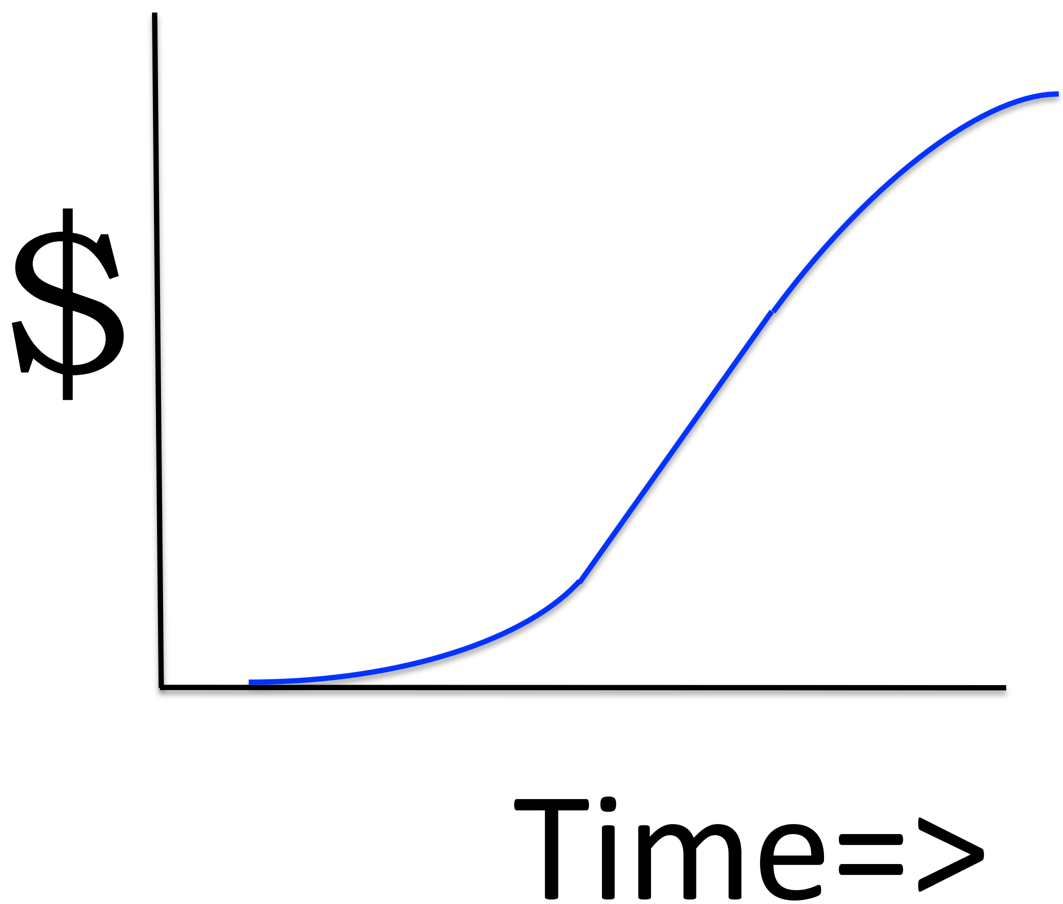
- Explorer ($150M)
- Midex ($120M)
- SMEX ($180M)
- Discovery ($350M)

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.

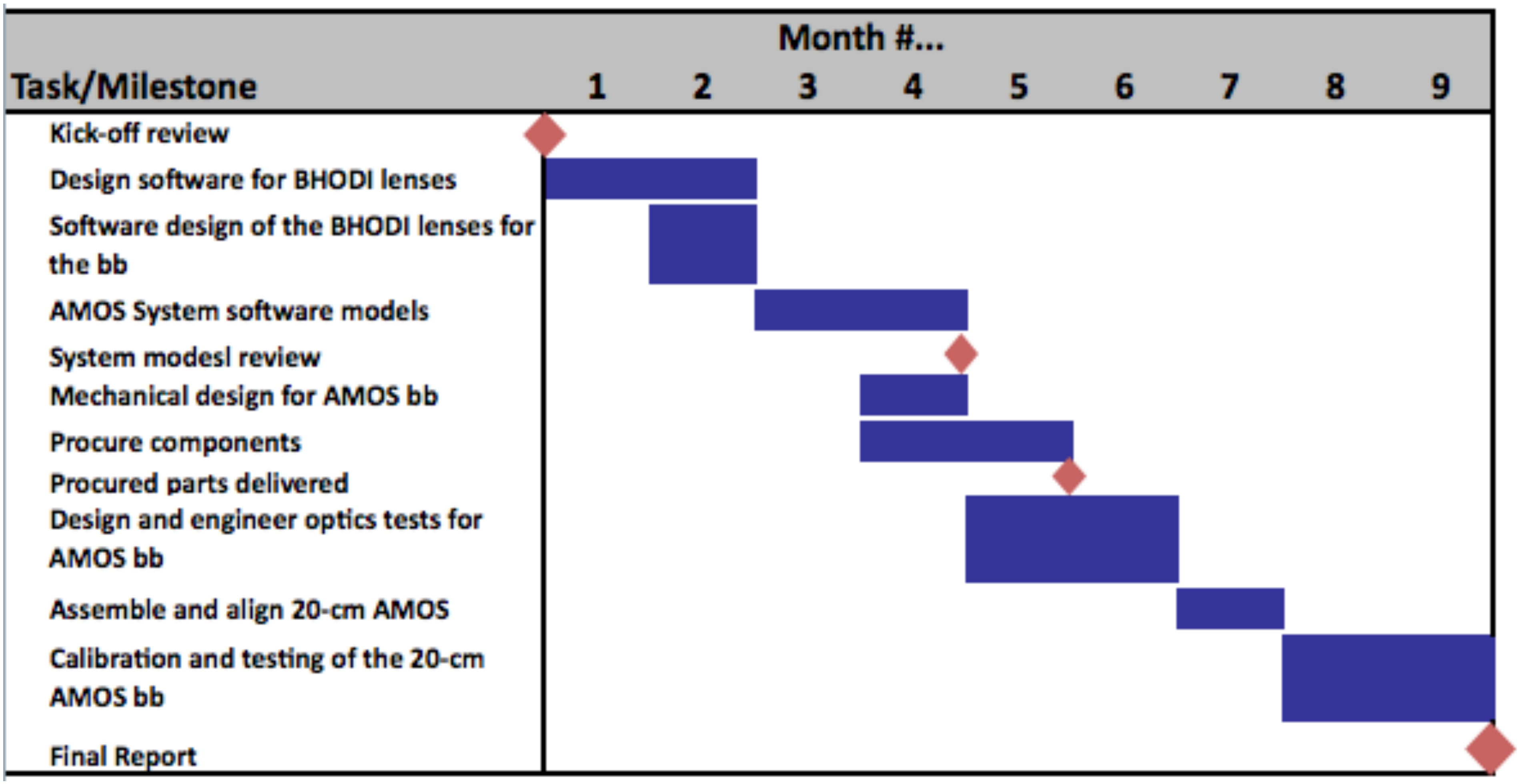
TRL #	Definition	Description	Criteria
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/ component breadboard is built and operated to demonstrate basic functionality and critical test environments	Documented test performance demonstrating agreement with analytical 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



Schedule example



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

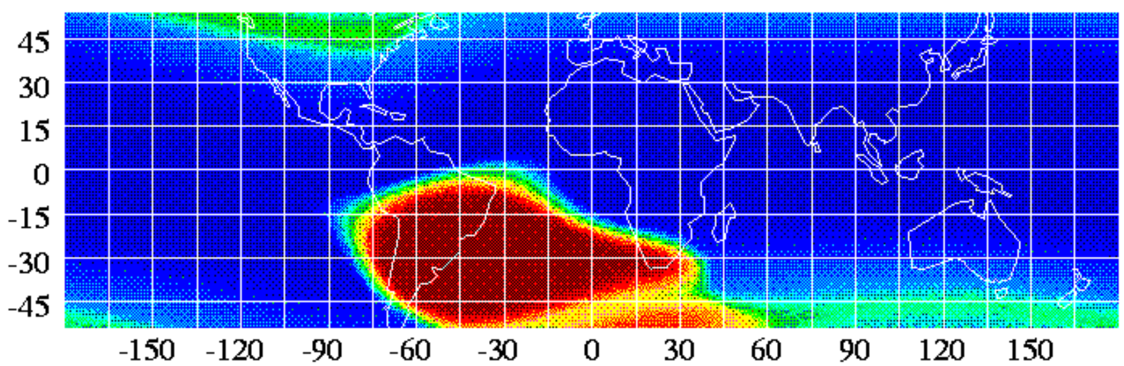
Radiation damage

- 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

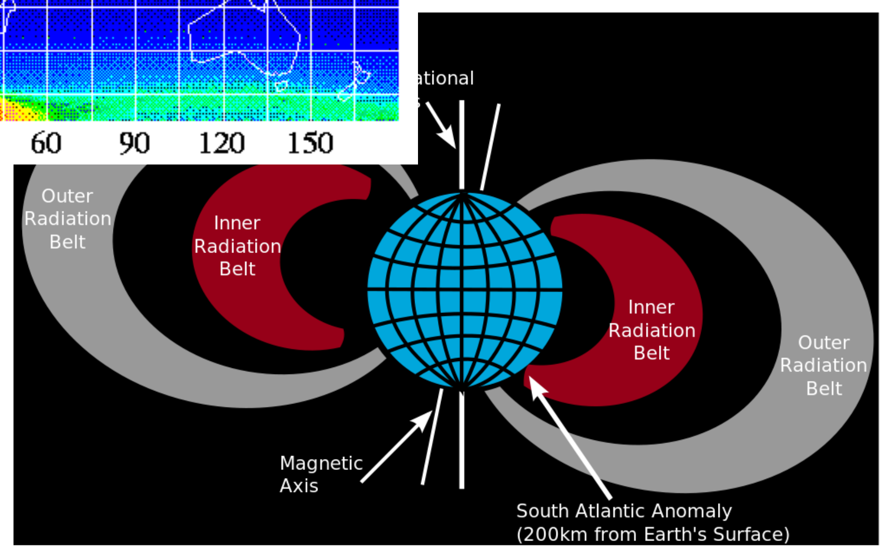
South Atlantic Anomaly

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



Electrostatics

- Telescopes travel through the magnetic field of the earth
- Surface charge build-up
- In space where is “ground”?
- Electronics built hardened against radiation
- Inflatable membrane mirror experiment oscillation without damping

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 (what moves heat?)

- Convection (ground-based)
  - Redistributes temperature
  - Atmospheric turbulence
    - Temperature fluctuations in the earth's atmosphere causes index of refraction changes which causes small, local changes in optical power to blur long exposure images.
- Conduction
- Radiative transfer

Thermal control

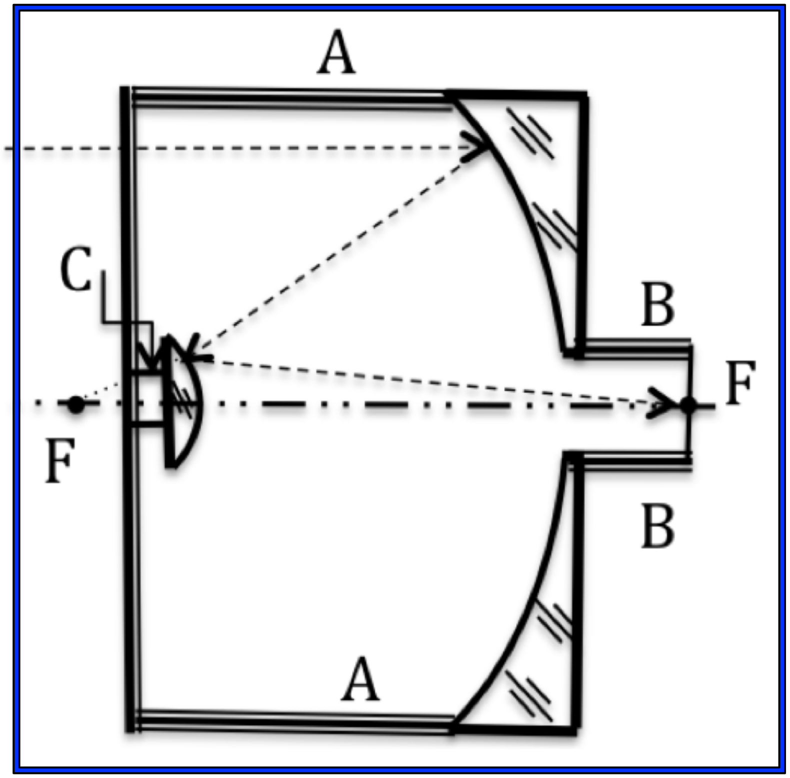
- Thermal infrared science
  - IRAS & Spitzer
  - Star and planetary formation from cold gas
  - Cosmology
- Ground systems
  - light bucket
  - diffraction limited then need A/O]
- Space systems
    - Sun, earth & moon
- Thermal noise in detectors

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 $22x10^{-6} \frac{m}{mK^0}$



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

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

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

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

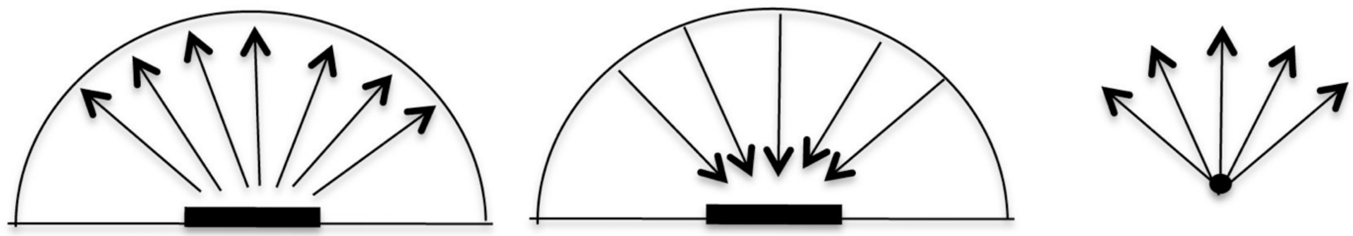
Thermal control

- 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 $10^{-6} \frac{m}{mK^0}$
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	$\mathbf{\Phi}$	$\frac{\partial Q}{\partial t}$	watt, W
Flux density		$\frac{\partial \Phi}{\partial A}$	
Exitance	M	$\frac{\partial \Phi}{\partial A}$	$\frac{\text{watts}}{\text{m}^2}$
Incidence	E	$\frac{\partial \Phi}{\partial A}$	$\frac{\text{watts}}{\text{m}^2}$
Intensity	I, J	$\frac{\partial \Phi}{\partial \Omega}$	$\frac{\text{watts}}{\text{sr}}$
Radiance	L	$\frac{\partial \Phi}{\partial A \cdot \cos\theta \cdot \partial \Omega}$	$\frac{\text{watts}}{\text{m}^2\text{sr}}$

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

$$\alpha \mathrm{Lyr\ (Vega)}$$

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

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

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

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

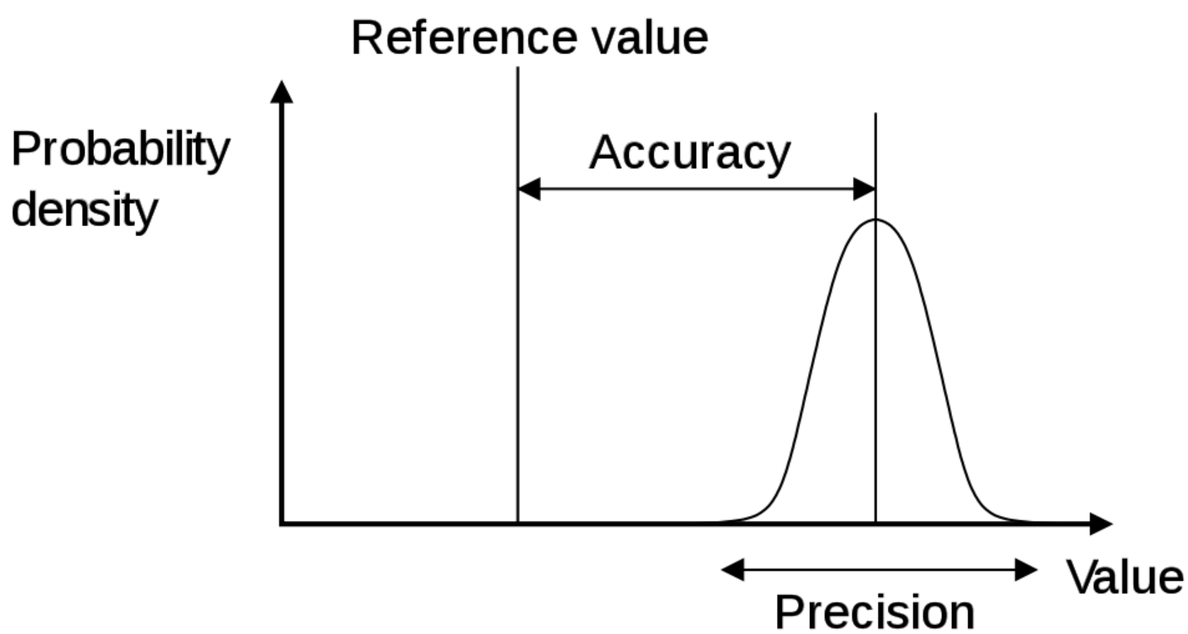
$$\frac{I_1}{I_2} = \left(2.512\right)^{m_1 - m_2} \quad \text{or} \quad \text{m}_2\text{-m}_1 = 2.5 \log\left[\frac{b_1}{b_2}\right]$$

But the detector adds noise of its own

Coming closer to answering the question:

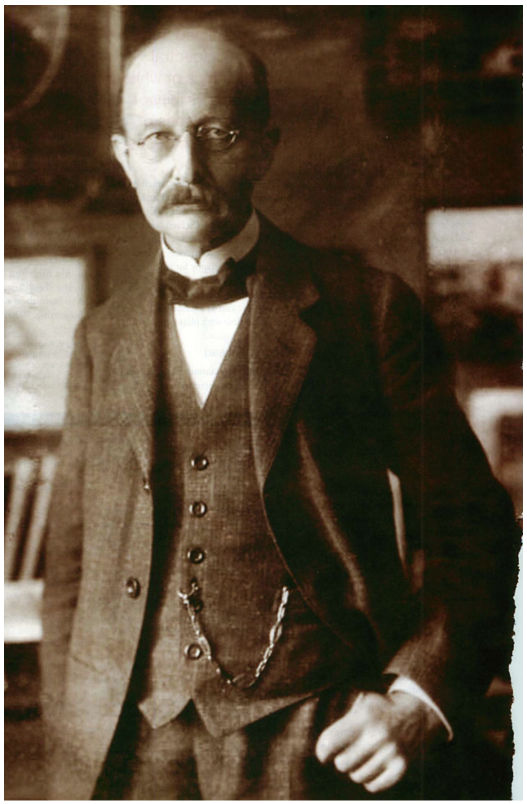
Example of a science measurement requirement

- 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



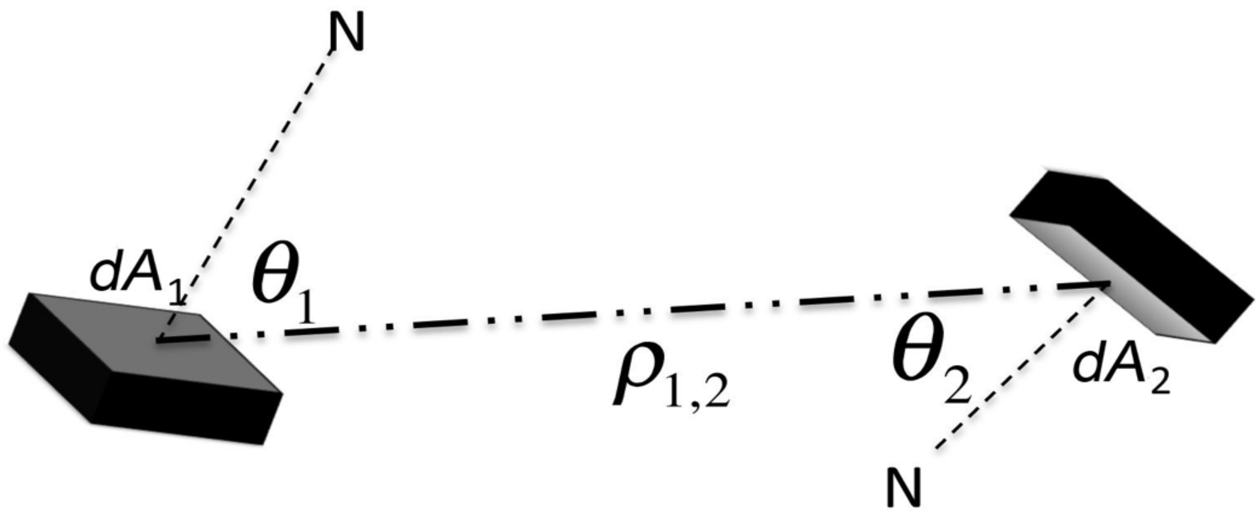
$$M_\lambda = \frac{2\pi hc^2}{\lambda^5\left[\exp\left(hc/\lambda kT\right)-1\right]},$$

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 system 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

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Thursday Jan 29, 2012

- Science in the noise
- Hubble Space Telescope
  - Prescription retrieval
  - How it happed
  - How we fixed it