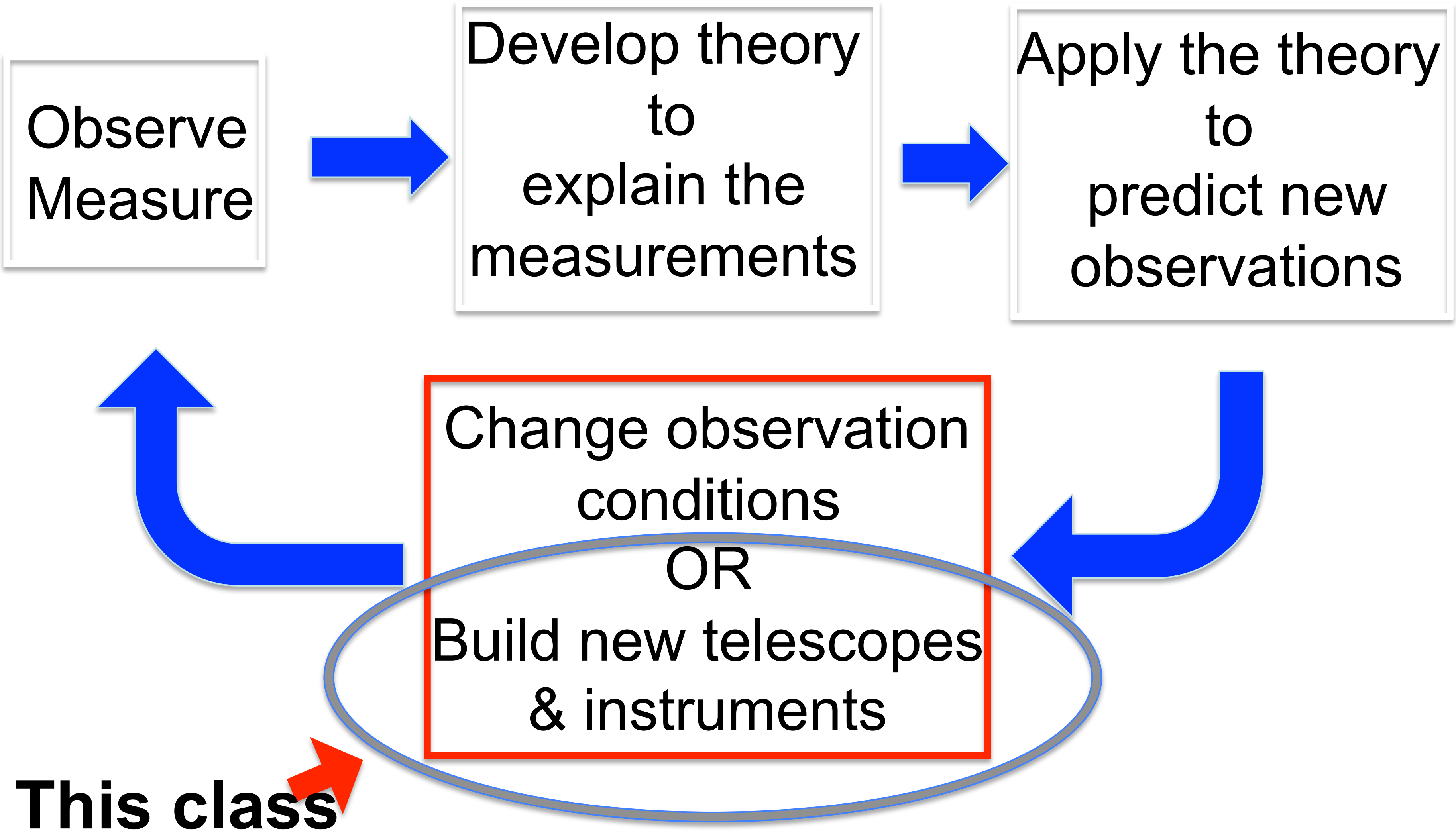
Lecture 4

- Class review – project summary
- Hubble space telescope
  error, how, prescription, & fix

Jim Breckinridge
Adjunct Professor
University of Arizona

29 January 2013

The scientific method



System development process

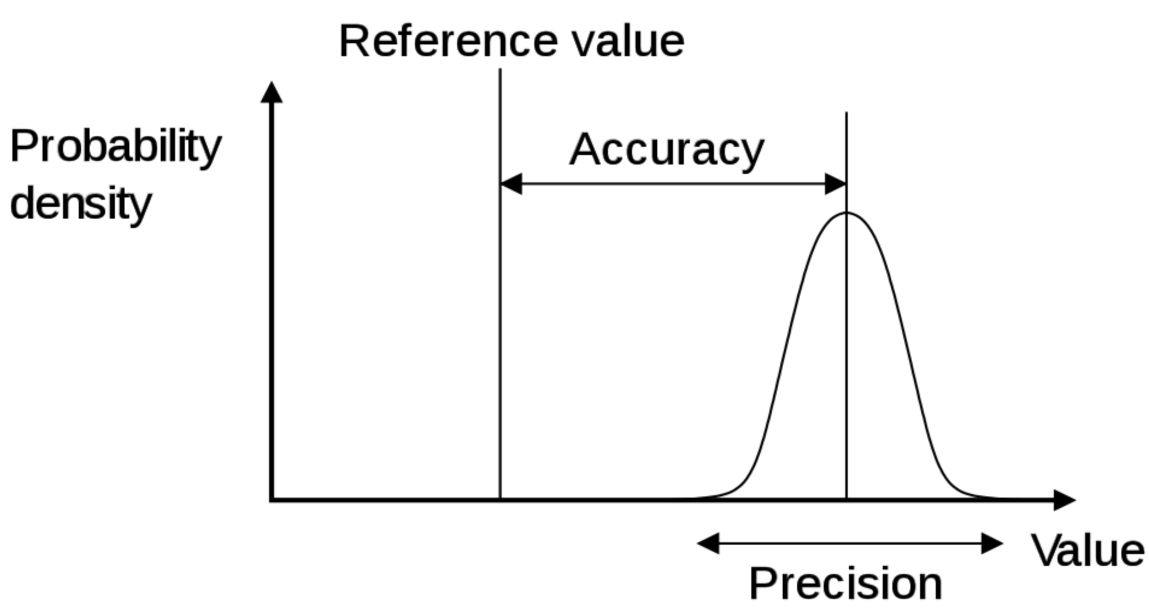
- Science
  - "Determine the scope of global warming"
- Science measurement objectives
  - "Measure the annual abundance of CO_2 to an accuracy of 0.1%"
- Functional requirements (constraints on the instrument & system)
  - "the needed signal to noise is 60:1, global measurements, season, field of view"
-

System development process

- Create a System architecture
  - "Telescope with spectrometer, low earth orbit, down link capacity
  - $A\Omega$
- Develop a point design
  - " Three-mirror anastigmat, Grating or Fourier transform spectrometer, spectral resolution, ..??"
- Model source, telescope/instrument and data processing to demonstrate the science measurement objectives have been met.
- Is new technology needed?

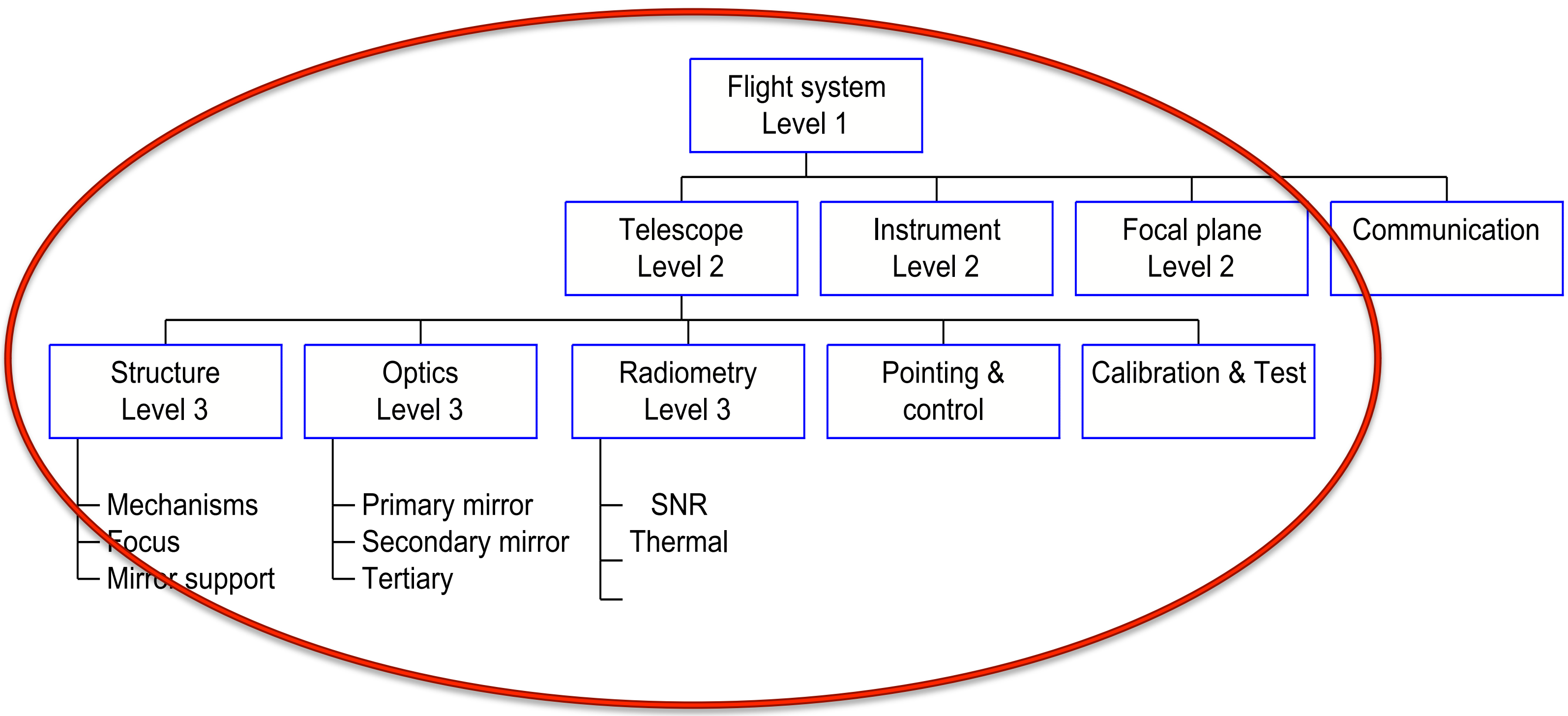
Example of a science measurement requirement

Measure the wavelength position of a line in the spectrum of a 26th magnitude star with 10% accuracy at the 95% confidence level

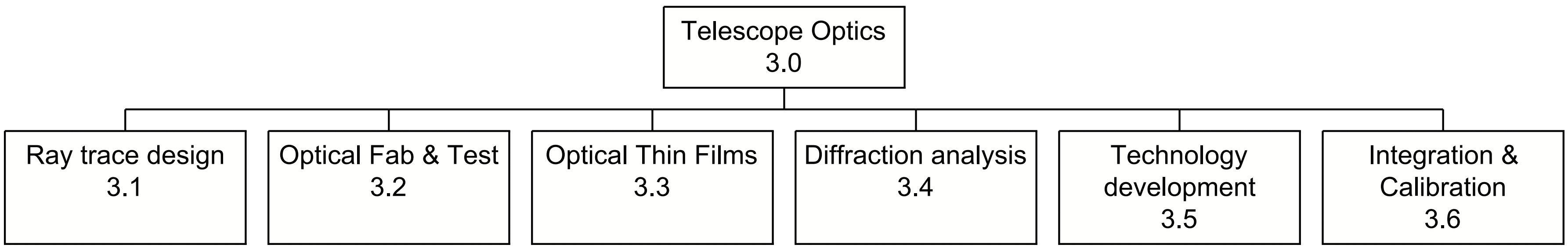


Where do we start?

- Develop system requirements
- Divide the system up into manageable subsystems
  - Write down a list of tasks that need to be done
  - Work break-down structure
- One person's subsystem is another person's system.



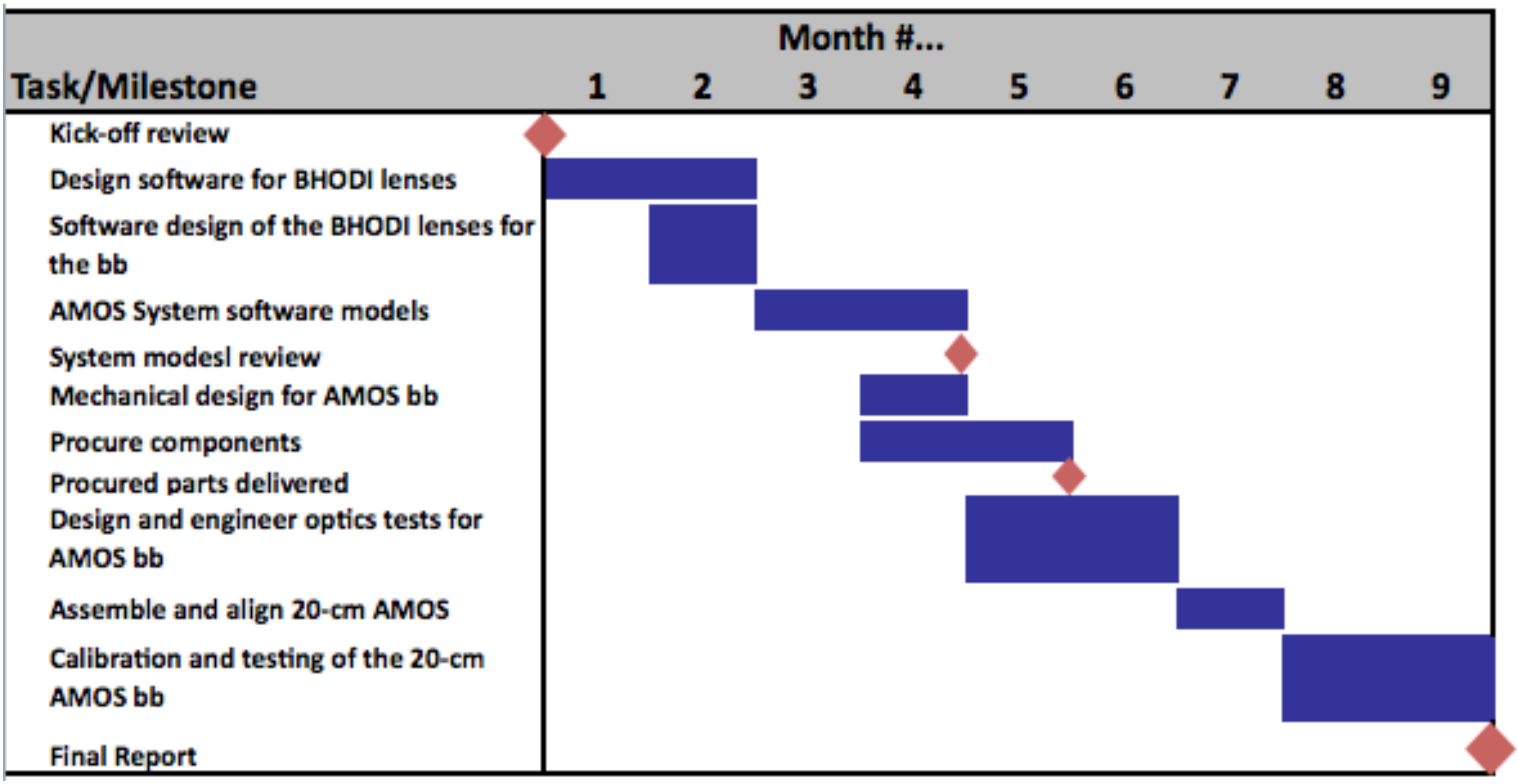
Example Optics WBS



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

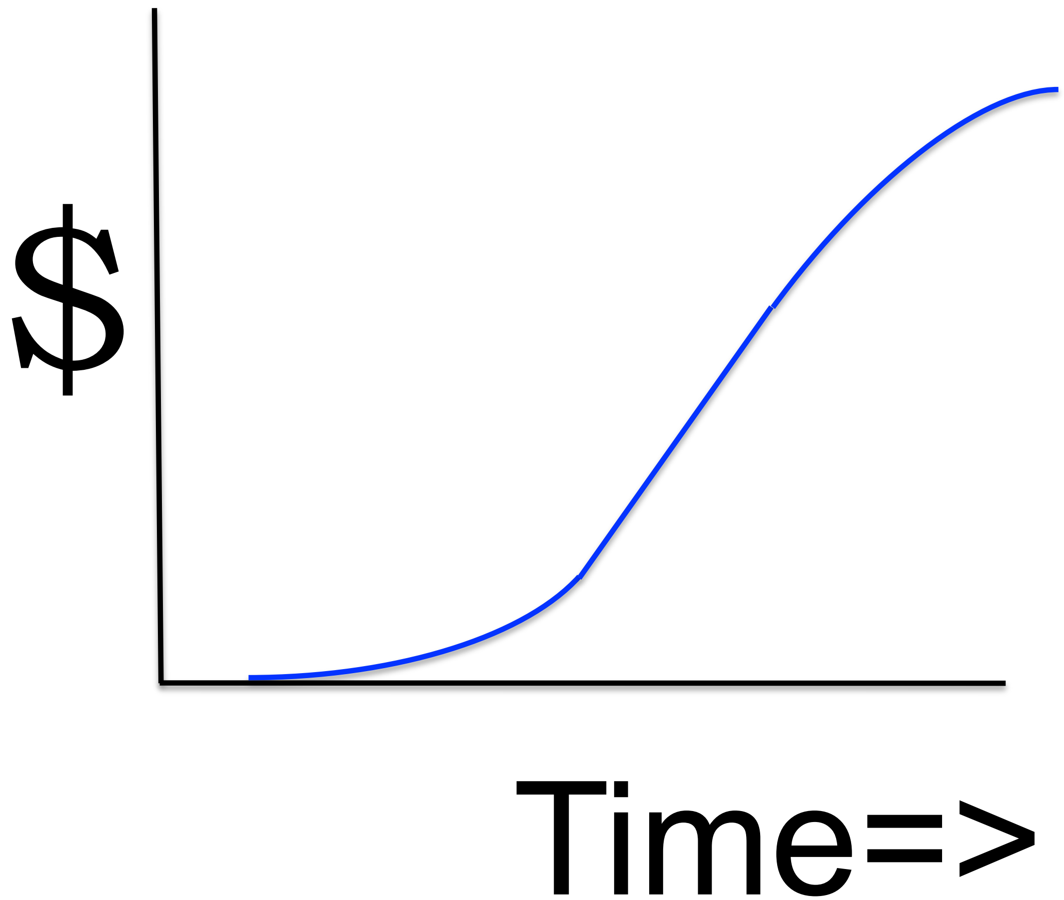
Schedule example



Project Milestones

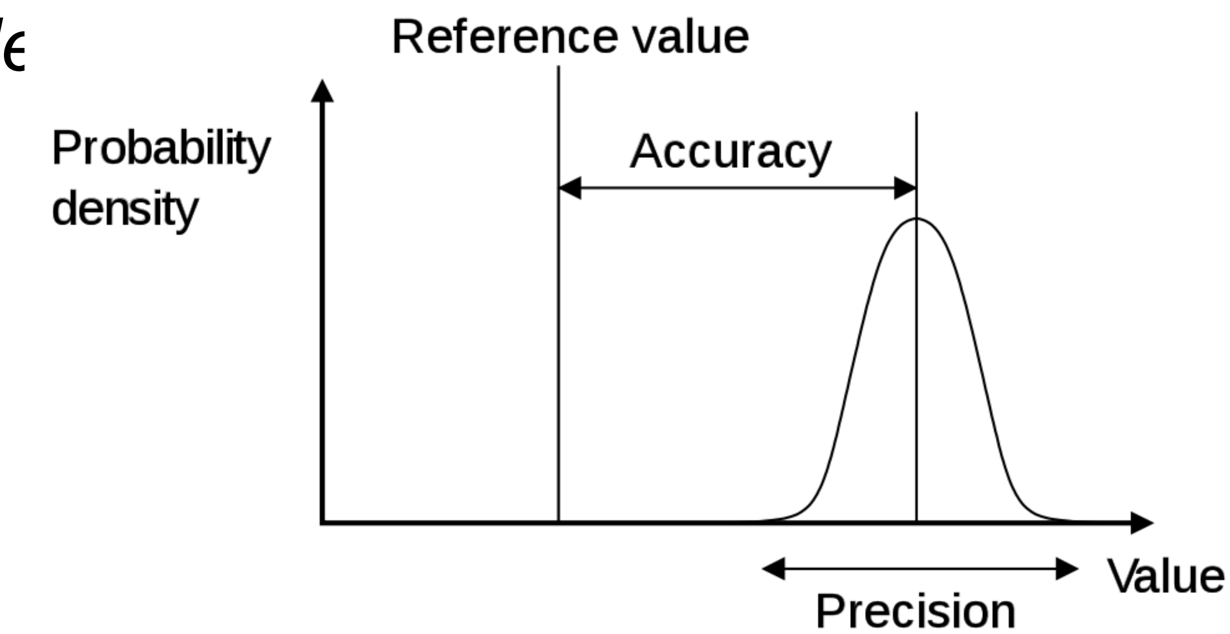
1. Mission concept review (MCR)
    - Science clearly stated measurement concept
2. System definition review (SDR)
3. Preliminary design review (PDR)
    - Assembly drawings
4. Critical design review (CDR)
    - Detail design complete ready to “cut metal (glass)”
5. Pre-ship readiness review

Project "S" curve



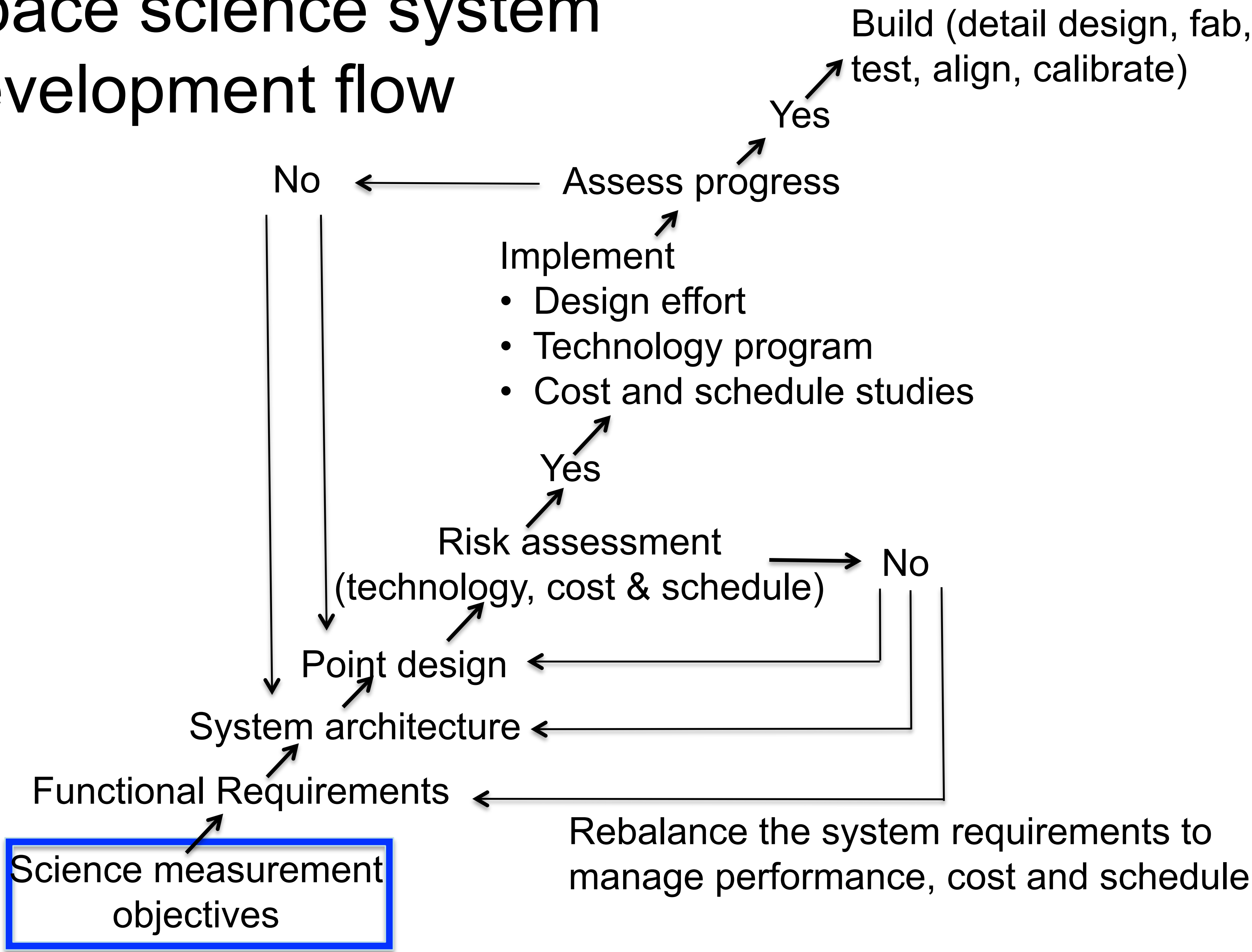
Clearly state the requirements

- 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% confide*



Engineers have numbers to design to and a measurable performance metric

Space science system development flow



Hubble Space Telescope Optical Systems

1. Failure
2. Hunt for the Optical Prescription
3. Correction of the error

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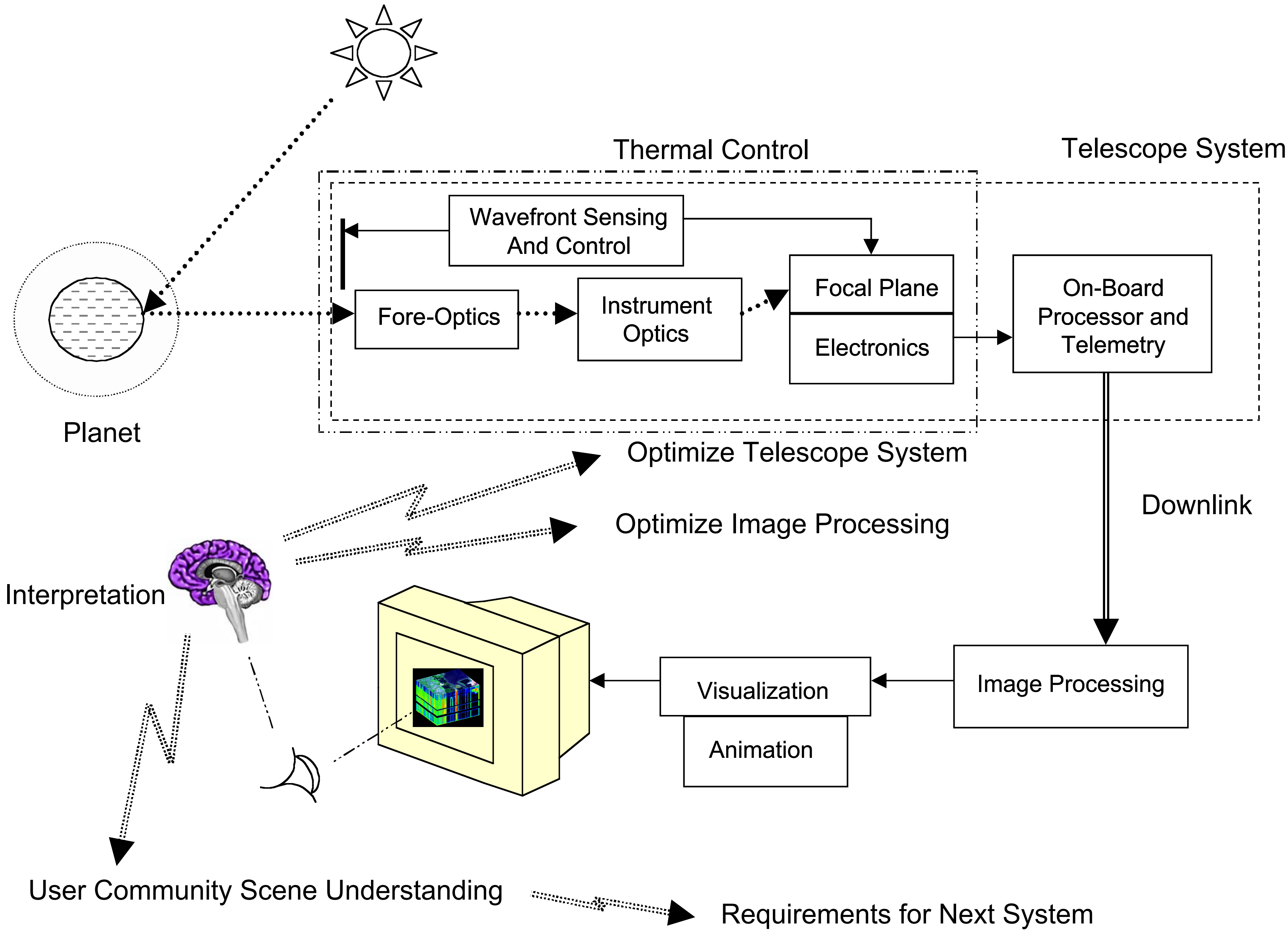
Modern space telescope system



Development

- Professor Lyman Spitzer (Princeton) in 1948 proposed a large space telescope
- Proposals issued & contract let by NASA for the Optical Telescope Assembly (OTA) in 1977 to Perkin-Elmer Co. [13 years before launch]
- Payload integration onto the space craft awarded to Lockheed Sunnyvale
- Five instruments were awarded to principle investigators & completed independent of the telescope contract

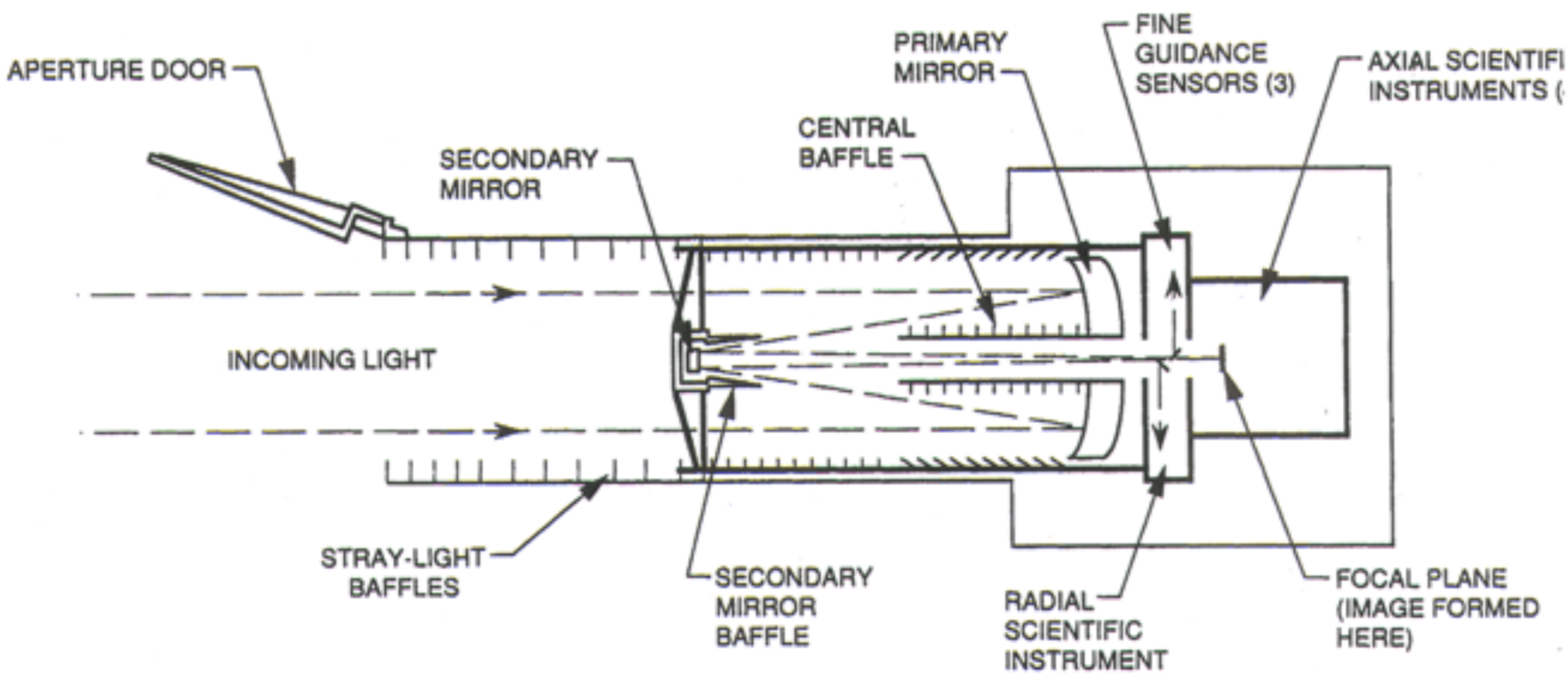
Development challenges

- Technically very challenging
- Delay of launch by 6 years
- 100 to 1100nm observations => keep it clean
- Cost overruns – annual & semi annual threats of cancellations
- Management of technical peer review flawed
- Single point failure in the development process was not recognized
- Corporate competition

Here we will discuss:

- The optical fabrication and test processes
- How the failure review board
  - Determined which mirror was in error
- The magnitude and sign of the error in the on-orbit telescope
- The approach used to fix the telescope
- Identify the five tests that suggested an error before launch

- Four axial bay instruments & one radial bay on-axis instrument
  - Wide field and Planetary Camera (radial)
  - Faint object camera (axial)



Hubble space telescope parameters

Mass	11,500 kg
Length	13 Meters
Diameter at widest	4.2 meters
Optical system	**Ritchey-Chretien**
Optical length	**57.6 m folded to 6.4 m**
Primary mirror	2.4 meters dia.
Secondary mirror	0.3 meters dia.
Pointing accuracy	**0.007 arsec for 24 hours**
Wavelength bandpass	**110 to 1100 nanometers**
Angular resolution	0.1 arcsec @ 632.8 nm
Orbit	611 km inclined 28.5 degrees
Orbital period	94 min.
Mission	15 years

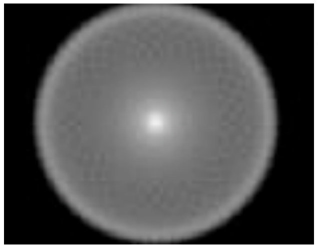
Some facts

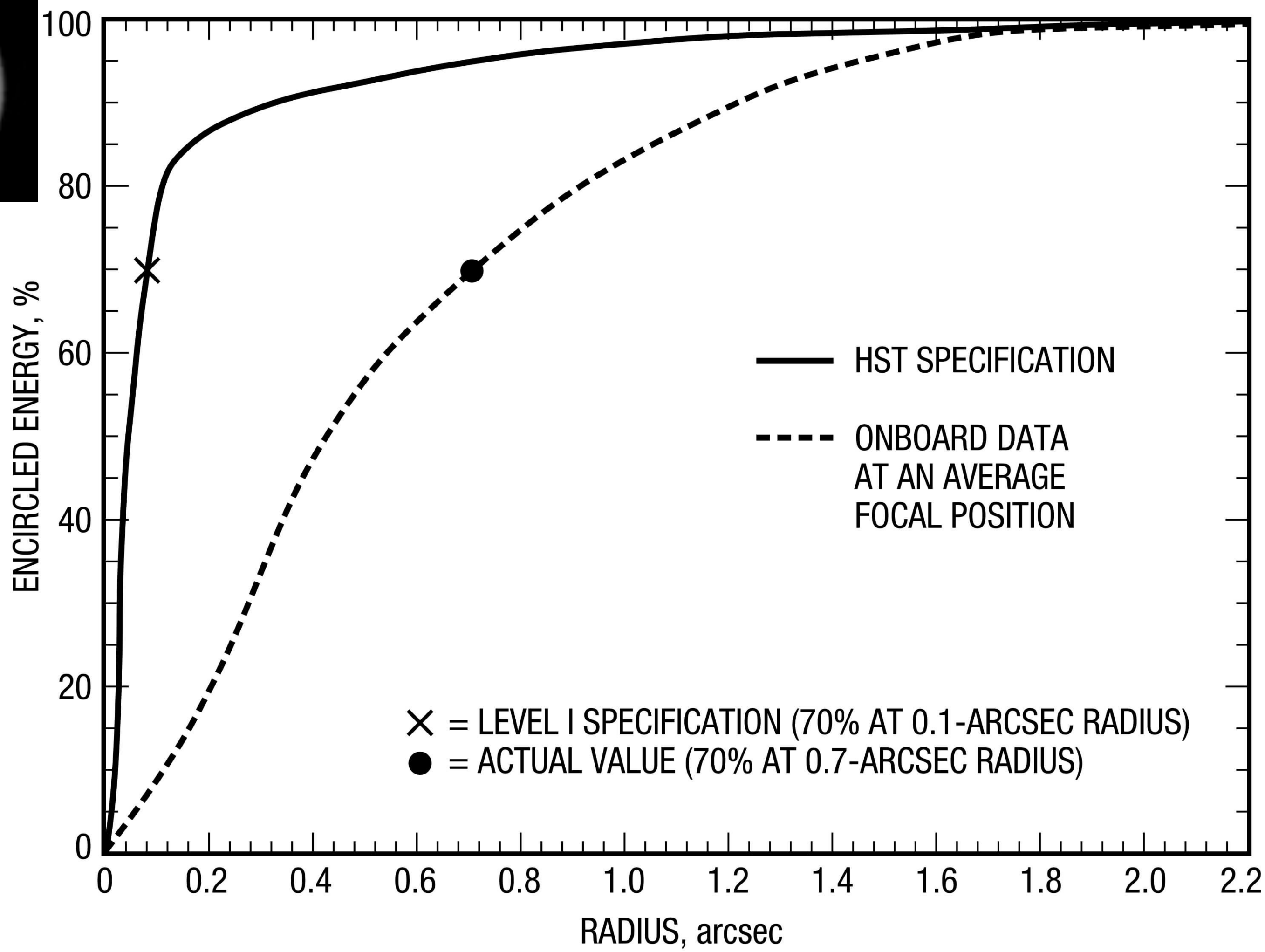
- Launch April 24, 1990
  - Originally manifested to follow challenger in 1984 => much confusion & $$ & stress
- May 21, 1990 NY Times publishes double star image on front pages
  - claim that astronomers were “amazed by excellent performance”!
- Project Manager announced failure June 21, 1990!

More facts

- NASA formed the official failure review board July 2
  - Presentation to congress & report published Nov 1990 (5 months from start)
- Prescription retrieval started August 1990
- By the spring of 1991, 7 teams using independent methods agreed on the on-orbit telescope prescription so the optical correctors could be made

Level 1 Optical system specification: Measured (on orbit) encircled energy





Failure Board Charter

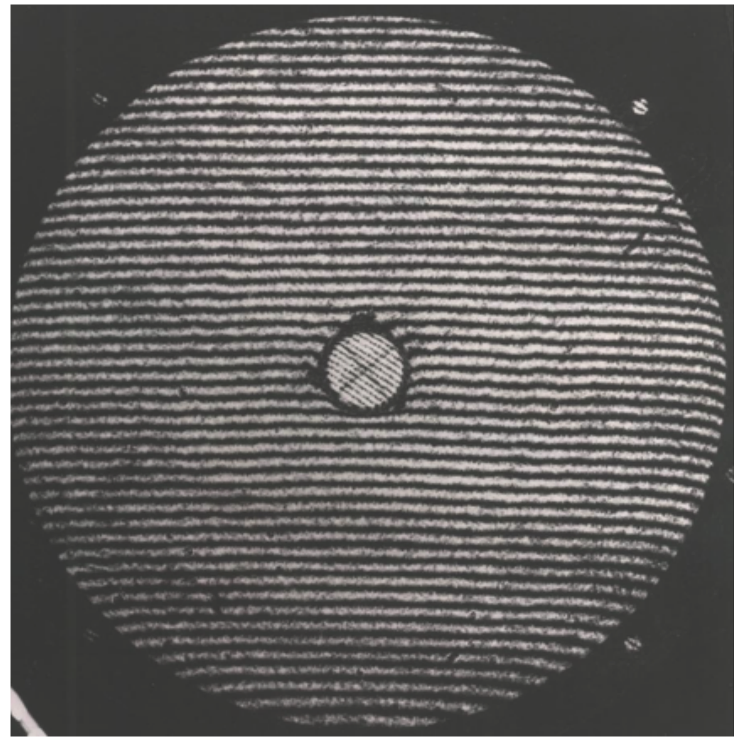
- Working group to review, analyze and evaluate facts and circumstances regarding the manufacture, development and testing of the Optical Telescope Assembly (OTA)
- Determine how & when the problems in the OTA occurred
- Determine how this aberration could go undetected prior to launch
- Not established to render, advise or make recommendation

Where was the error?

- Primary
- Secondary
- In wide-field planetary camera
- In faint object camera
- Both WF/PC and FOC showed the same error!
- Therefore on the primary or the secondary

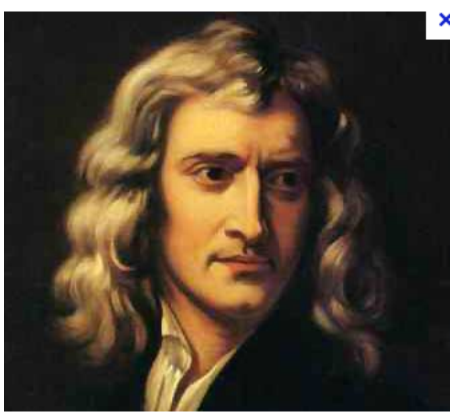
HST Secondary Optical Interferogram

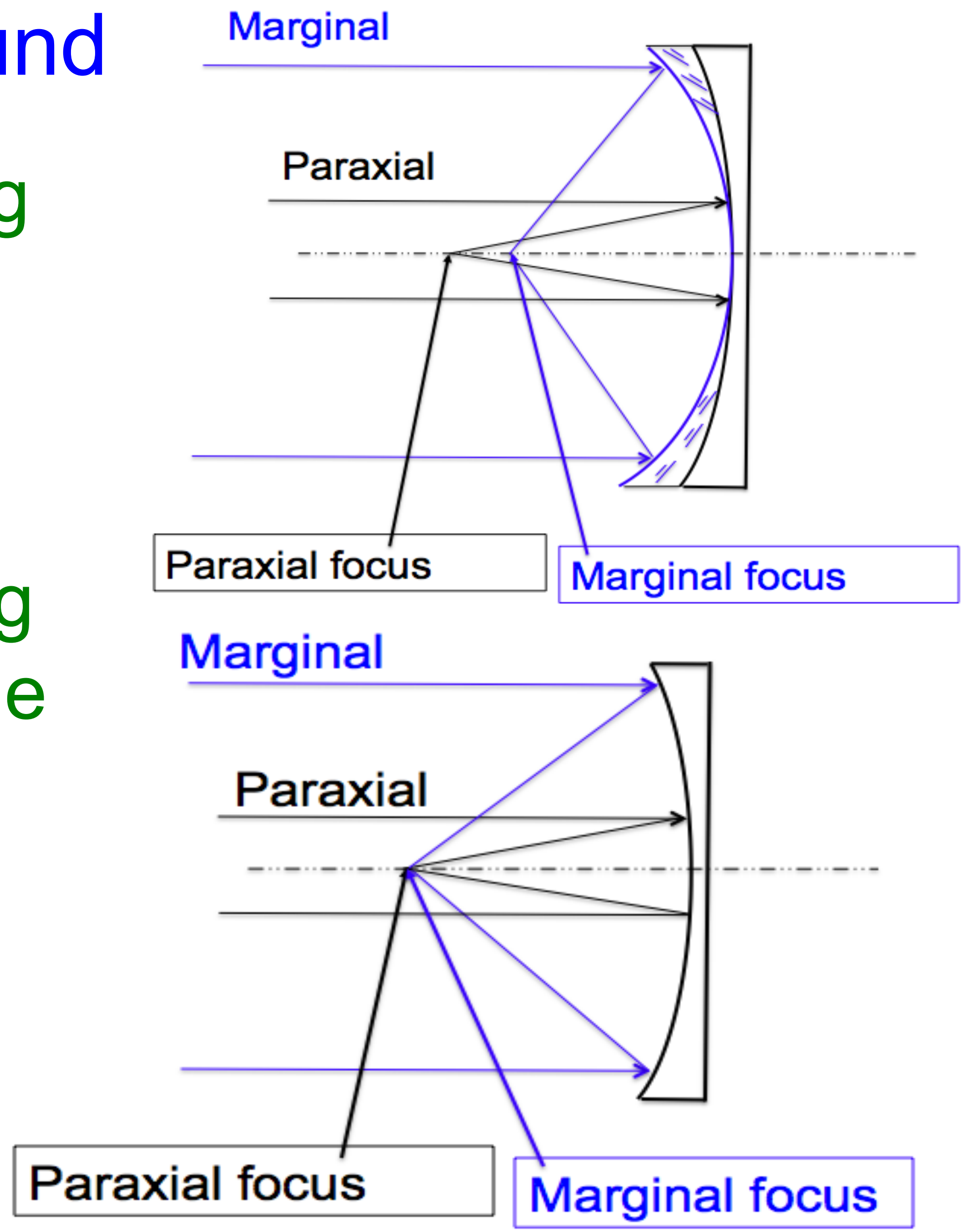
- Hindle sphere test configuration
- Recorded on August 31, 1981.
- Shows that the secondary was figured correctly.
- Therefore the cause was not the secondary mirror
- The spare was retested after error announced & found good.



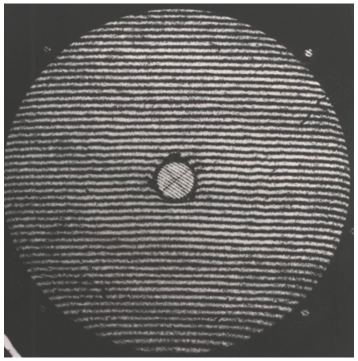
Spherical-Background

- During manufacturing phase
- Mirrors show spherical aberration
- Additional Processing needed to “flatten” the outside



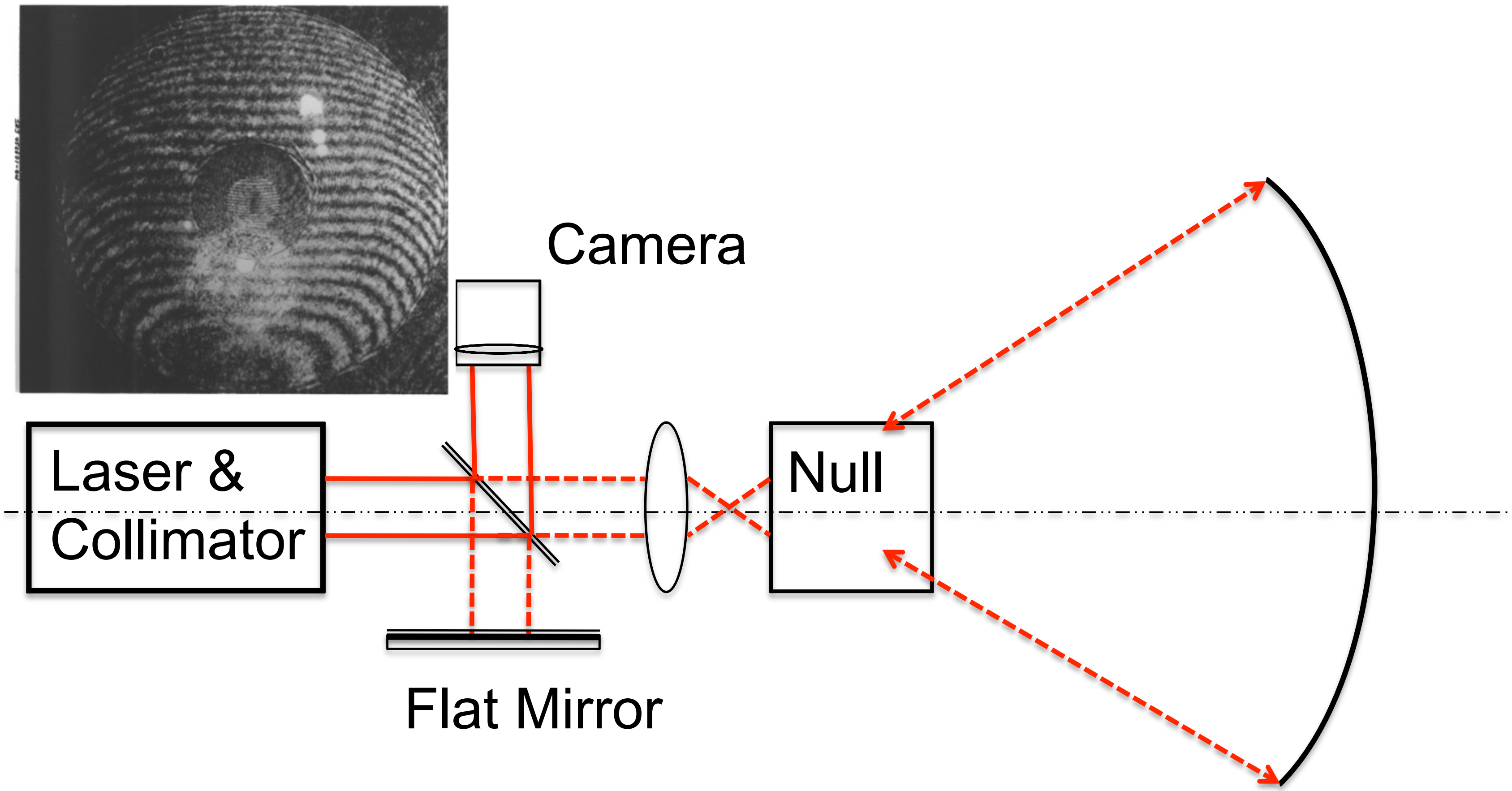


Investigation & recovery



- What was available to investigate?
  - "Fossil" hardware in bonded stores at the contractor
    - Null correctors, fixtures, interferograms, personal note books and PR photos
    - Interview engineers
- Sources of information about the on-orbit prescription
  - Star images recorded on axis and off axis by
    - OTA + WF/PC
    - OTA + Faint Object Camera (FOC)

Interferometric null corrector



Correct surface => straight line fringes

Primary mirror process

Corning casts mirror blank

Rough grind at PE Wilton

Tested with **refractive** null $\lambda / 4$

Fine figuring at PE Danbury

Tested with **reflective** null $\lambda / 100$

R_c tested with Refractive null

Coated & integrated

Finished in 1982
Launched in 1990

Primary Mirror Processing (1)

- One facility accepted the blank and
  - Rough & fine-ground the concave front surface to near net shape
  - Designed and manufactured a two lens refractive null corrector which used spherical and planar surfaces – very simple & less room for error
  - Tested the fine ground surface using the refractive null & shipped the mirror to another facility for polishing & figuring

Primary Mirror Processing (2)

- The second facility accepted the rough ground mirror
  - Designed and built a special purpose reflective null corrector for testing to the UV $\lambda / 100$
  - Completed figuring and final polish in April 1981 using the reflective null

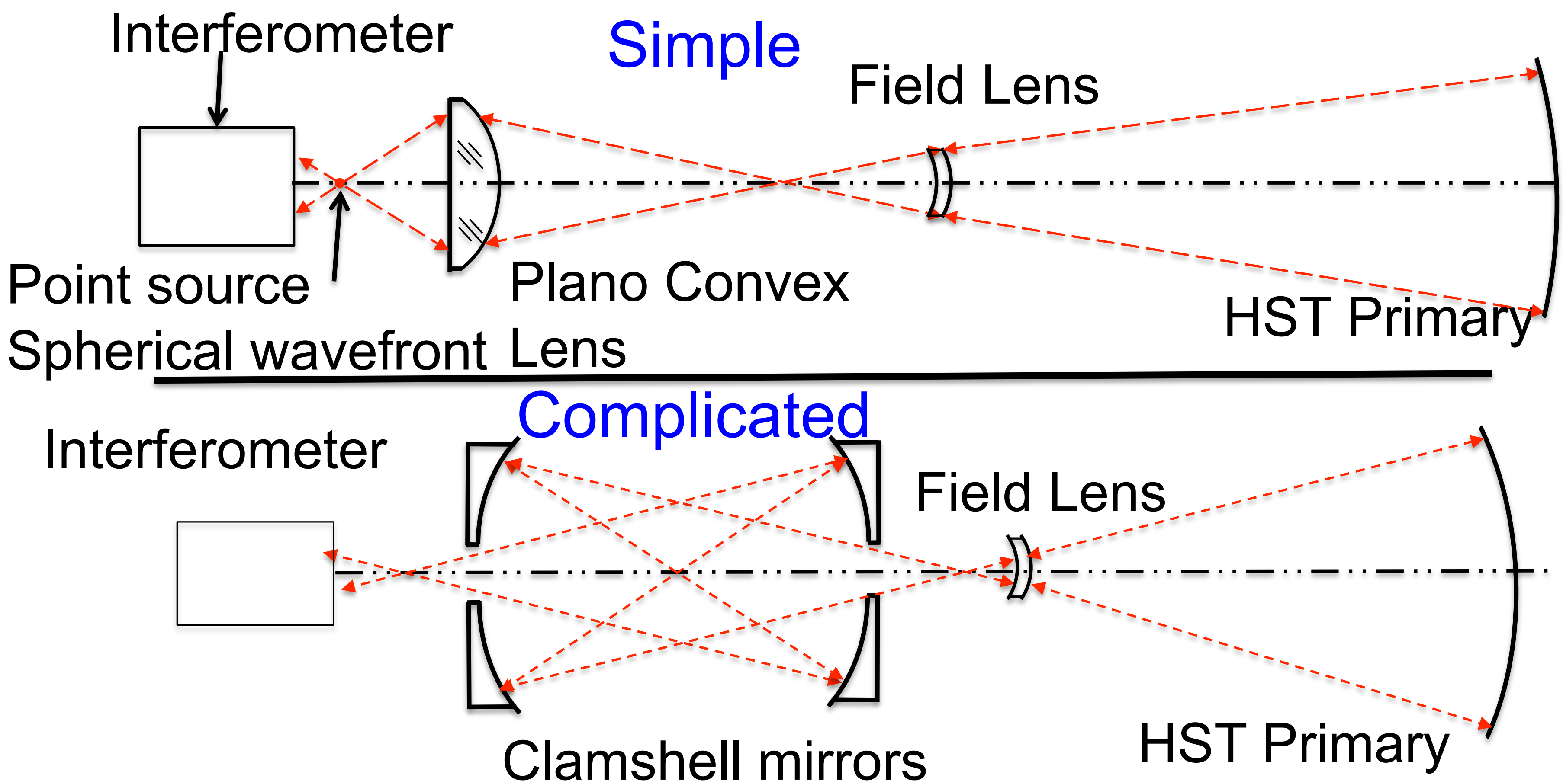
Primary Mirror Processing (3)

- At this second facility,
  - Radius of curvature was verified with the refractive null.
    - Interferogram shows the spherical aberration error, but not recognized! That was not the purpose of the test!
  - Peer-review panel did not review this material

Null correctors

- Refractive null correctors have a performance limit given by the uniformity of the index of refraction in the bulk glass or refractive material
- Reflective null correctors are opto-mechanically more complex, but their performance limit is given only by surface smoothness (10 to 100 times better than refractors)

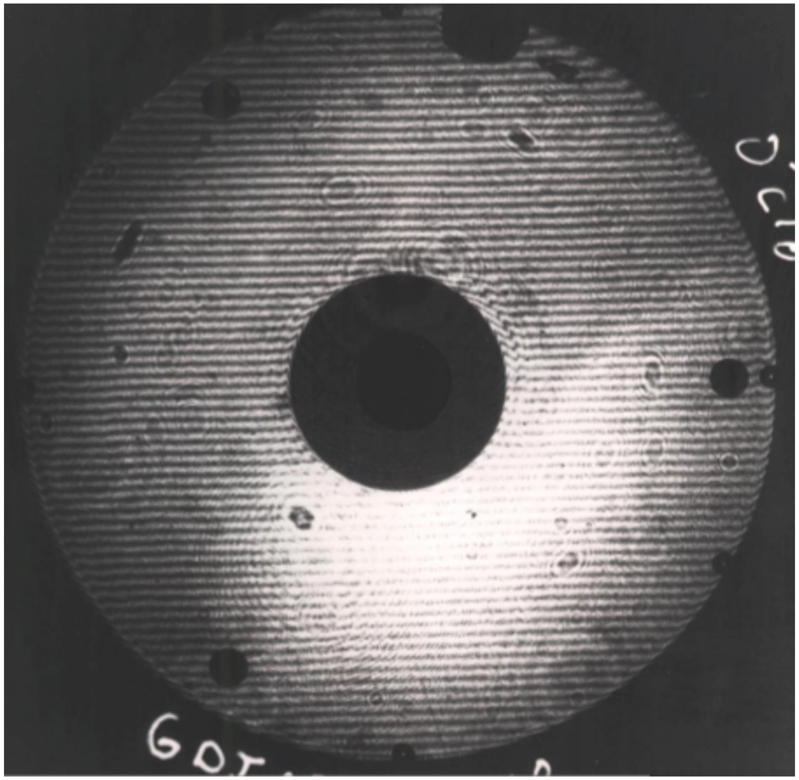
Refractive & reflective null



The refractive nulls use transparent glass.
Predicted they could not meet the specification because of the non-uniform index of refraction in the glass.
Therefore the complicated reflective null was required

Primary Mirror Optical Interferogram

- Recorded on February 1982
- Shows that the primary was figured to the reference wavefront provided by the **reflective clamshell null corrector**
- After launch we learned that the reference wavefront was wrong!



The primary mirror after fabrication

Reflective null corrector

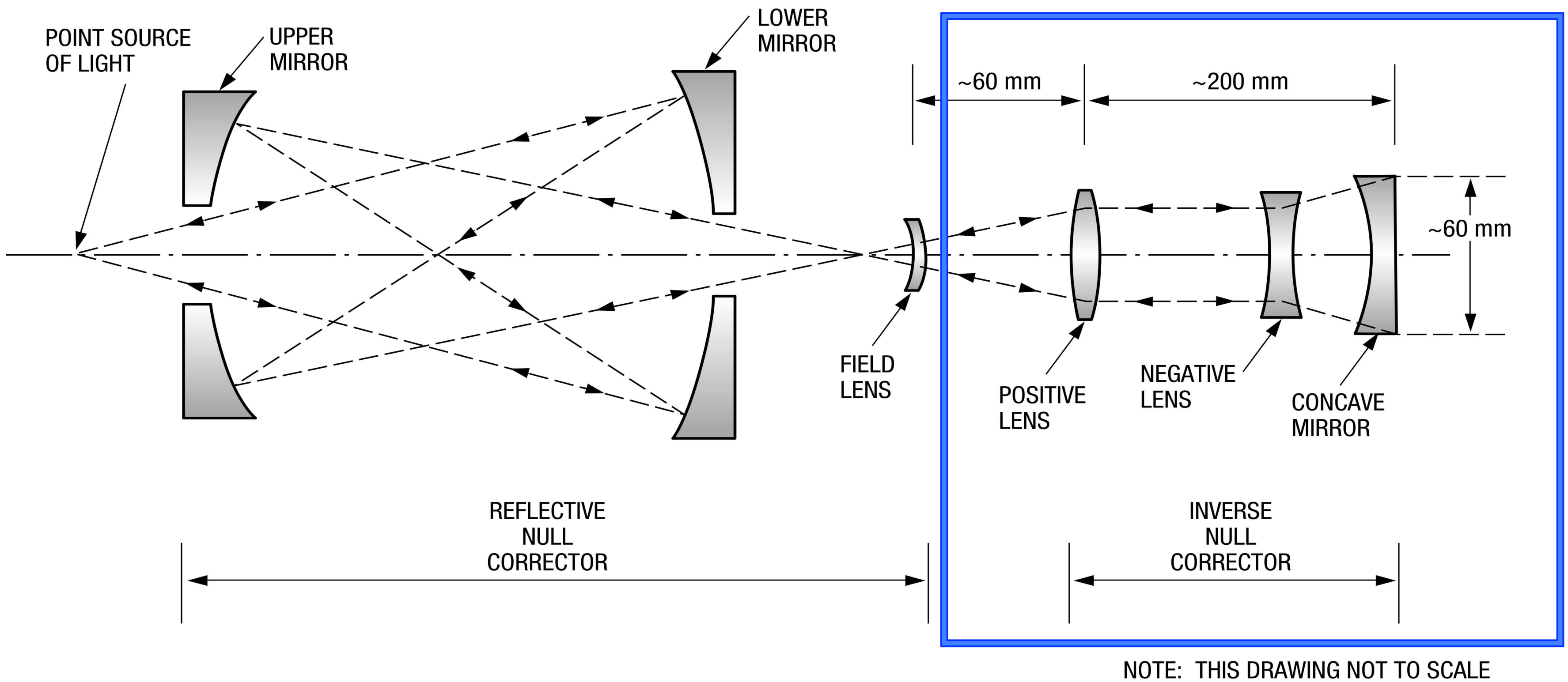
Refractive null corrector interferogram recorded to verify focus location

- Sometimes after polishing the base radius of curvature has changed
- Optical tests of the polished figure are recorded to verify the focus has not changed
- The focus is OK **the wavefront is bad**

Reflective null?

- How could the error be in the reflective null?
- They built and used an inverse null corrector to verify that the reflective null did not change
- But . . . . .check the inverse null again with the reflective null . . . . .

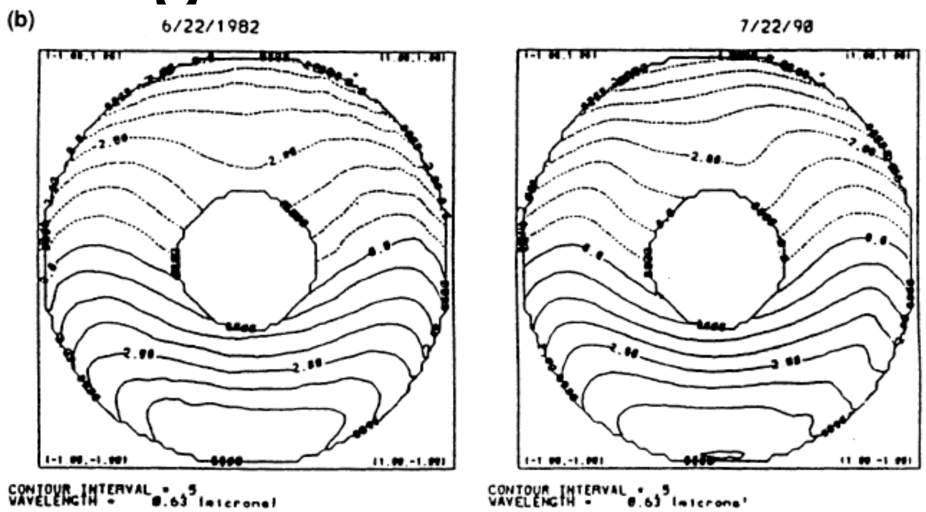
The reflective null The Inverse Null



The inverse null simulated the desired HST surface. It was used to verify there were no drifts in the Reflective null during figuring. The error should have been visible here, but the optician was told only to look for changes. The clamshell was the “absolute reference” – not the inverse null!

Null change between 1982 & 1990?

6/82



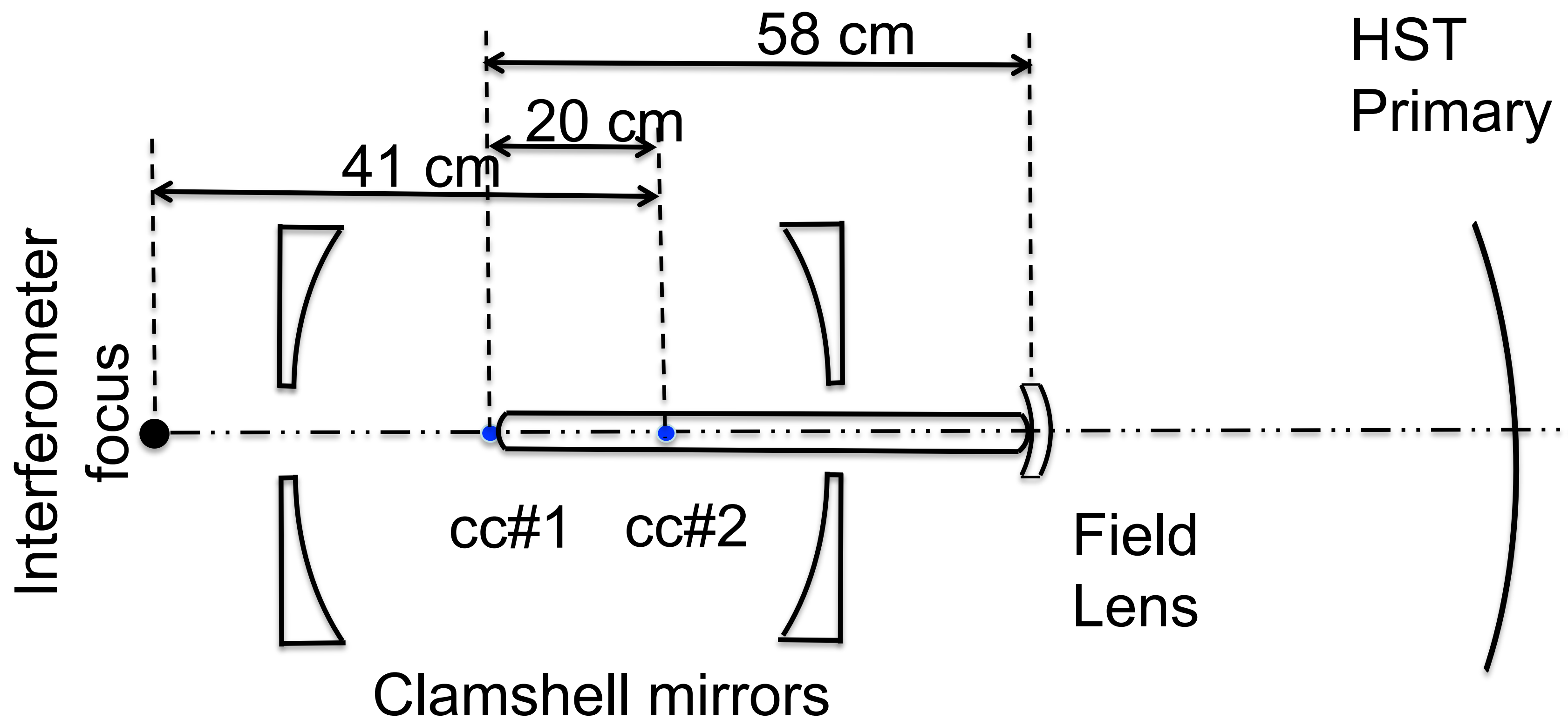
7/90

- We retested the reflective null – no changes
- Tests in 1990 are just like the 1982 tests
- 1982 interferogram from employee's personal notebook
- But this interferogram showed the spherical aberration in 1982!! -- launch was 1990!
- Just assumed the 6 –waves error was in the reference null or ….?

Fault tree analysis of the reflective null corrector indicated possible error sources

- Field lens inserted backward
- Wrong index of refraction glass used in the field corrector
- Optical elements incorrectly spaced
- CAD analysis quickly showed only an error in spacing of the all reflecting null was the most likely source.

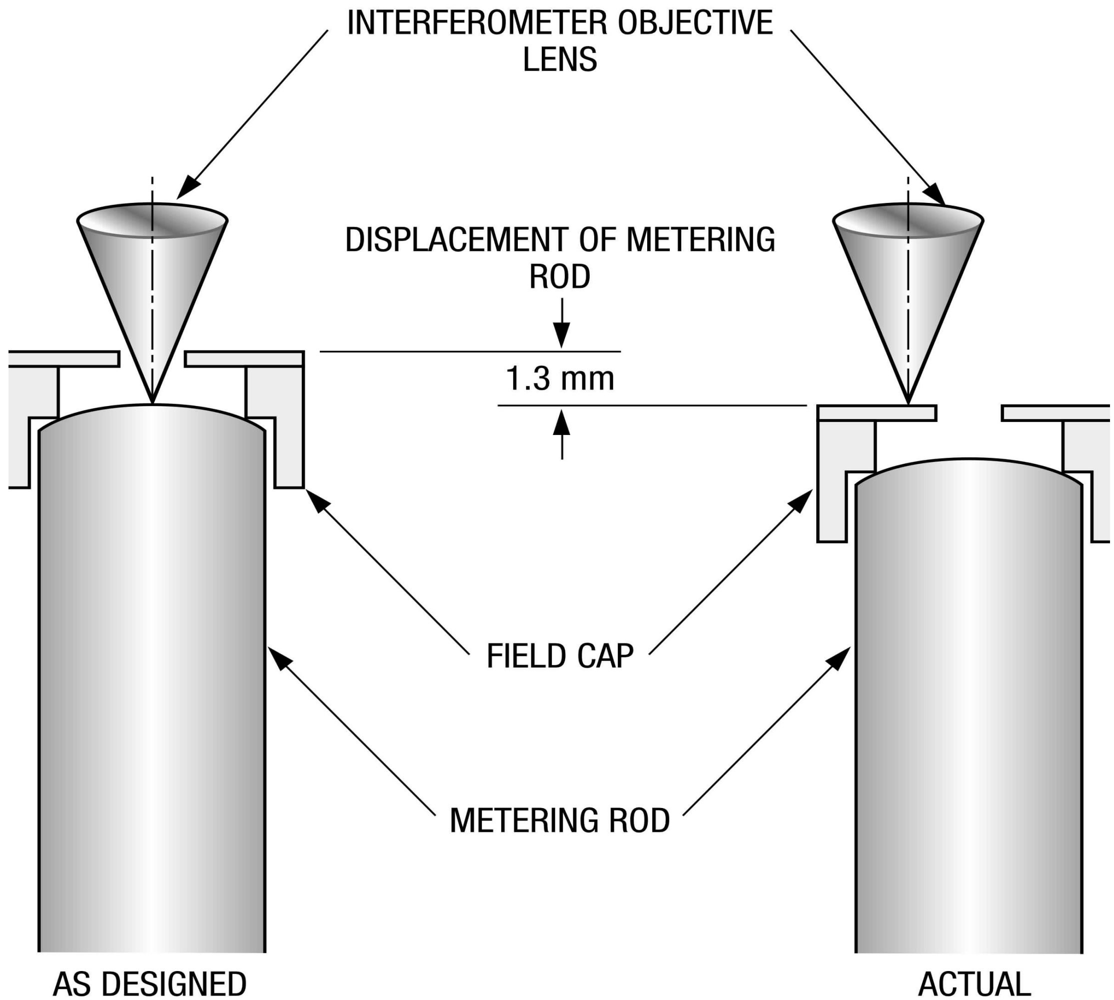
How was the reflective null spacing determined?

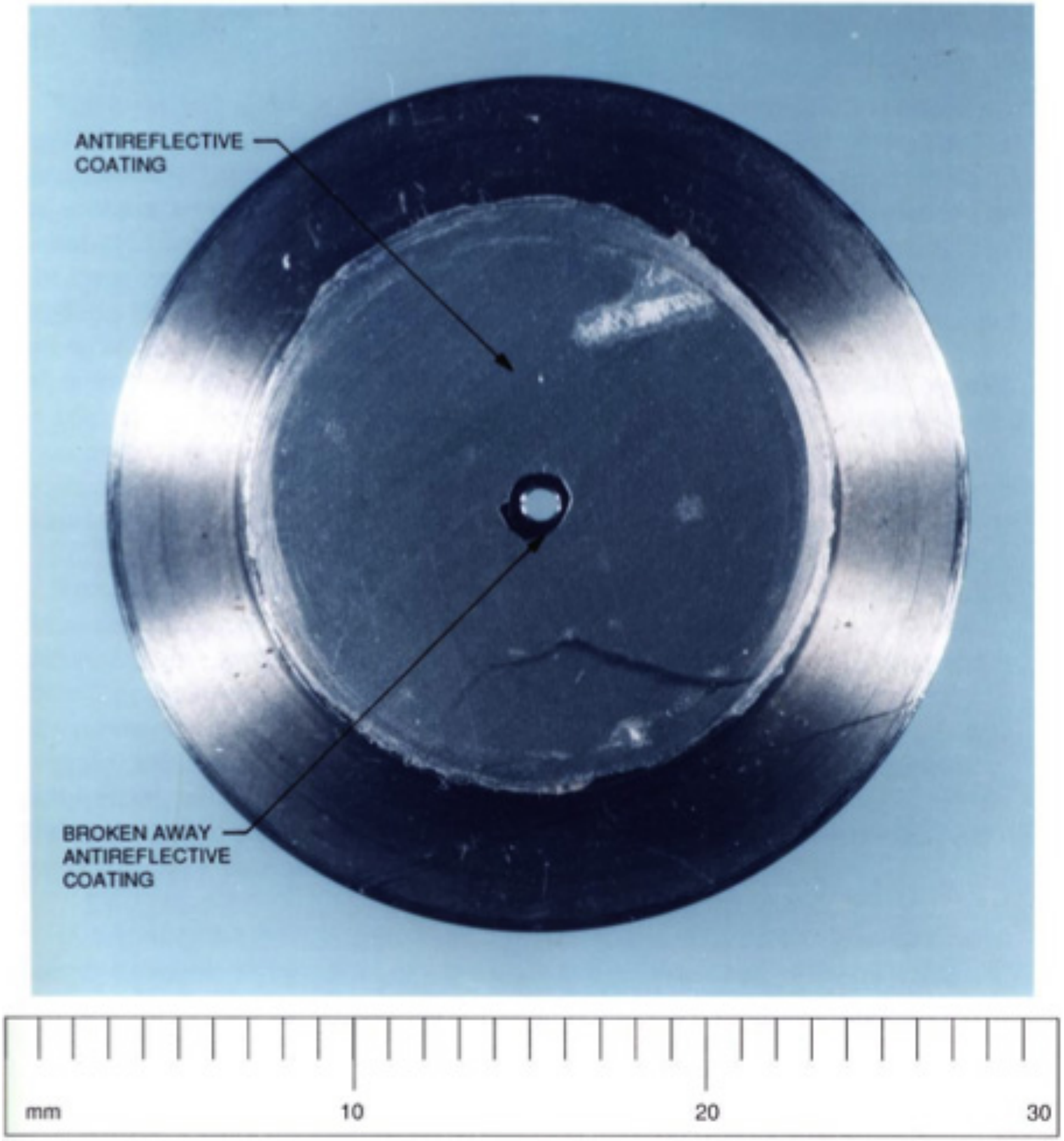


The only mechanical drawings for the Reflective null corrector were on publicity photo recorded of the instrument with the drawing hanging in front. We had it enhanced.

1.3 mm spacing error

- The end of the rod is rounded & polished
- Collar was built to ensure centering
- Alignment interferometer set on wrong surface
- Never double checked
- “measure twice cut once not followed”





Top view of the field cap, showing the small aperture and the area where the antireflective coating had broken away

Management errors

- The designer of the null test Abe Offner was not invited to climb the tower to verify his test worked!
- NASA QA did not request, nor were they invited to participate in the assembly of the null corrector! They seem to have been unaware of its importance!

When could the error have been questioned or discovered?

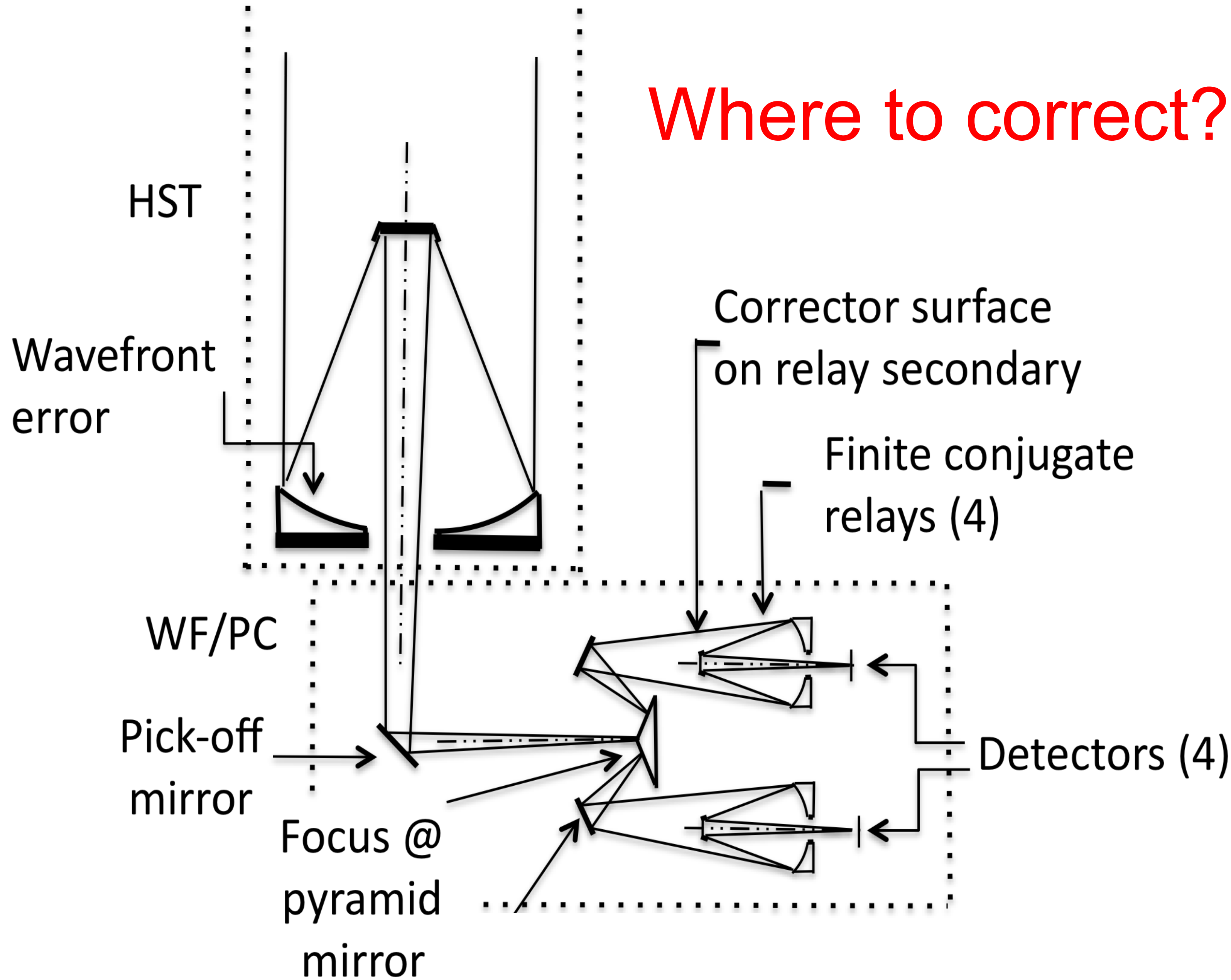
- Proper analysis of the
  - Interferogram recorded by the refractive null corrector on the finished mirror
  - Interferogram recorded by the inverse null
- Independent double check on the metering rod separation
- Second shift to grind mirror needed?
- Lockheed 16-inch telescope test used to verify focus location.

Fix it!

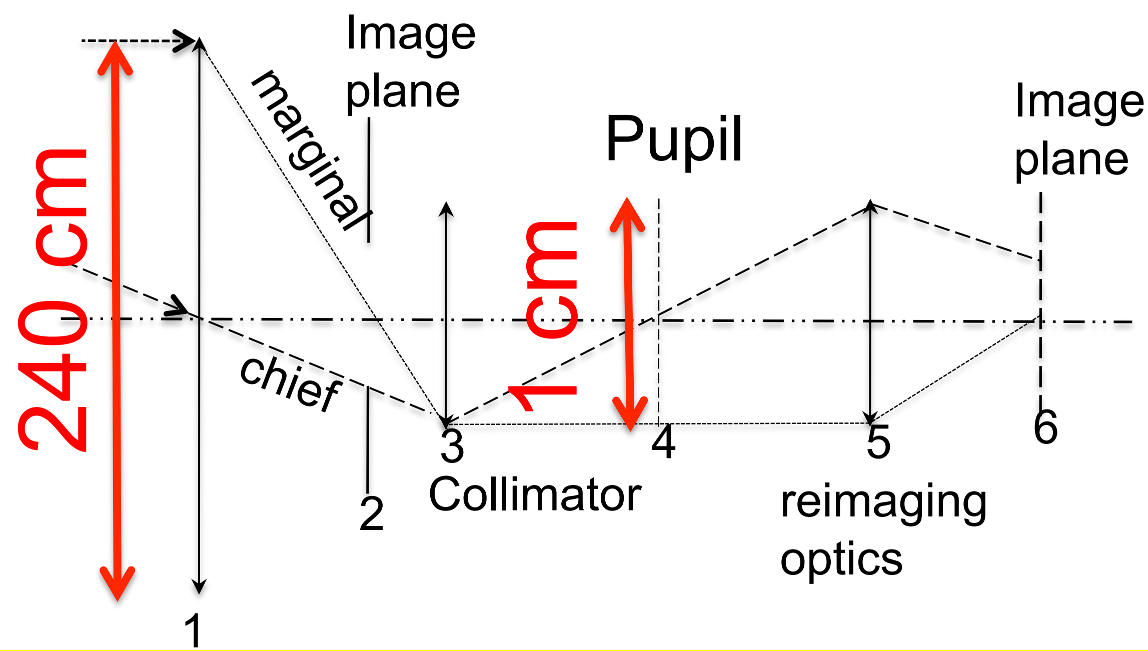
- NASA had given the go-ahead several months before original launch to build a second camera
- Hardware was ordered and some parts were in house
- The 36 month schedule became ~18 months
- Needed the correct magnitude and sign fast
  - But it had to be right!
- Challenge:
  - Correct the telescope error with minimum rework to existing WF/PC2 hardware and build it fast!

WF/PC Optics Schematic

Where to correct?



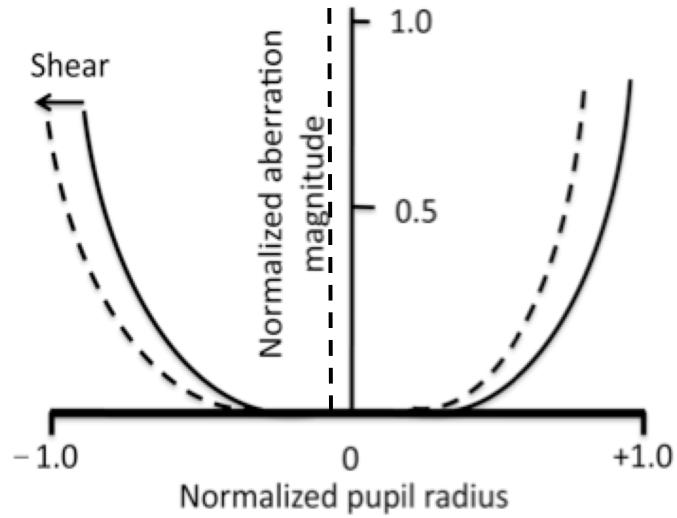
Alignment tolerance between WF/PC and HST



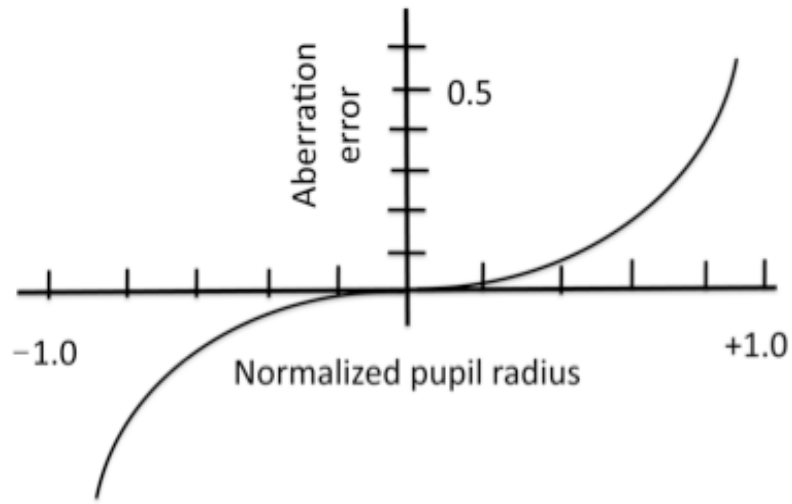
- Entrance pupil to internal pupil image distances in the x, y plane undergo a minification of 240 to 1
- Distances in the z direction (phase error) remains unchanged

But ….. pupil shear!

The spherical aberration and a shifted aberration corrector. The axes are not collinear.



The difference between the two or the residual that remains uncorrected is the characteristic asymmetric aberration of coma



What does this mean for WF/PC2 and HST?

Unfortunately, the telescope was launched with –6.6 waves of error at 0.63 µm of spherical aberration over its 2.4-m diameter. Calculate the error delta *y* that the axes an be displaced.

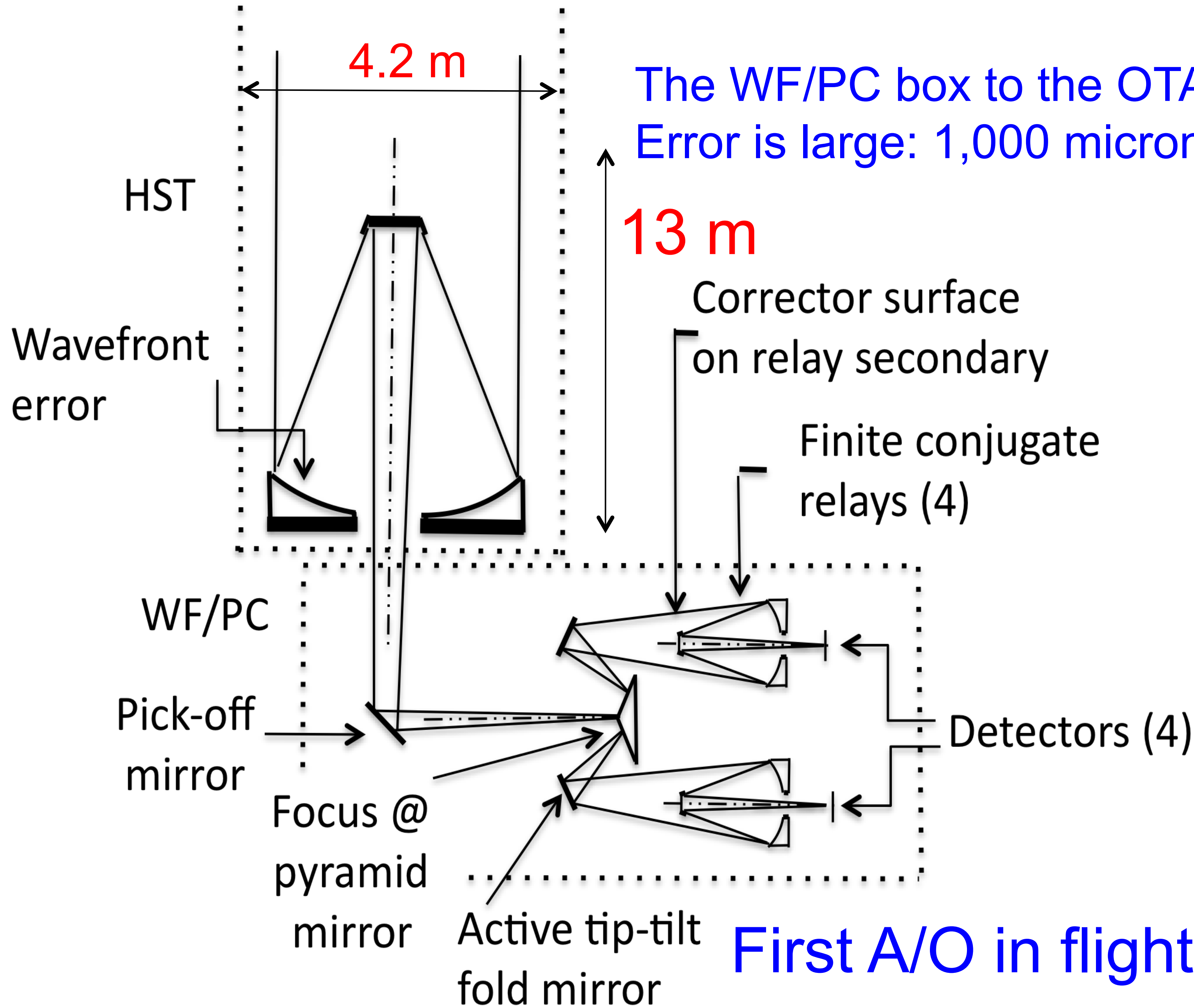
$$y = 7{,}500\ microns$$

$$W_{131} = 0.2\ \text{waves (assumed tolerable)}$$ => $$\Delta y = 28\ \text{microns}$$

$$W_{020} = 6.6\ \text{waves (as built HST)}$$

The system axis of the wide field and planetary camera needs to be co-linear with the axis of the HST within a 28 micron error

WF/PC Optics Schematic



The WF/PC box to the OTA Error is large: 1,000 microns

First A/O in flight

What is the precise error?

- On-orbit optical prescription measurements
  - Prescription retrieval
- Fossil equipment measurements
  - Null correctors
  - 1981 Recorded interferograms
  - Secondary mirror

Conic constant is the metric

The equation that gives the coordinate for the surface as a function of *x* and *y* for a conic surface rotated about the *z* axis can be written as

$$z = \frac{C\left(x^2 + y^2\right)}{1 + \sqrt{1 - (1+\kappa)C^2\left(x^2 + y^2\right)}}$$

Value of the conic constant	**Figure of revolution**
$\kappa = 0$	Sphere
$\kappa = -1$	Paraboloid
$-1 < \kappa < 0$	Ellipsoid (prolate spheroid)
$\kappa < -1$	Hyperboloid
$\kappa > 0$	Oblate spheroid

- The HST is a Ritchey-Chrétien hyperboloid & we expect numbers to be less than -1

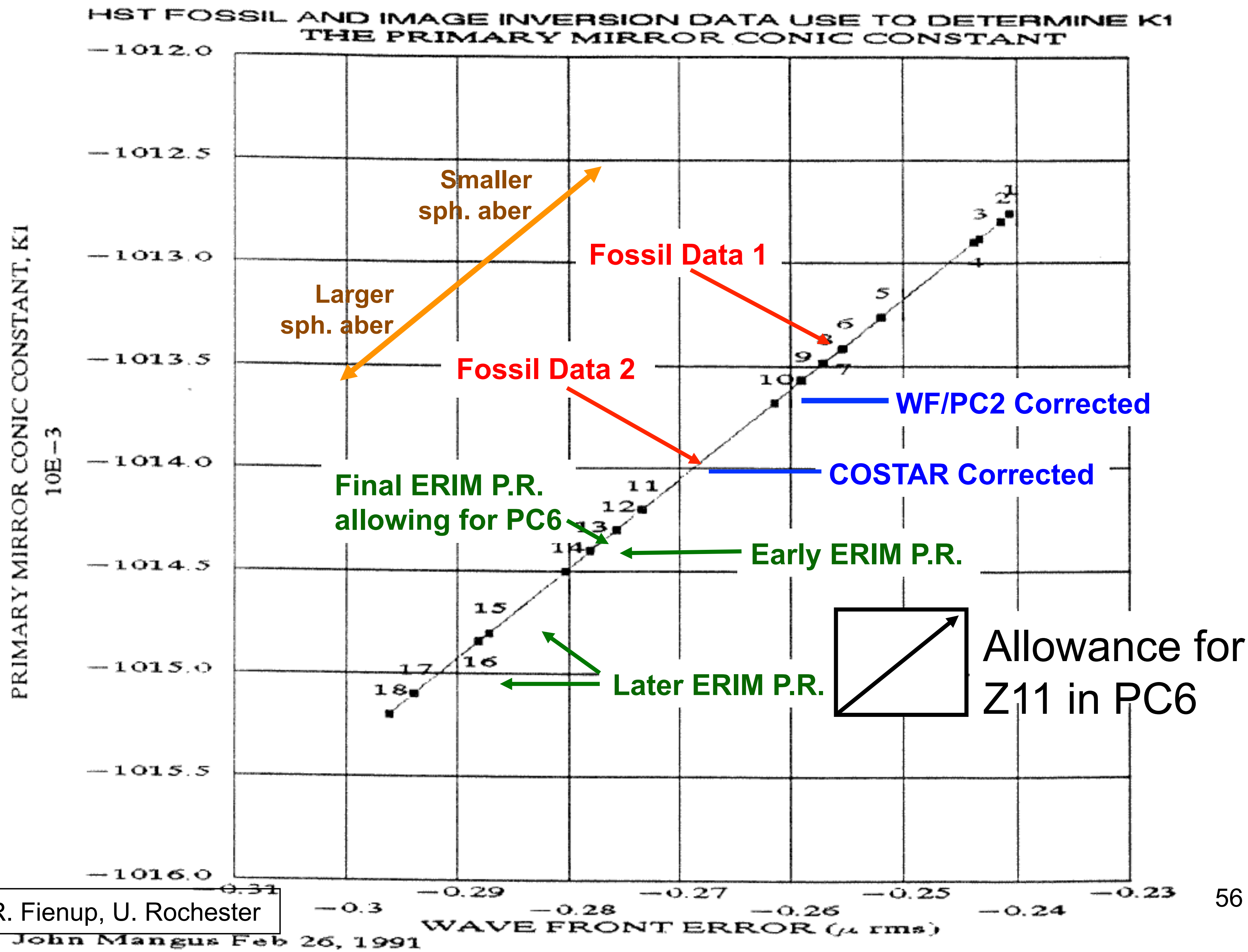
Data

- Star images [point spread function, PSF] recorded digitally at ~16 bits
  - At focus intervals between the marginal and paraxial focii (~15 cm)
  - Across the fields of view within each of the four narrow angle cameras
- Ten groups used 6 independent methods

On-orbit data quantitative results

DATA SOURCE 26-Feb-91	CONIC CONSTANT	ERROR BARS	WFE (μ rms)	ERROR BARS (μ rms)
1 WETHERELL: RNC, note 1	-1.01276 ±		-0.2405 ±	
2 MANGUS: INC, note 2	-1.01280 ±	0.0008	-0.2415 ±	0.0183
3 FUREY: RvNC, note 3	-1.01288		-0.2433	
4 FUREY: RNC, note 1	-1.01290 ±	0.0002	-0.2437 ±	0.0046
5 MANGUS : RvNC, note 4	-1.01326 ±	0.0008	-0.2520 ±	0.0183
6 MIENELS': PAD LOCATION	-1.01341 ±		-0.2554 ±	
7 MIENELS' : RIM IMAGE	-1.01342 ±		-0.2556 ±	
8 FUREY : RNC, note 5	-1.01349 ±	0.0006	-0.2571 ±	0.0137
9 LYONS : HDOS-FOC, HARP I	-1.01357 ±		-0.2590 ±	0.0005
10 BURROWS: ScI-FOC, HARP I	-1.01368 ±	0.0008	-0.2615 ±	0.0183
11 FABER/HOLTZMANN : WF/PC-PC	-1.01420 ±		-0.2734 ±	0.0000
12 LYONS : HDOS-PC, HARP I	-1.01430 ±	0.0005	-0.2757 ±	0.0114
13 LYONS: HDOS-WF	-1.01440 ±	0.0009	-0.2780 ±	0.0205
14 RODIER : PC, HARP I	-1.01450 ±		-0.2802 ±	0.0000
15 BURROWS : HST Sci Inst-PC,HARP I	-1.01480 ±	0.0003	-0.2871 ±	0.0068
16 VAUGHN : PAD LOCATION	-1.01484 ±	0.0003	-0.2881 ±	0.0068
17 FIENUP : ERIM - PC, HARP I	-1.01510 ±	0.0007	-0.2939 ±	0.0160
18 SHAO : JPL-PC, HARP I	-1.01520 ±		-0.2962 ±	0.0000

e 1; assumes M2 to FL, M1 to M2 and CORI to M1 errors are real
e 2; assumes as built errors had correct spacing to correct for element fab error
e 3; assumes reticle in and EPI to NL distance adjusted by +.68 mm
e 4; assumes earliest as built data given in August 1990, Allen Comm.
e 5; assumes only FLPE as real , other spacing measurements as


HST FOSSIL AND IMAGE INVERSION DATA USE TO DETERMINE K1
THE PRIMARY MIRROR CONIC CONSTANT
PRIMARY MIRROR CONIC CONSTANT, K1
10E−3
−1012.0
−1012.5
−1013.0
−1013.5
−1014.0
−1014.5
−1015.0
−1015.5
−1016.0
−0.31
−0.3
−0.29
−0.28
−0.27
−0.26
−0.25
−0.24
−0.23
WAVE FRONT ERROR (μ rms)
John Mangus Feb 26, 1991
Smaller
sph. aber
Larger
sph. aber
Fossil Data 1
Fossil Data 2
WF/PC2 Corrected
COSTAR Corrected
Final ERIM P.R.
allowing for PC6
Early ERIM P.R.
Later ERIM P.R.
Allowance for
Z11 in PC6

Current status

- Error is still on the primary mirror
- All HST optical instruments require corrector
  - Ground test equipment is required to have the error built in
- Still fully operational after
  - 30 years since construction
  - 22 years on orbit
  - 5 re-servicing missions

Judgmental statements

- NASA accepted the PE proposal to rely entirely on the Reflective null should have alerted NASA and PE personnel that special attention be given.
- The conclusion that the Reflective null was the only device that could have the accuracy led PE to fail to consider any independent measurement
- NASA project management did not have the necessary expertise to critically monitor the optical activities of the program

Judgmental statements

- The NASA science advisory group did not have the needed expertise, depth of experience or skill
- The P-E Technical advisory group did not probe deeply into optical manufacturing processes
- The most capable optical scientists at PE were closely involved with the demonstration mirror and design of the HST. BUT implementation took place in another division.

Judgmental statements

- The implementing division operated in a closed door environment which permitted discrepant data to be discounted without review.
- The basic product assurance requirements & formal review process were procedurally adequate to raise critical issues in most safety, material and handling matters, but not in optical matters.

Thank you

- James Breckinridge
- jbreckin@optics.arizona.edu