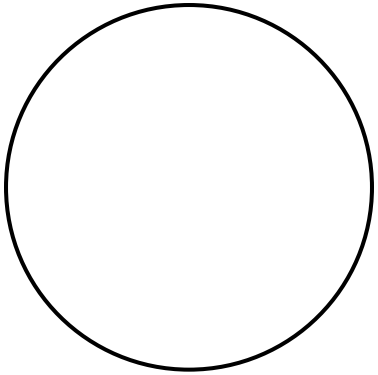
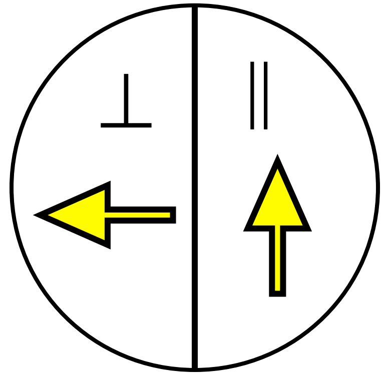
Quiz?

Exit pupil of a diffraction limited optical system



Open



Two polarizers

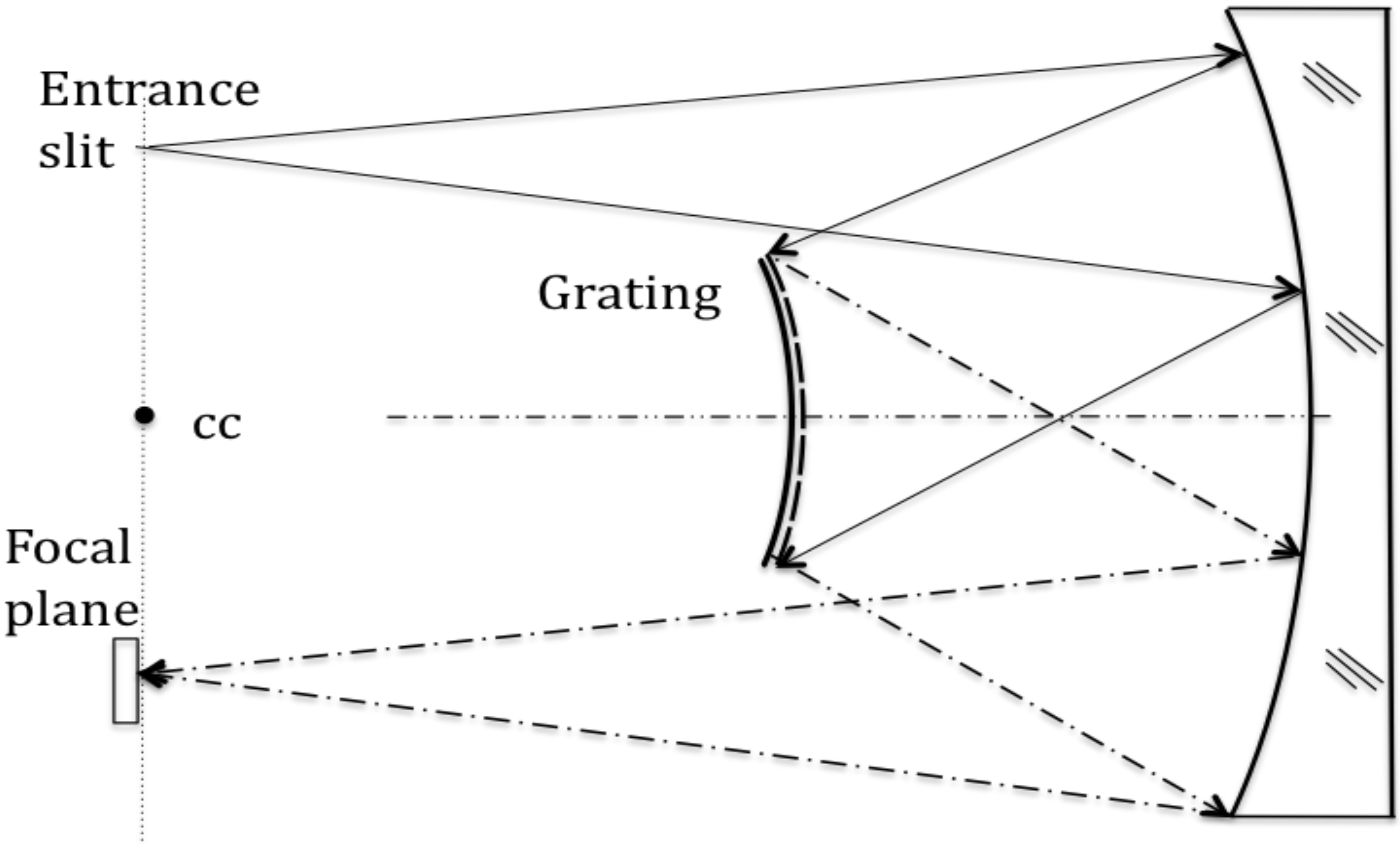
What does the image plane look like in each case and why?

Expensive mistakes

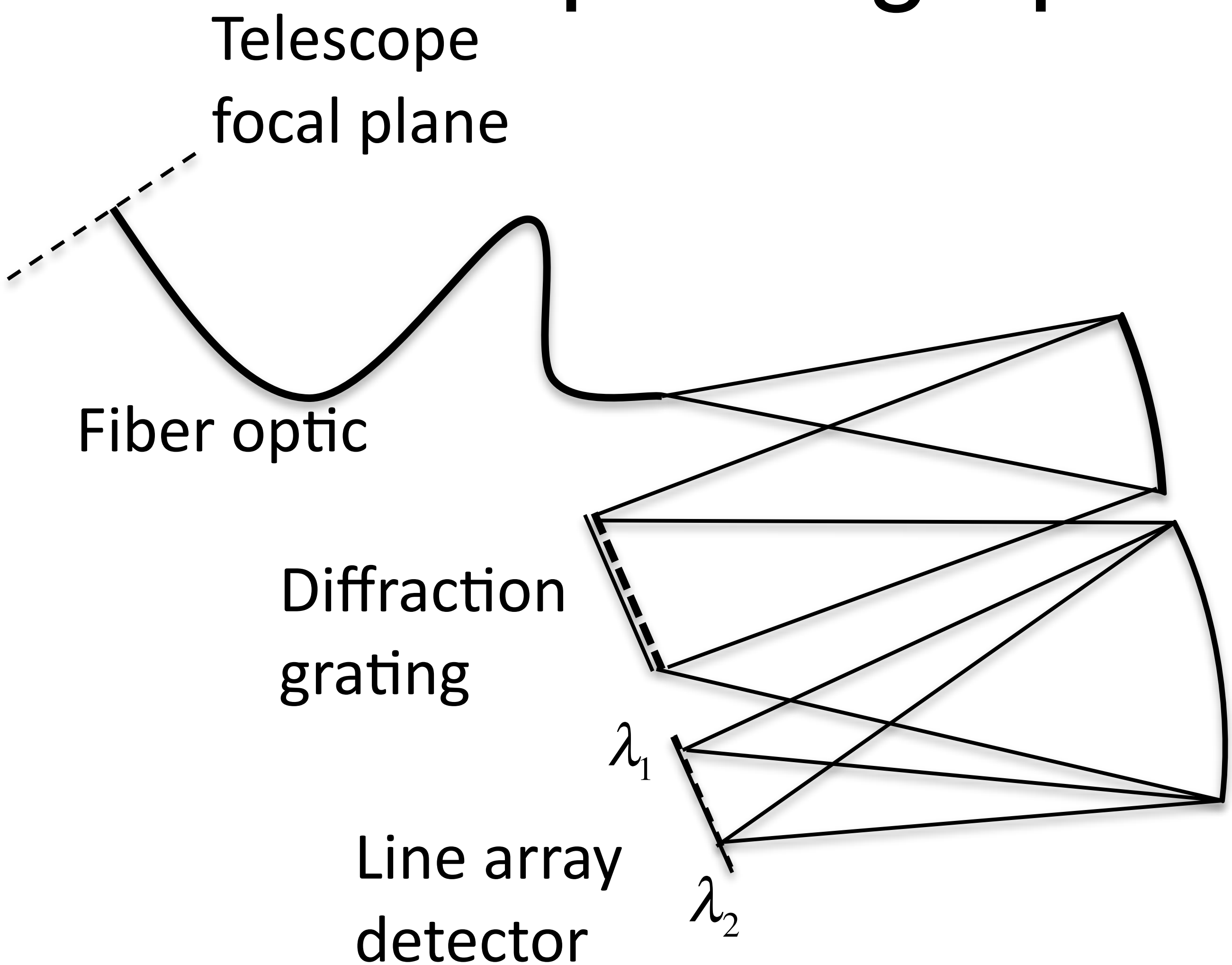
- Orbiting carbon observatory
- Hubble Space Telescope

Diffraction grating spectrometers

Offner relay spectrometer shows ~ full scal

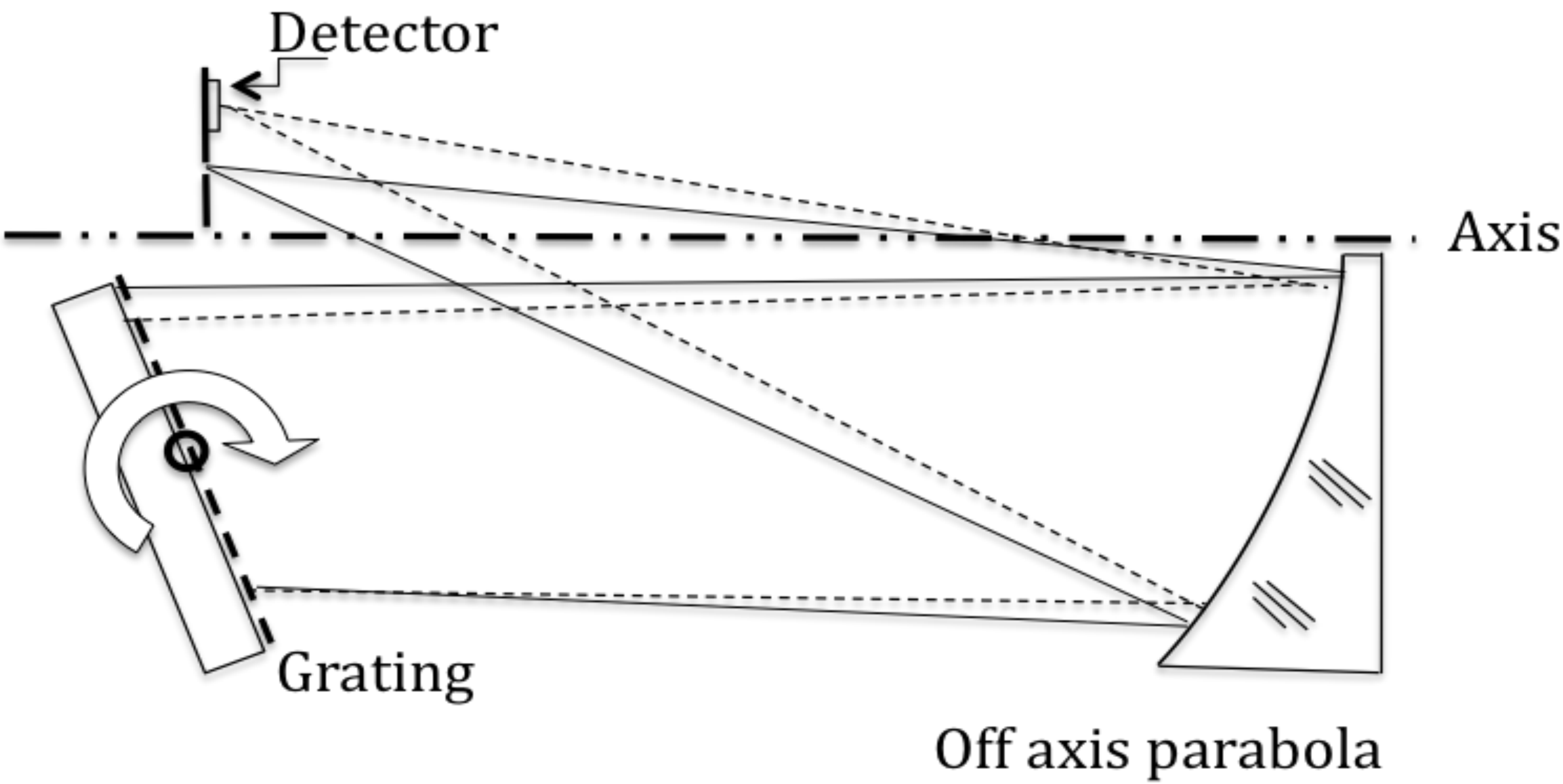


Fiber fed spectrograph

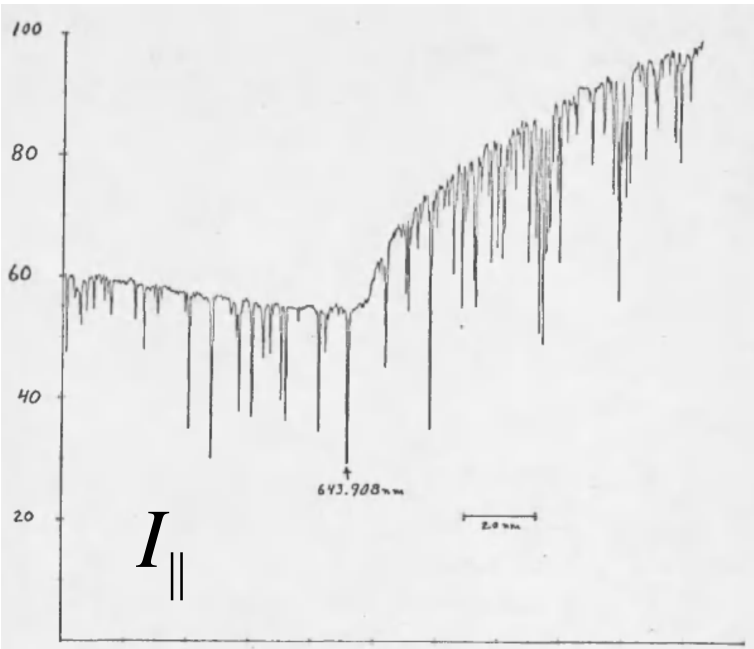


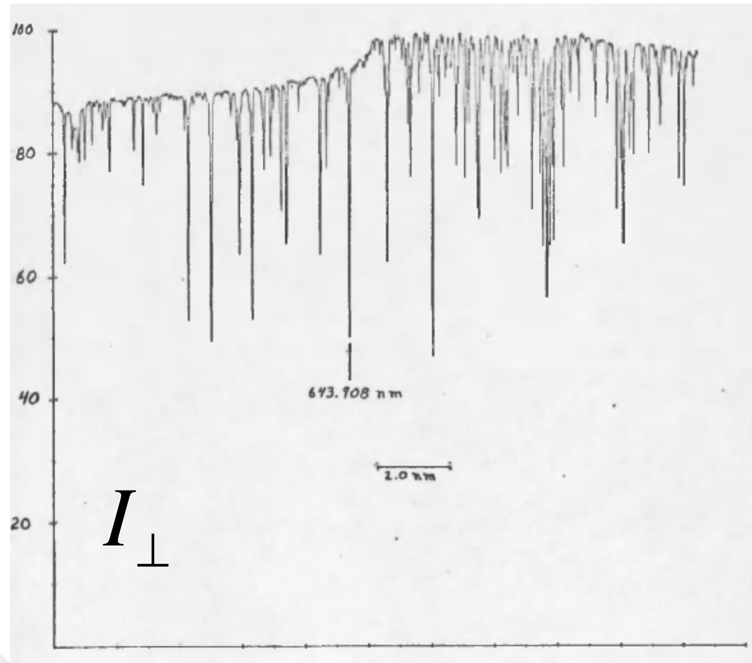
Diffraction grating spectrometers

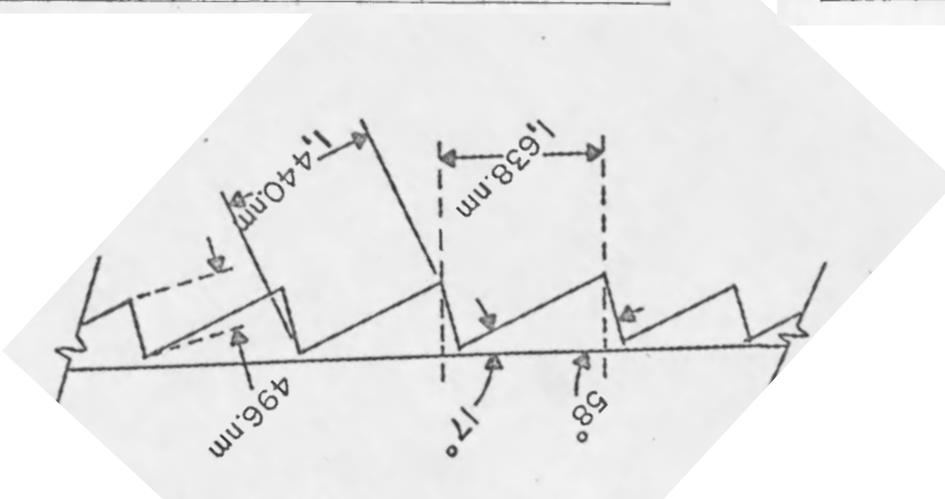
Littrow mounting



Profile of a Wood's anomaly







$$n\lambda = 2d\sin\theta$$

What happens to the light in order n-1 when theta exceeds 90-degrees?

Hubble &
how we used A/O to fix it:

failure analysis,
measure on-orbit prescription
WF/PC2 redesign

21 April 2015

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Adjunct professor
College of Optical Sciences
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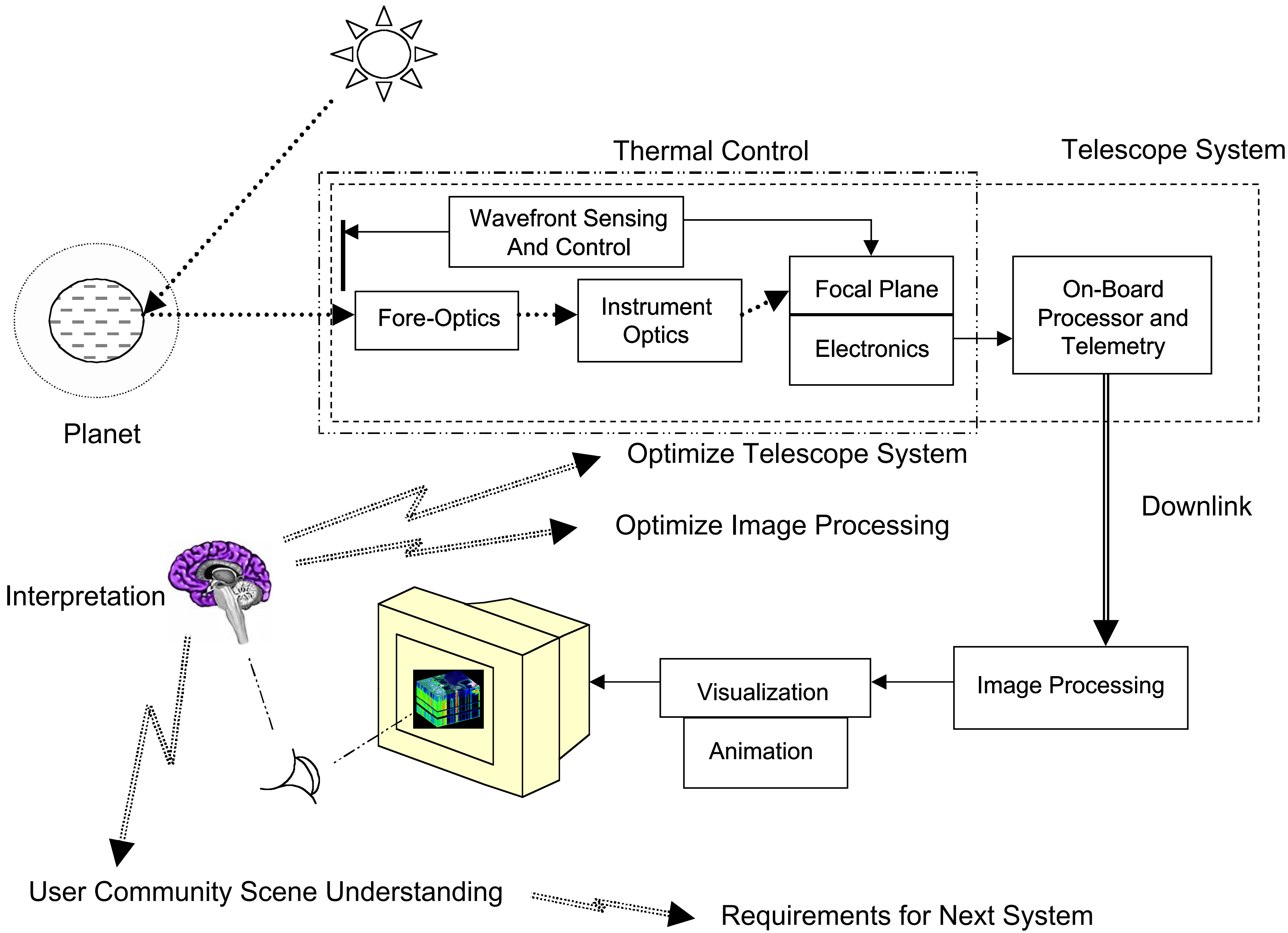
Modern space telescope system



As an astronomer . . .

- You will be asked to peer-review
  - Telescope design
  - Fabrication of optical elements & mechanical structures
  - Instrument design
  - End to end optical system calibration
  - Sign-off that the >$100M system will record the data you need for your astronomy
- You need to understand what
  - Is right
  - Can go wrong!
- Today’s talk covers a case study of HST failures

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.
- Payload integration onto the space craft awarded to Lockheed Sunnyvale
- Five instruments were awarded to principle investigators & completed independent of the telescope contract

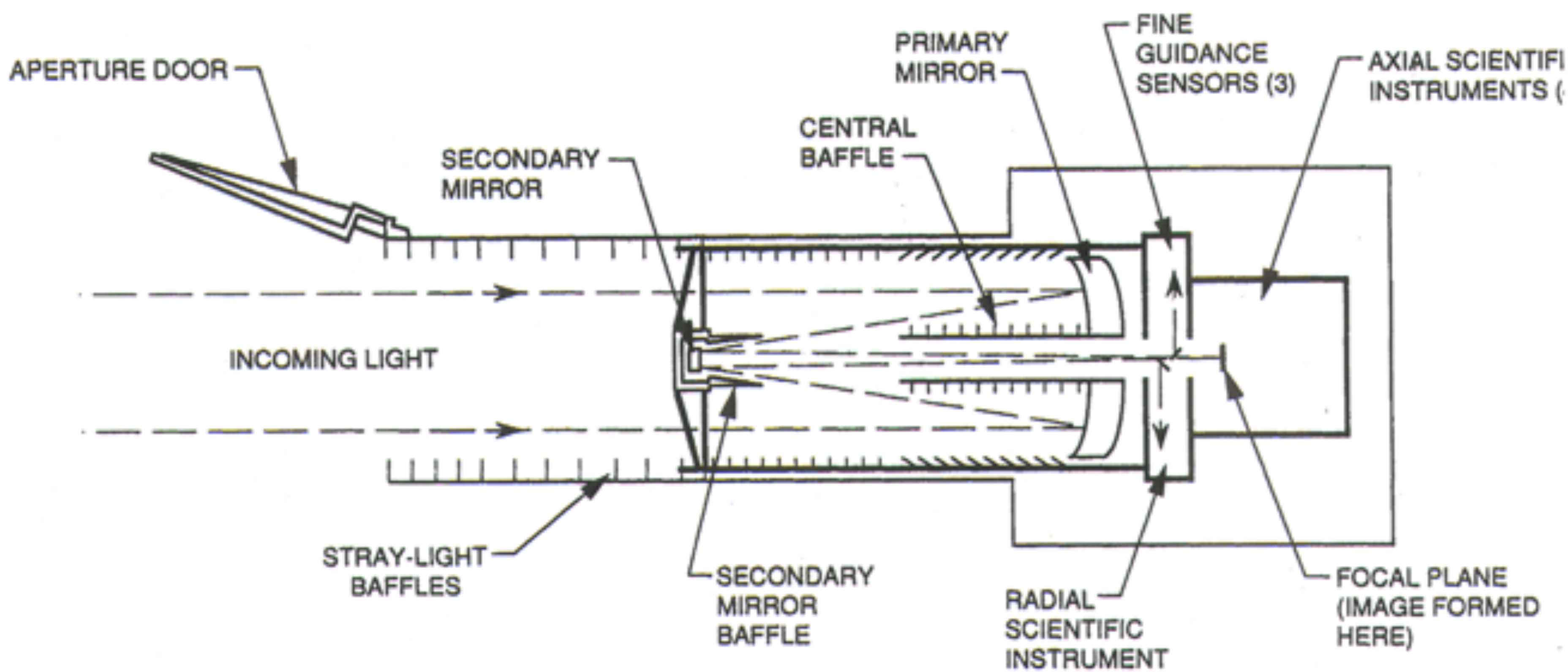
Development challenges

- Technically very challenging
- Delay of launch by 15 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
- The cold war environment
- 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

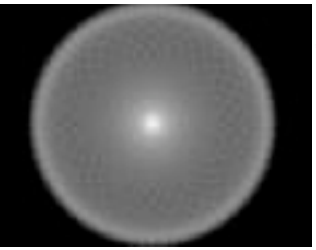
Some facts

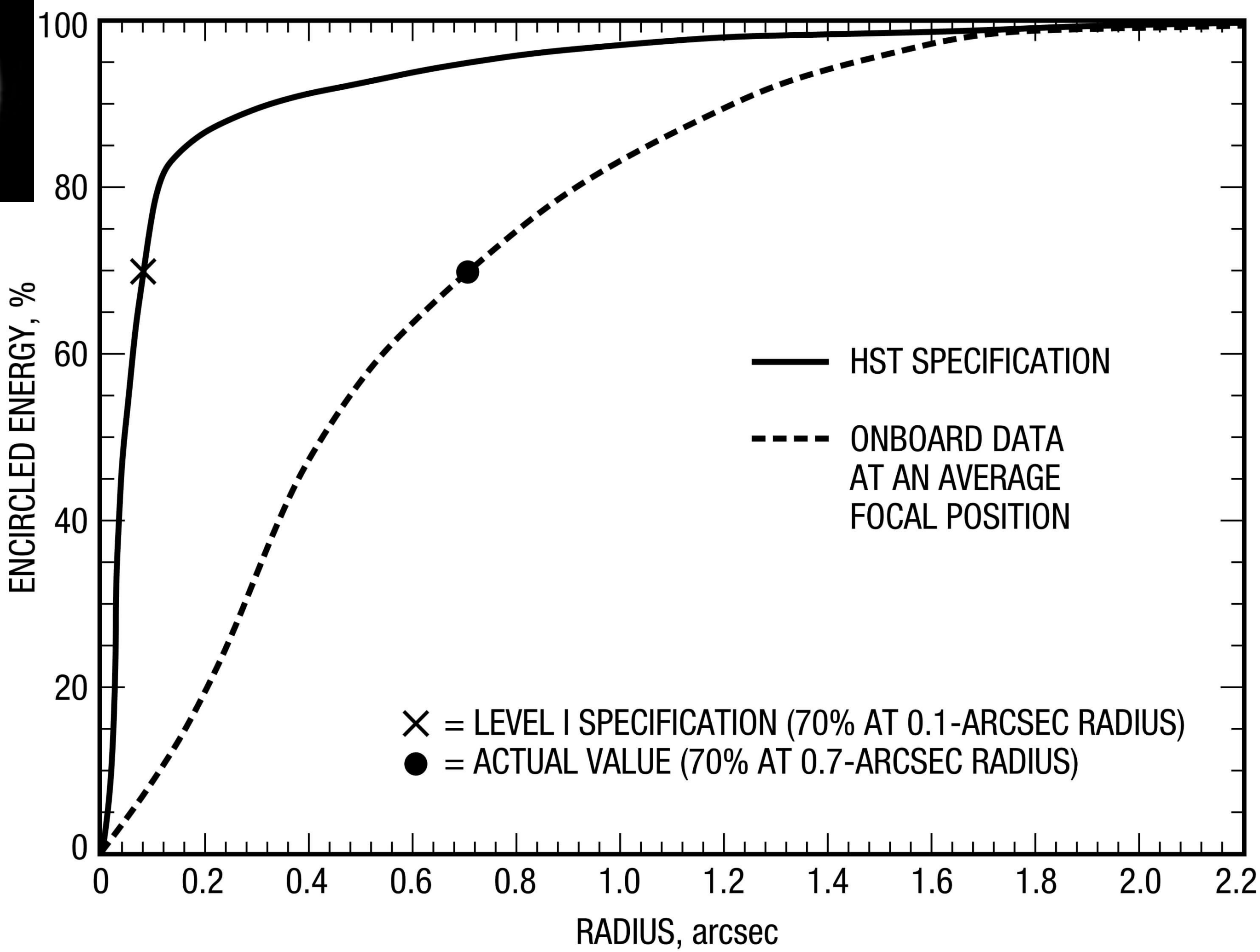
- Launch April 24, 1990
  - Originally manifested to follow challenger in 1984 => much confusion & $$ & stress
- May 21, 1990 NY Times publishes double star image on front pages
  - claim that astronomers were "amazed by excellent performance"!
- Project Manager announced failure June 21, 1990!

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 gathered @ JPL to agree 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
- 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

What we found

- Boxes of notebooks, interferograms & drawings were shipped to the city dump several months before launch
  - Dispute over costs of storage
- The hardware, all test fixtures, critical interferometers, null correctors and optical components were untouched ("in bonded stores") for ~ 9 years at the contractor's.
- A very irate science community
- We were very much in the spotlight
- The pressure was on!!

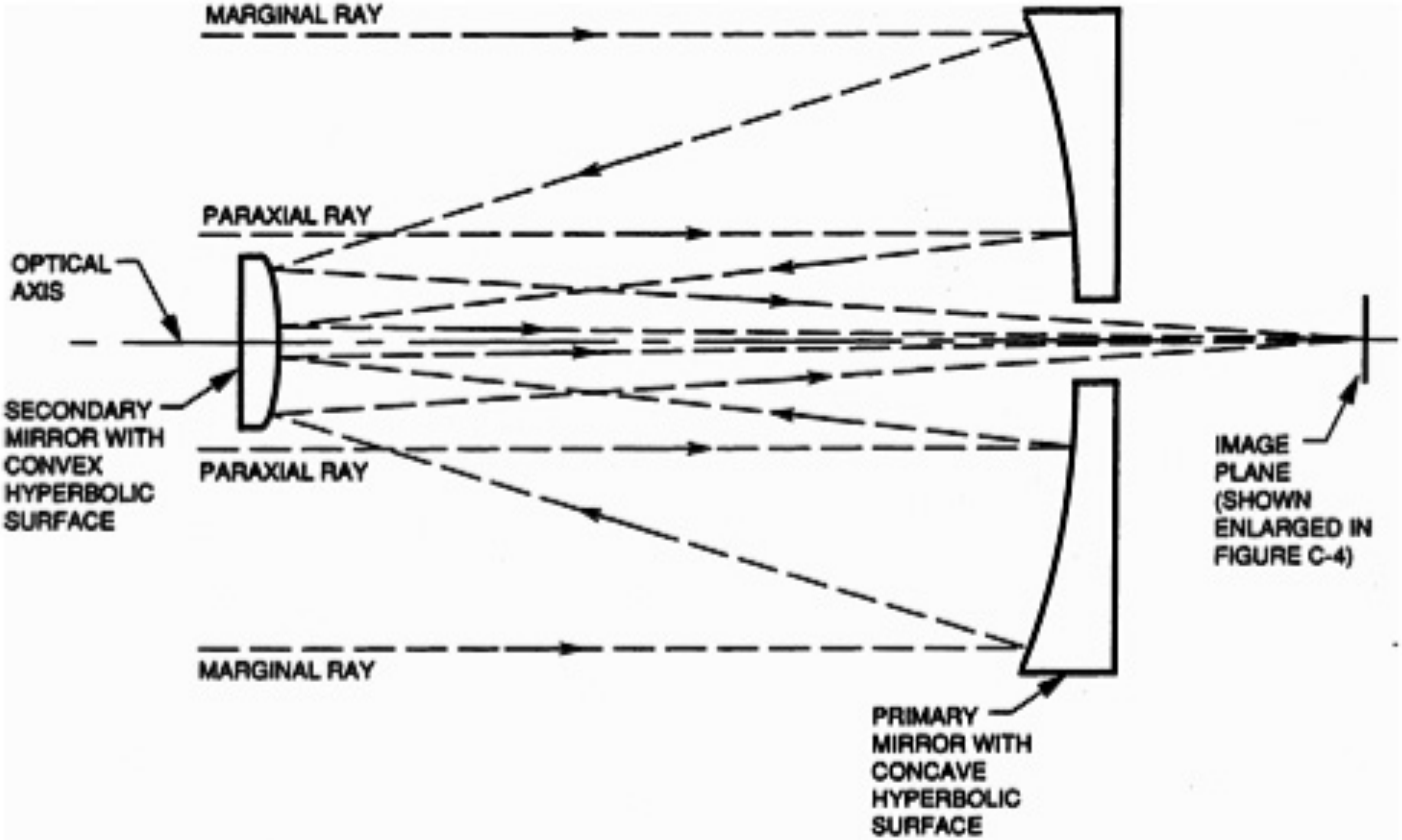


Figure C-3. The HST's Ritchey-Chretien optical system. Two hyperbolic mirrors are used to correct for spherical and coma aberrations.

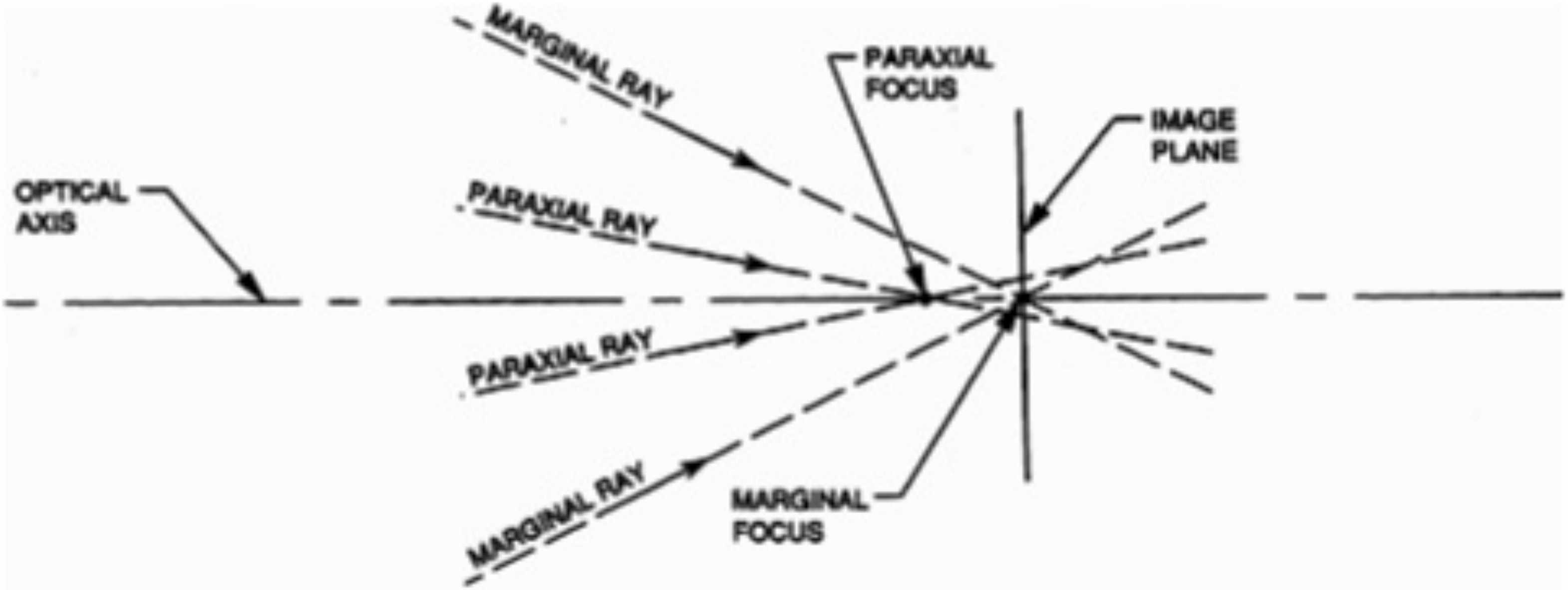
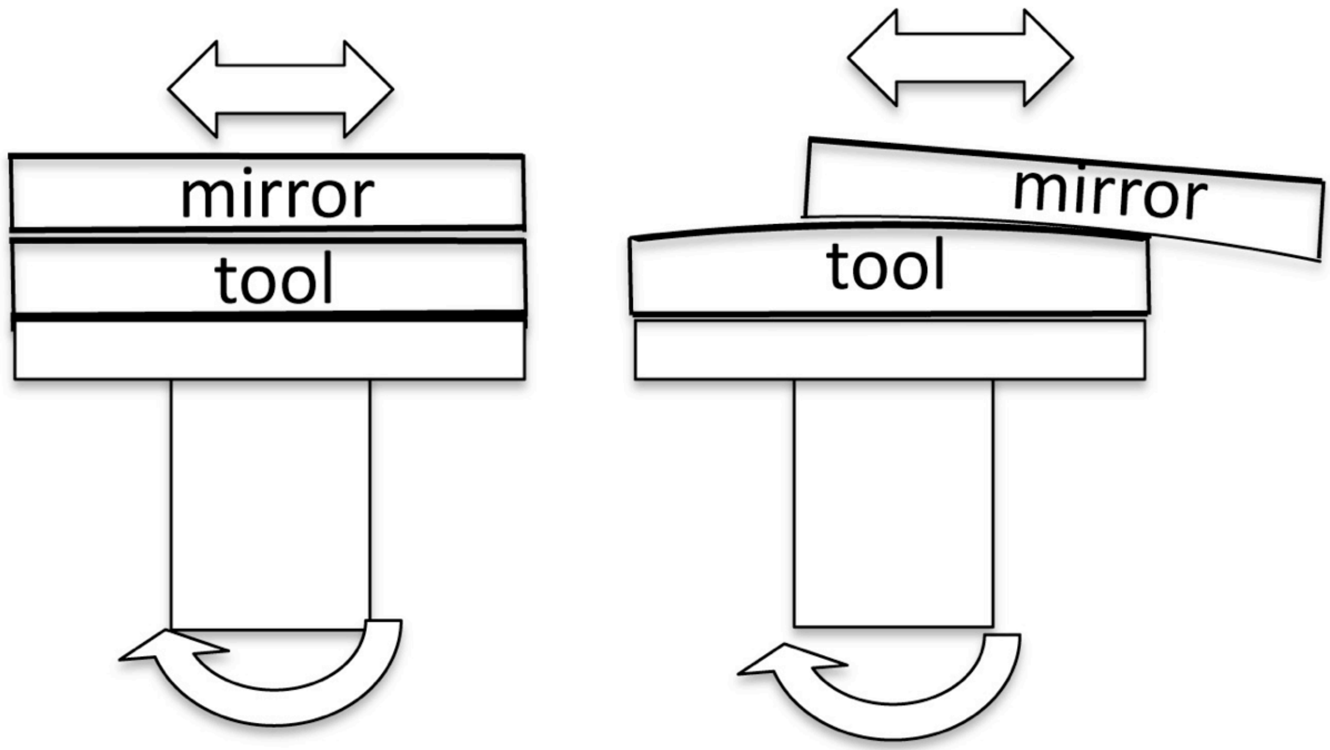


Figure C-4. Image-plane enlargement of the HST Ritchey-Chretien optical system. In the HST, too much material from the edges of the primary mirror was removed, and the marginal focus was moved past the paraxial focus. This is characteristic of an optical system overcorrected for spherical aberration.

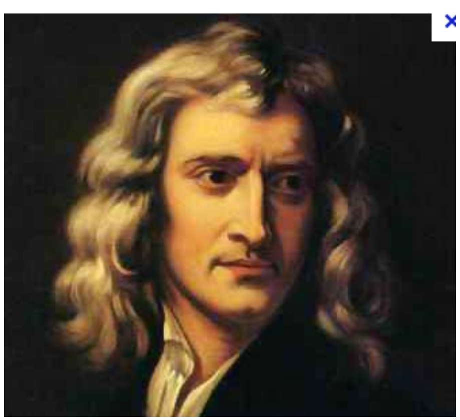
Spherical $a_{040}\rho^4$

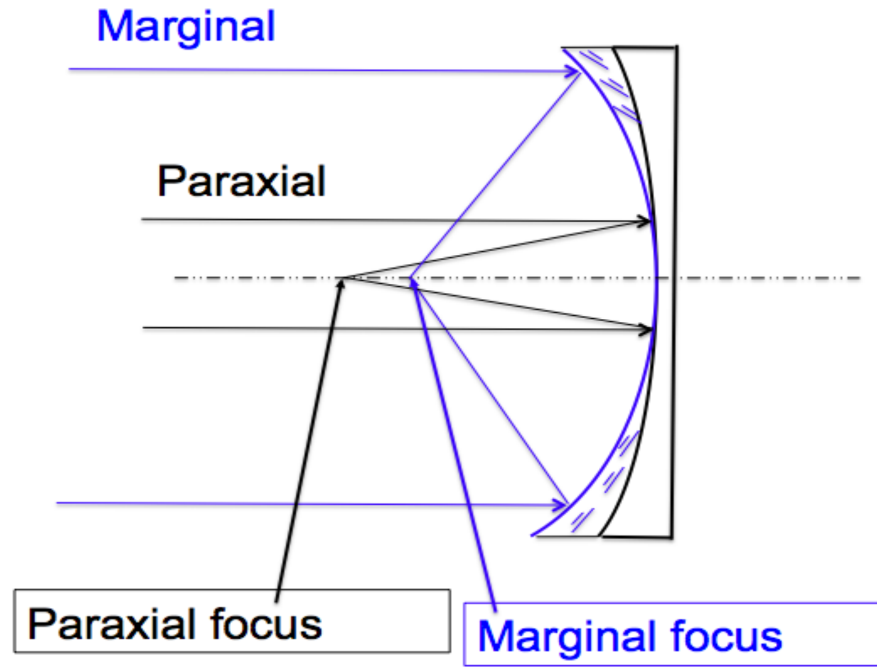


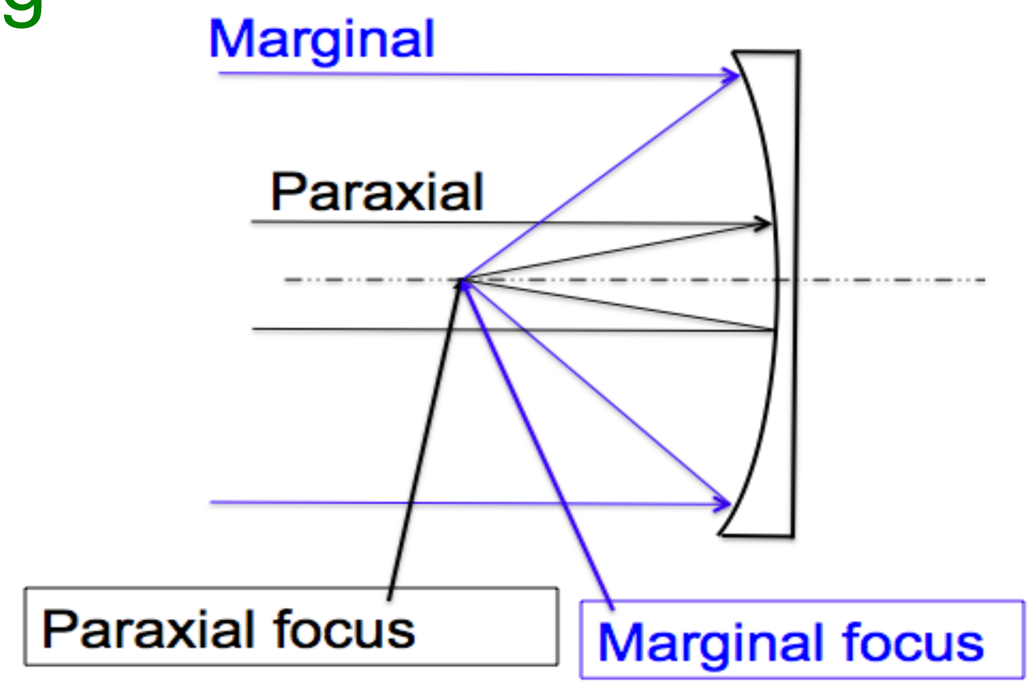
(a) (b)

Spherical

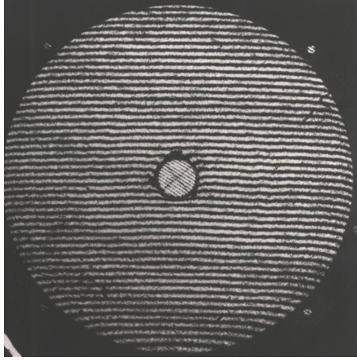
- During manufacturing phase
- Mirrors show spherical aberration
- Additional Processing needed to "flatten" the outside





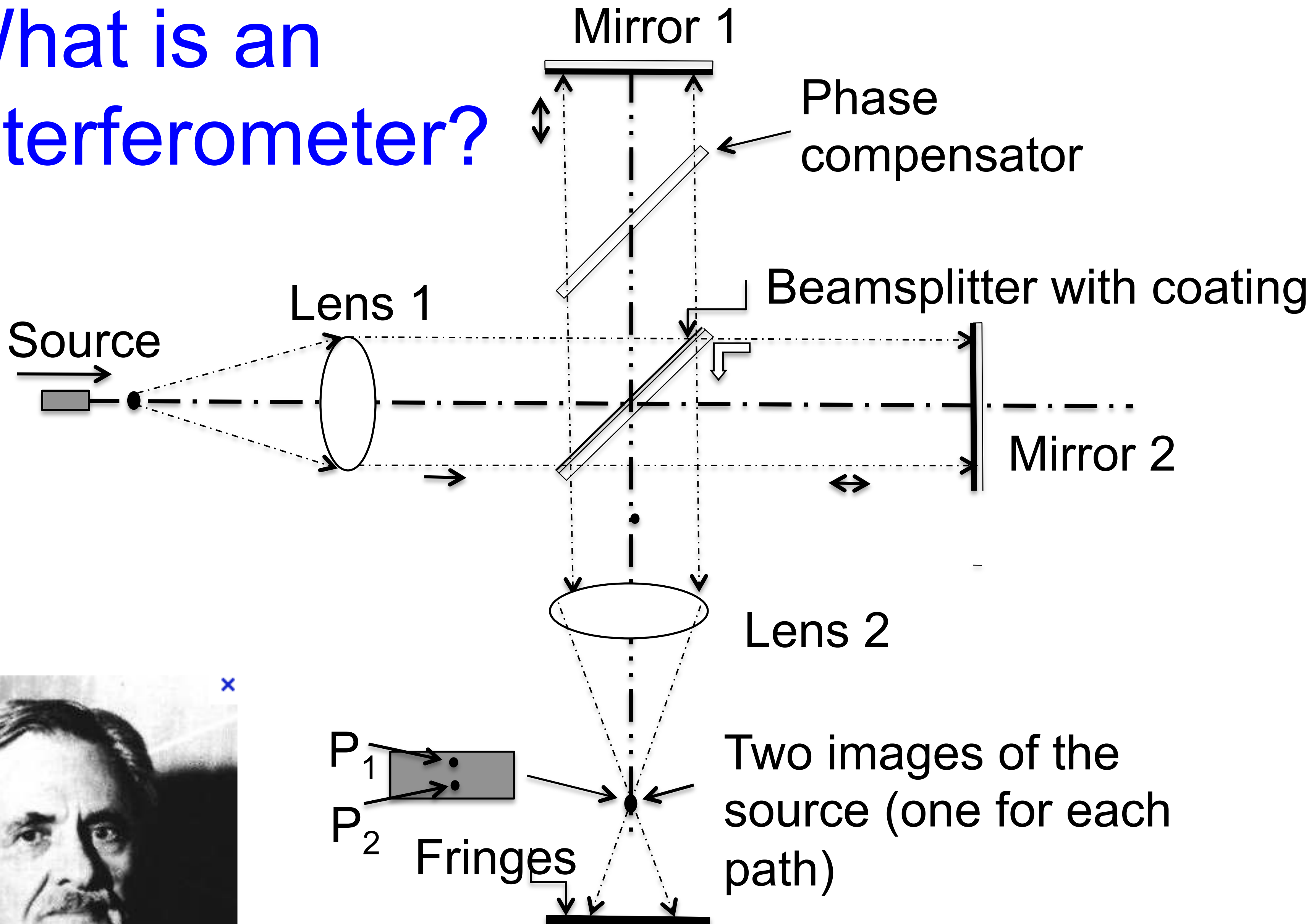


Investigation & recovery

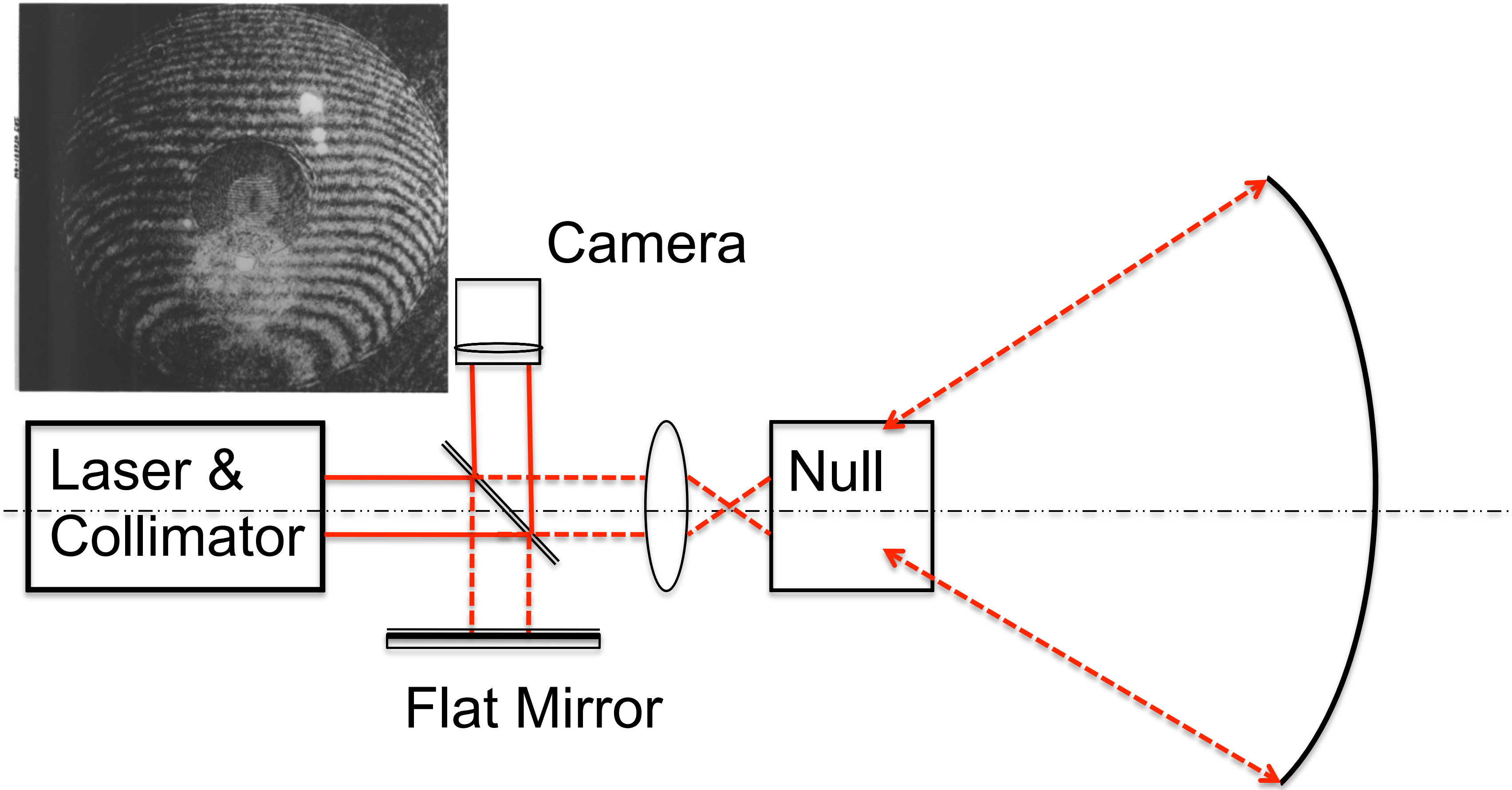


- What was available to investigate?
  - “Fossil” hardware in bonded stores at the contractor
    - Null correctors, fixtures, interferograms, personal note books and PR photos
    - Interview engineers
- Sources of information about the on-orbit prescription
  - Star images recorded on axis and off axis by
    - OTA + WF/PC
    - OTA + Faint Object Camera (FOC)
- Evidence error was on the primary
  - Spare secondary mirror perfect
  - Recorded star images showed error both in WF/PC and FOC

What is an interferometer?



Interferometric null corrector



Correct surface => straight line fringes

Primary mirror process

Coated & integrated

R_c tested with Refractive null

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

Fine figuring at PE Danbury

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

Rough grind at PE Wilton

Corning casts mirror blank

Finished in 1982
Launched in 1990

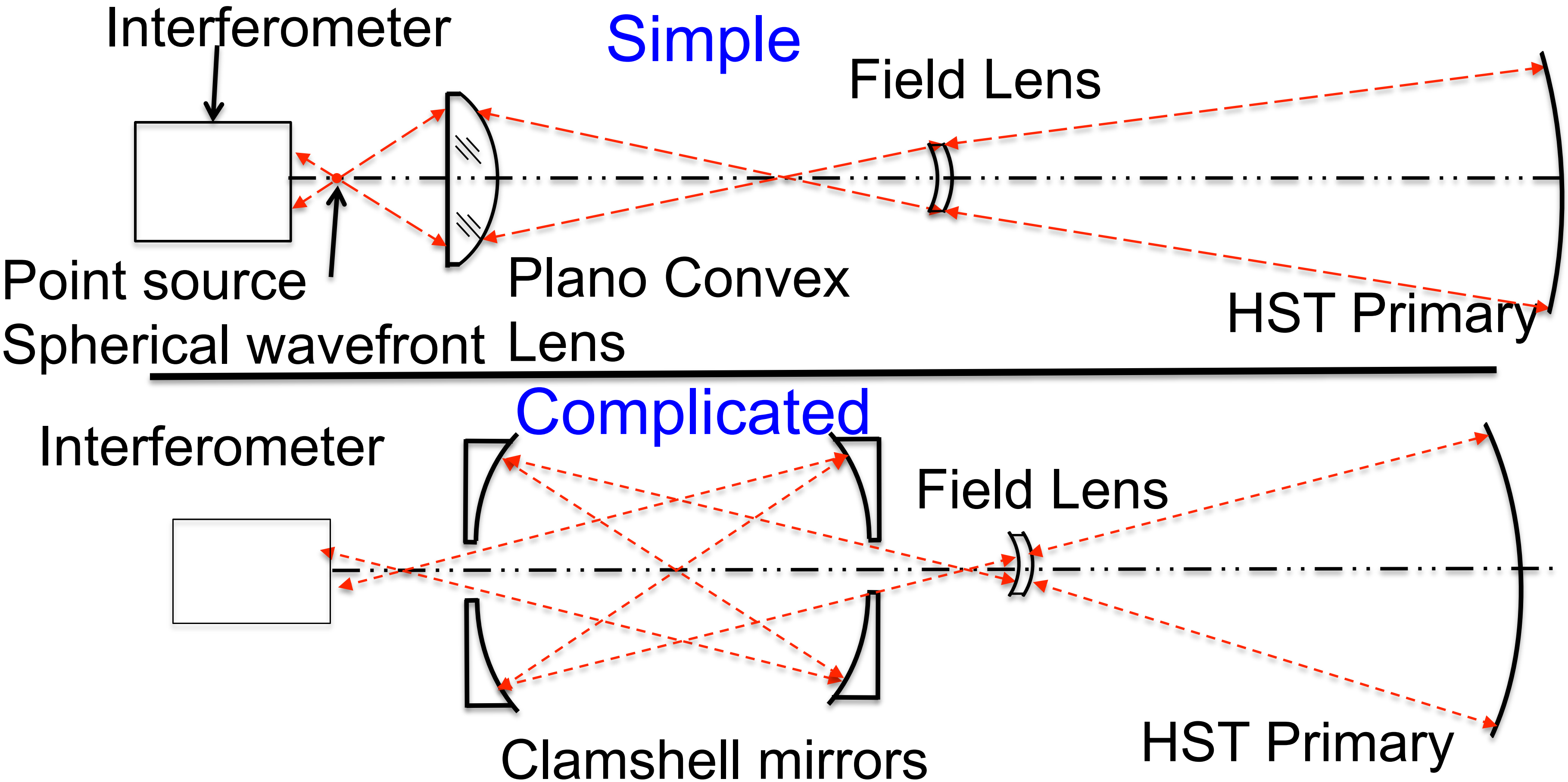
Primary Mirror Processing (1)

- 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
  - Completed figuring and final polish in April 1981 using the reflective null $\lambda / 100$
  - 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

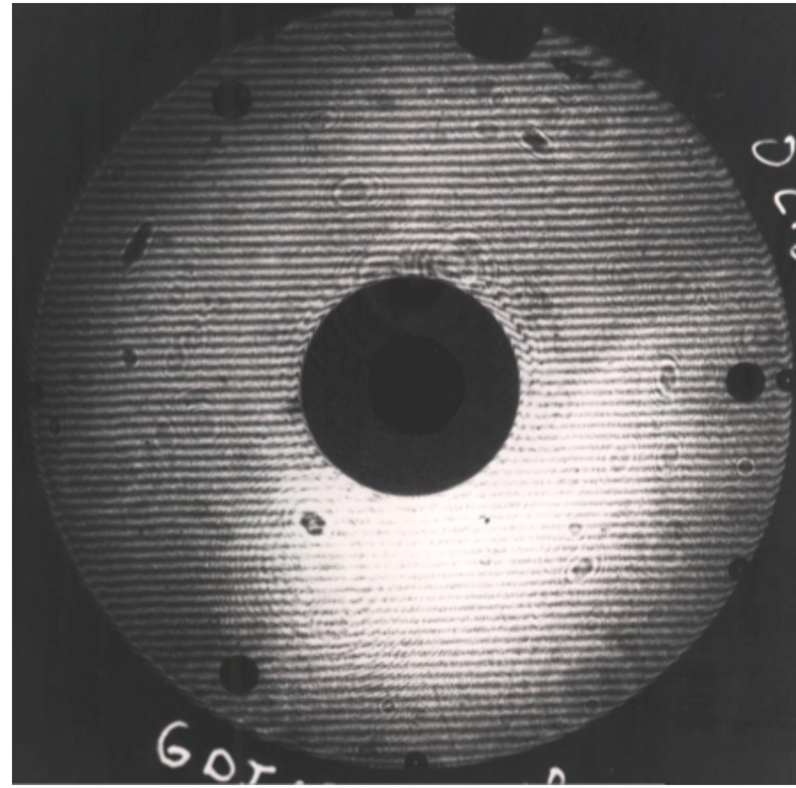
Refractive & reflective null



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

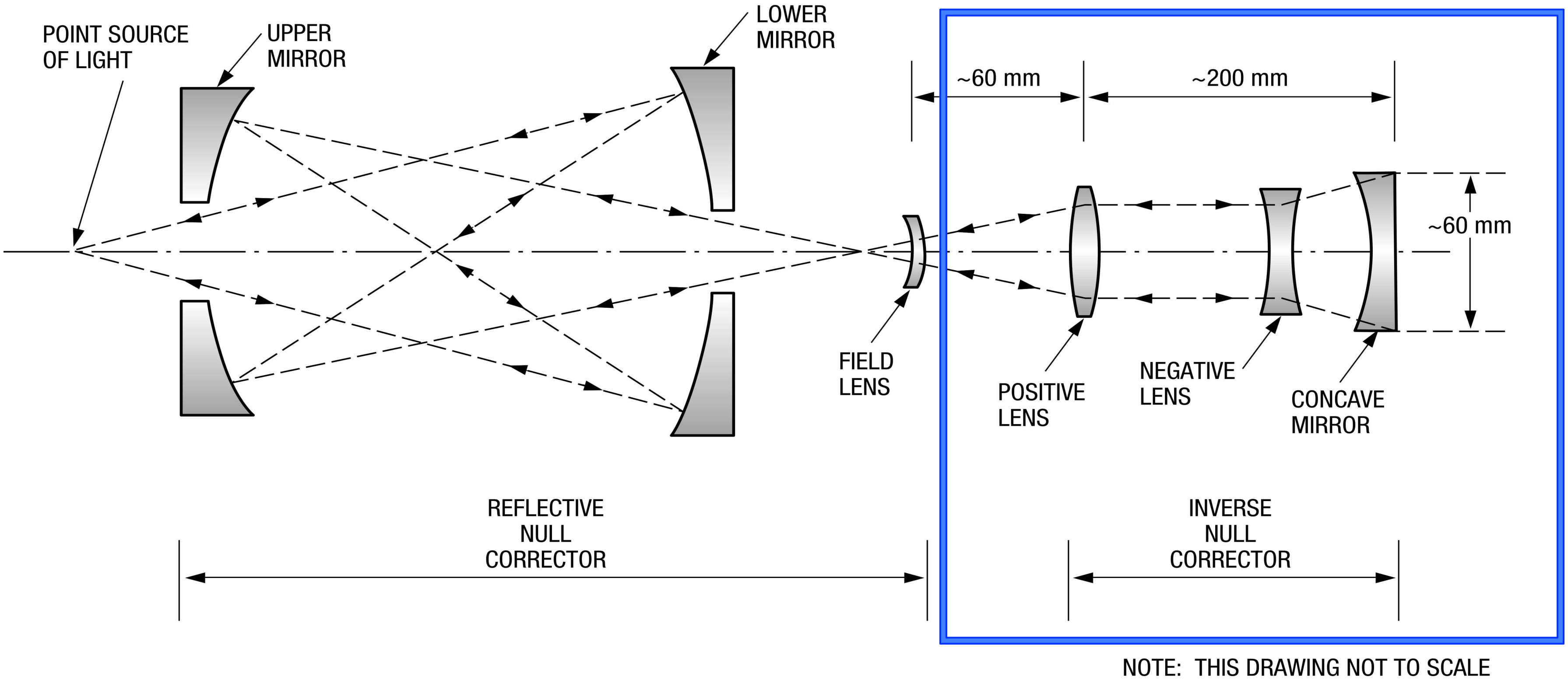
Primary Mirror Optical Interferogram

- 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

The reflective null The Inverse Null



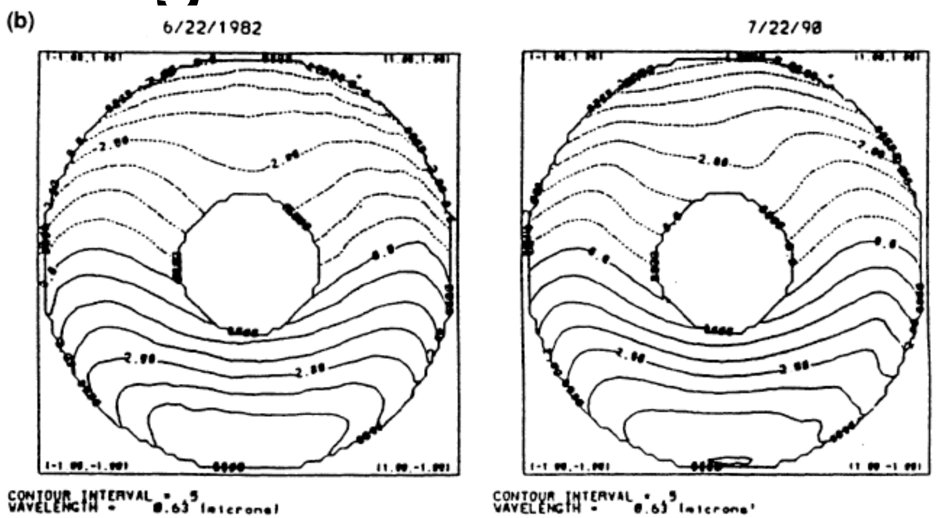
The inverse null simulated the desired HST surface. It was used to verify there were no drifts in the Reflective null during figuring. The error should have been visible here, but the optician was told only to look for changes. The clamshell was the "absolute reference" – not the inverse null!

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.

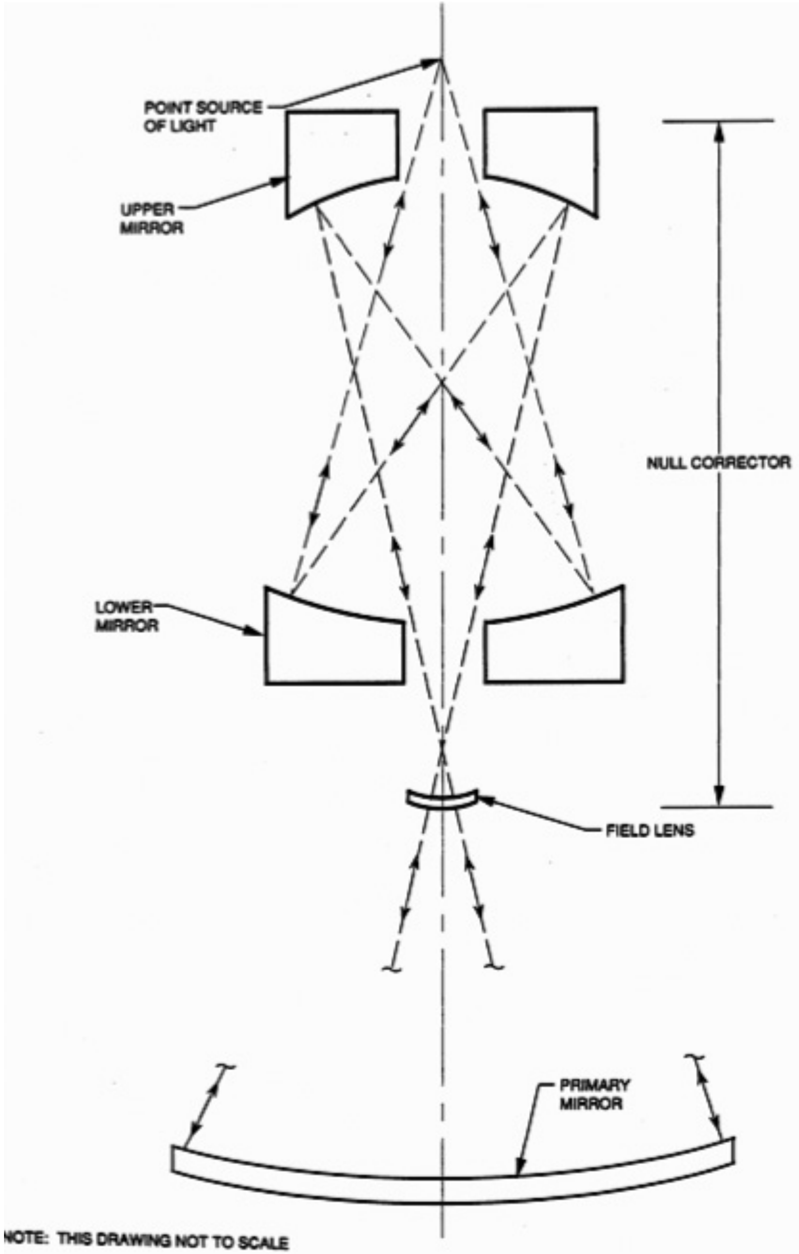
Null change between 1982 & 1990?

6/82



7/90

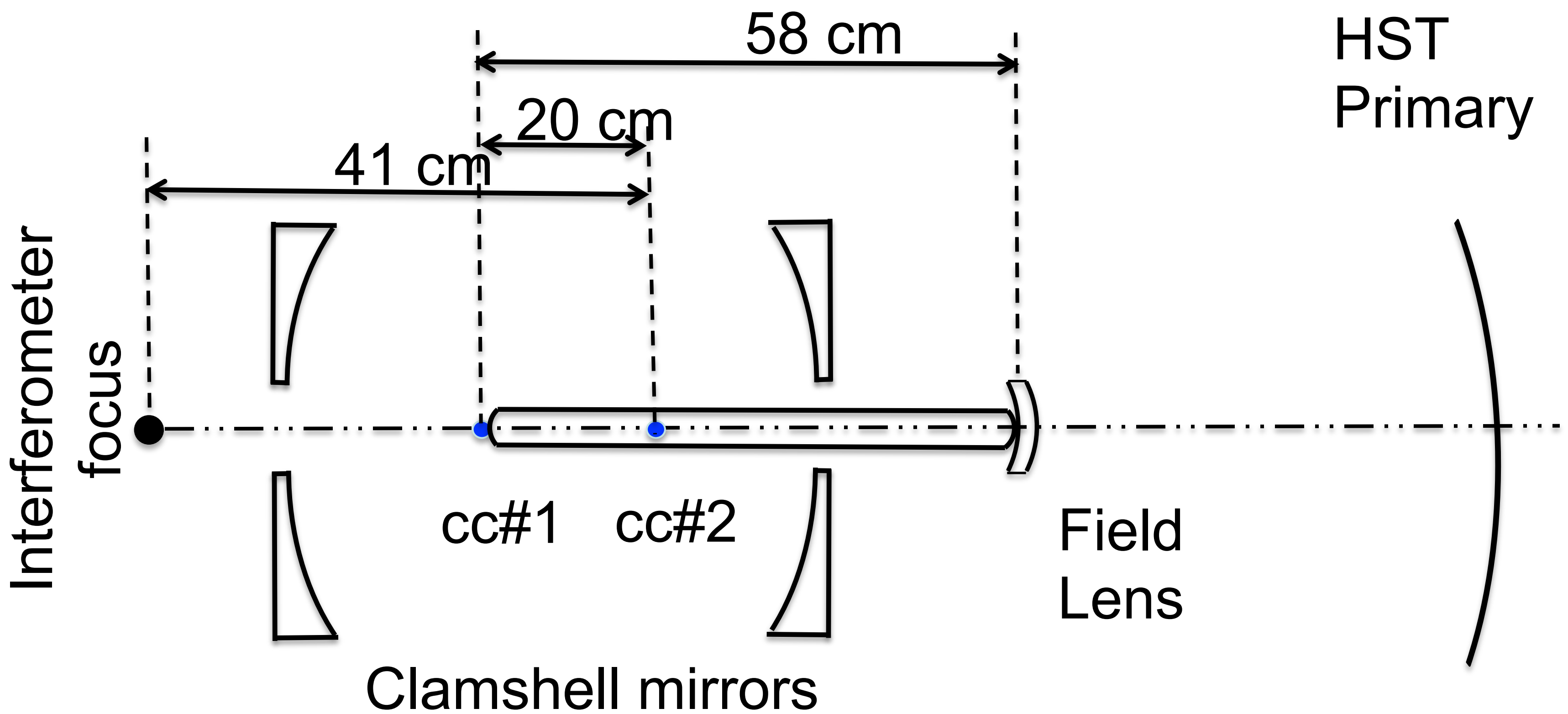
- We retested the reflective null – no changes
- Tests in 1990 are just like the 1982 tests
- 1982 interferogram from employee's personal notebook
- But this interferogram showed the spherical aberration in 1982!! --
- Just assumed the 6 –waves error was in the reference null or ….?



Reflective null corrector

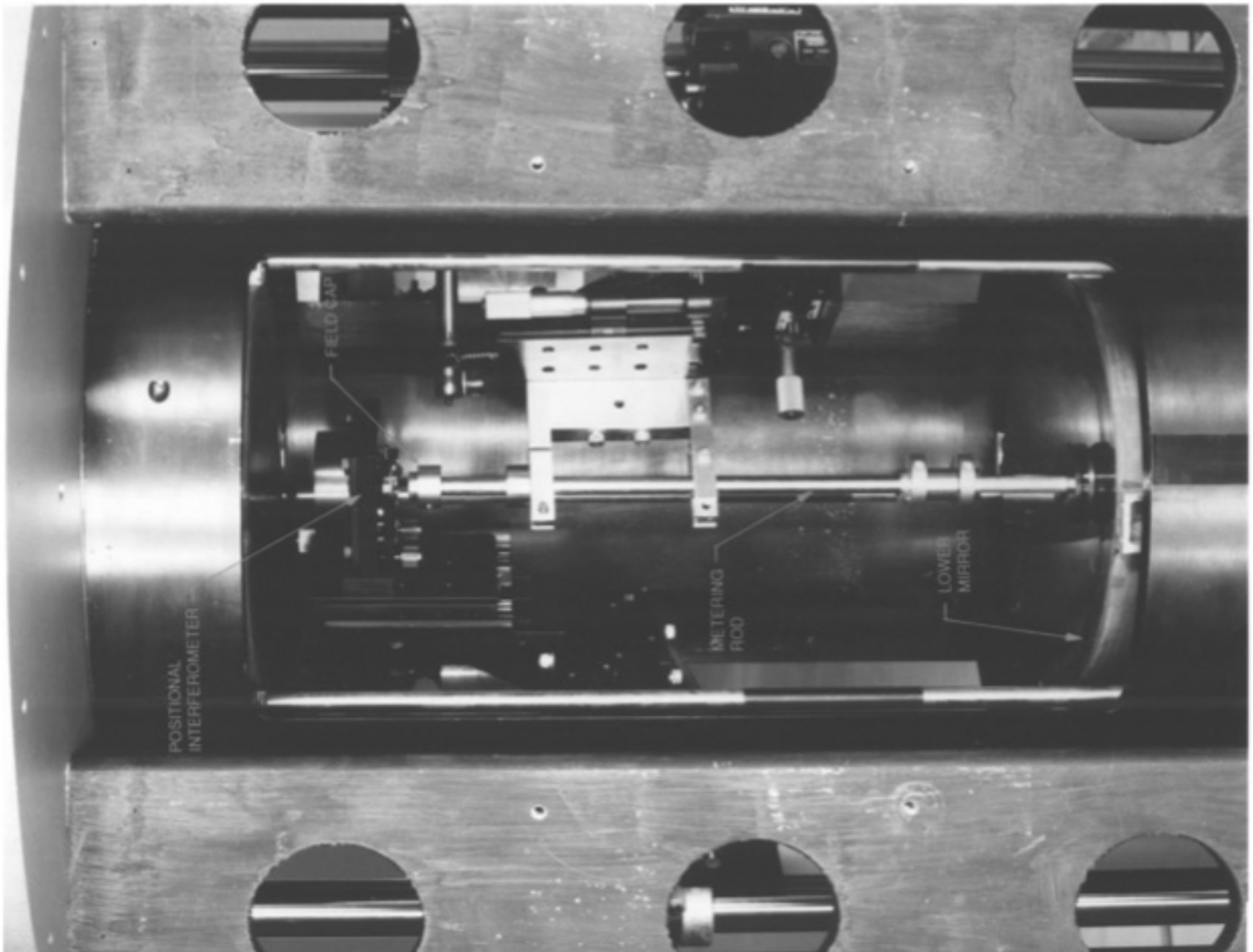
- Smoother wavefront than the refractive NC
- More complicated
- Metrology difficult

How was the reflective null aligned?



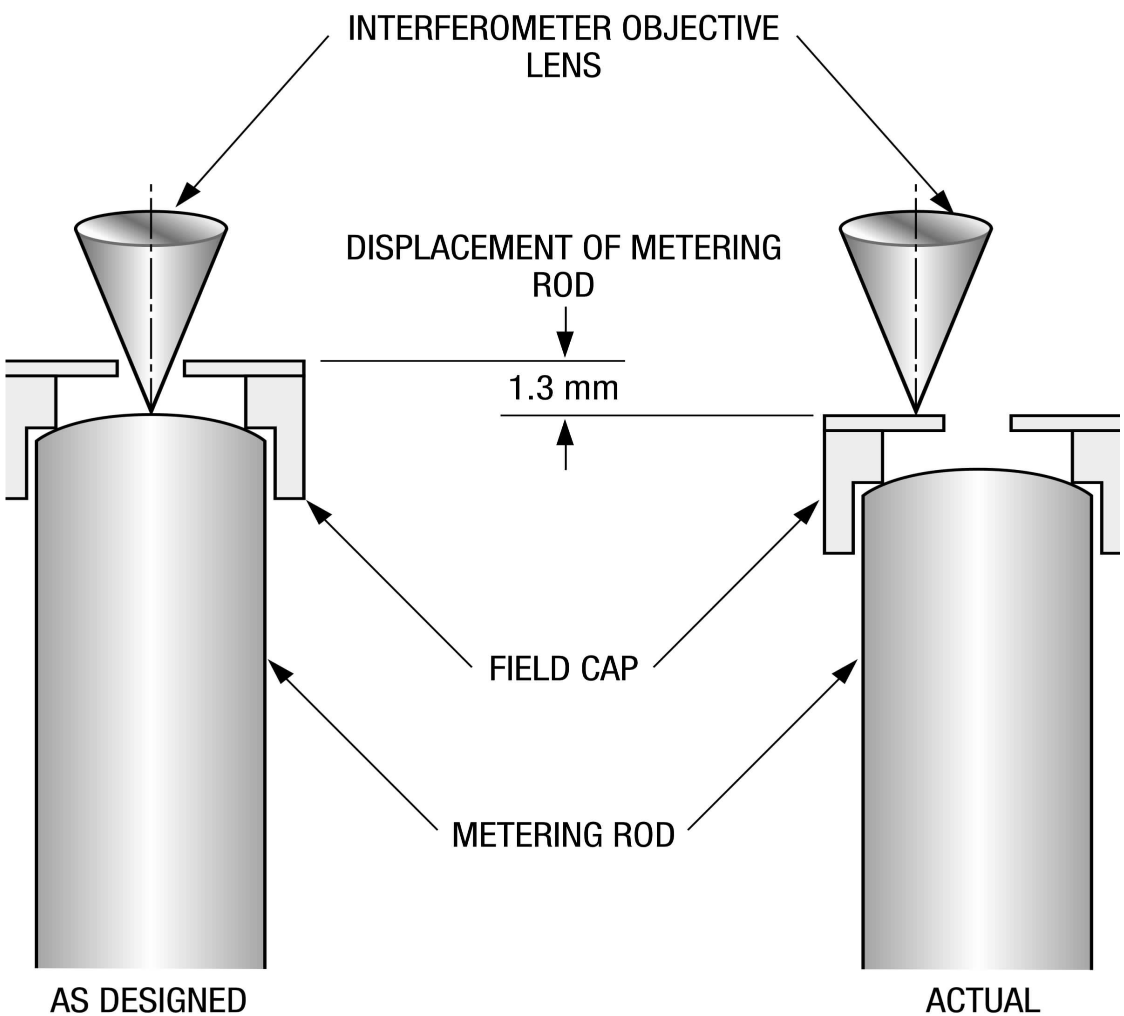
The only mechanical drawings for the Reflective null corrector were on publicity photo recorded of the instrument with the drawing hanging in front. We had it enhanced.

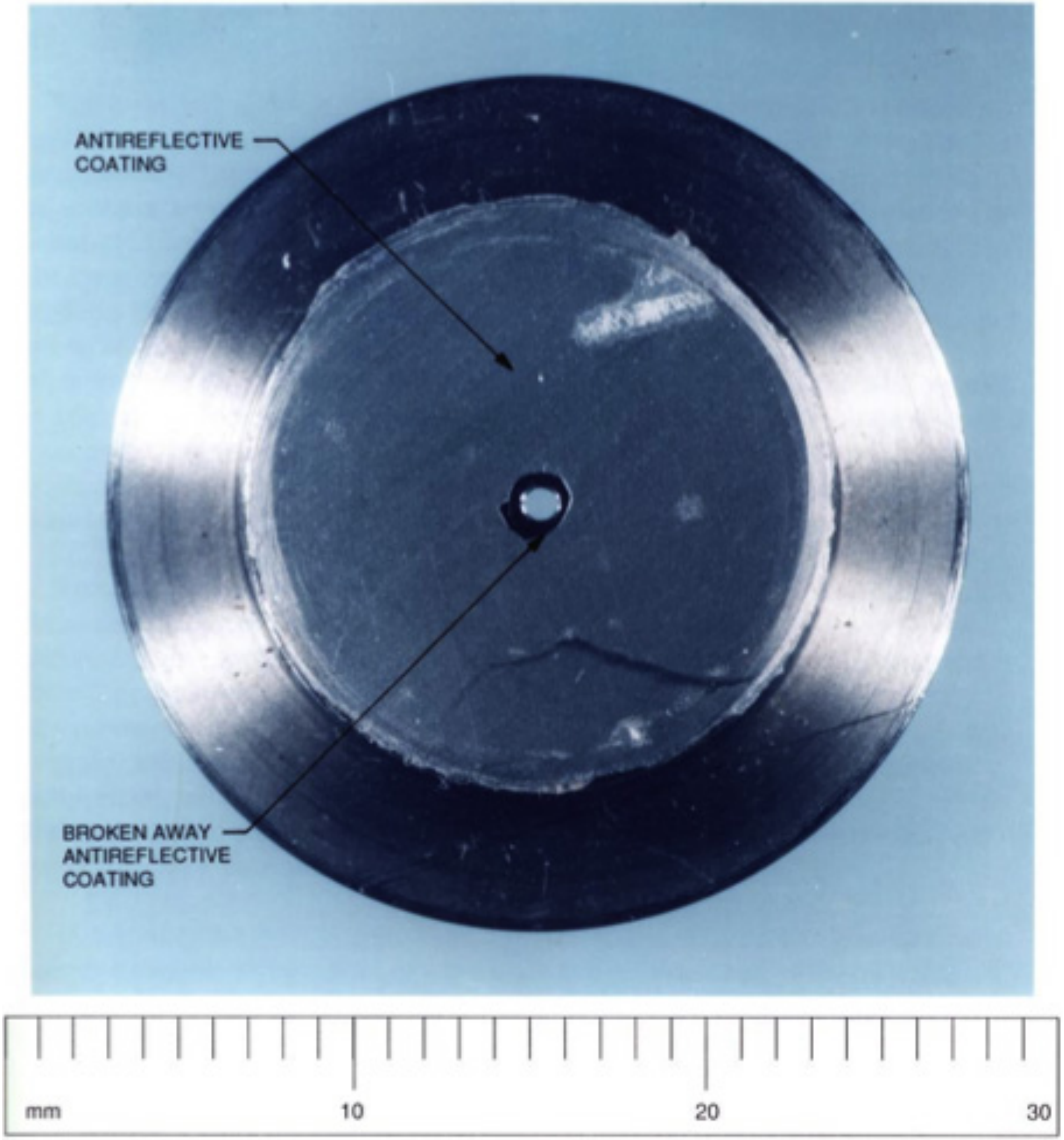
Metering rod in position between the field lens and the CC of the lower mirror in the reflective null corrector



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

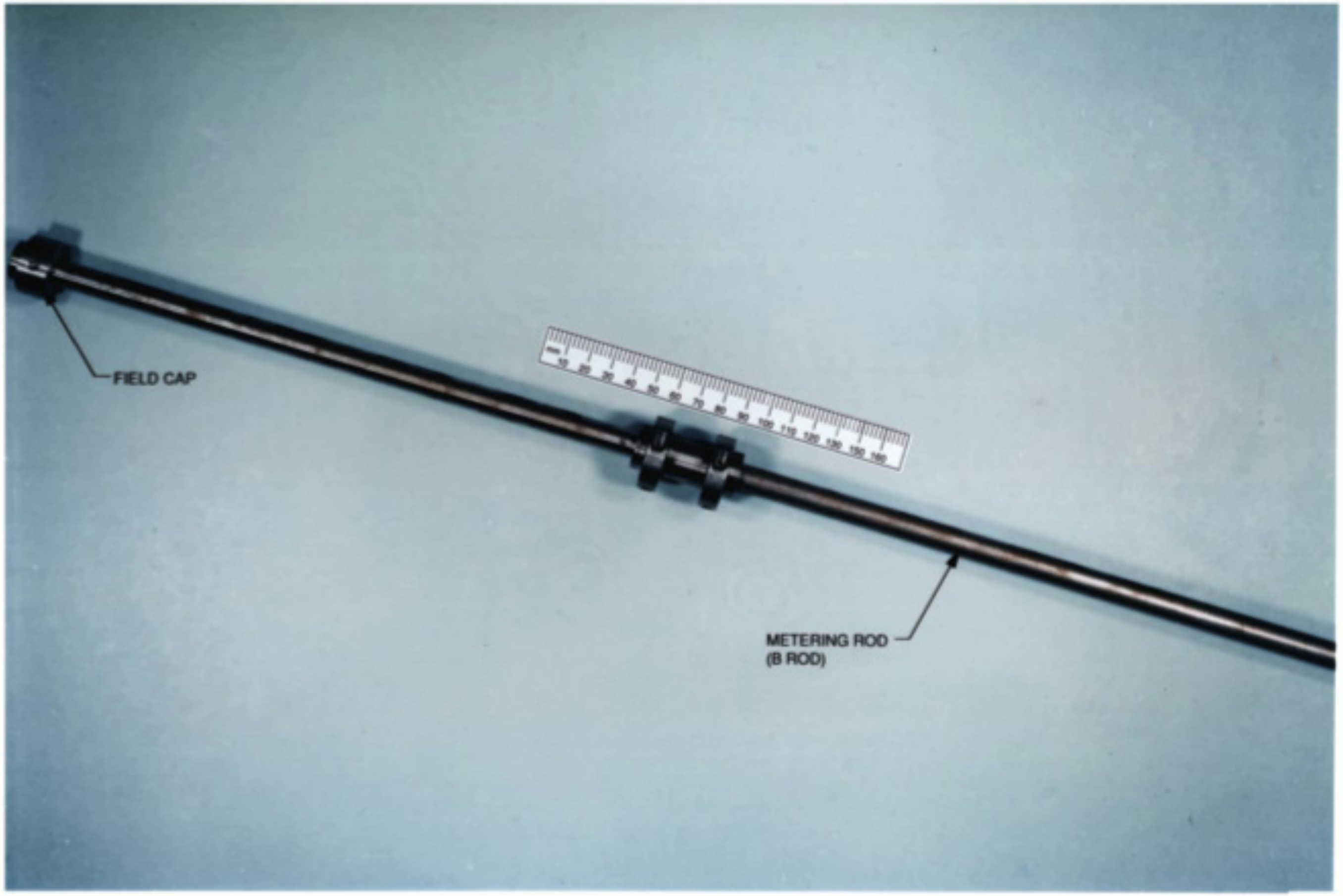


Figure 7-2. Metering rod (B rod) used to space the field lens and the center of curvature of the lower mirror in the reflective null corrector.

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.

Refractive Null Corrector

Figure D-2. RvNC interferogram of the primary mirror, taken in May 1981.

Management errors

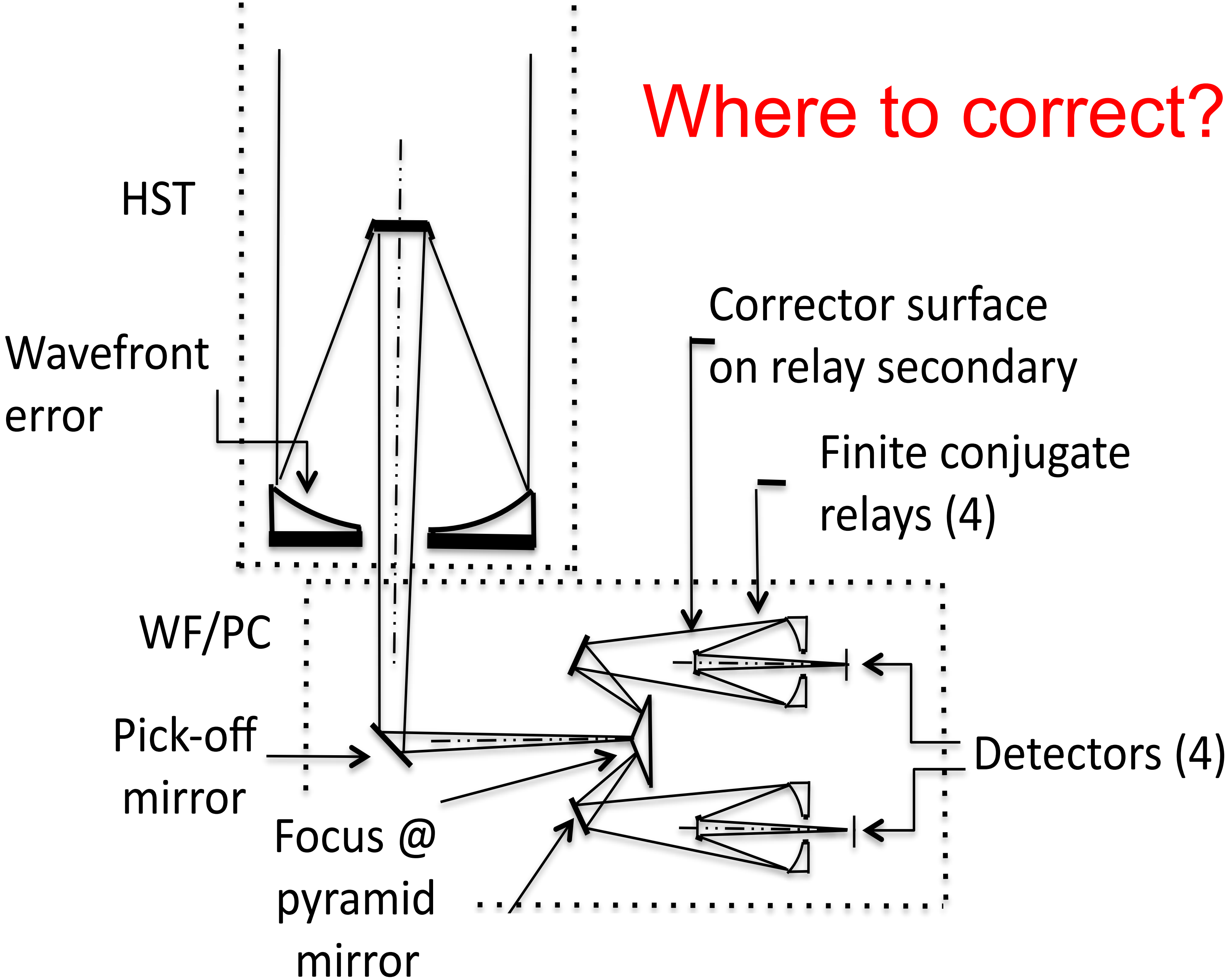
- The designer of the null test Abe Offner was not invited to climb the tower to verify his test worked!
- NASA QA did not request, nor were they invited to participate in the assembly of the null corrector! They seem to have been unaware of its importance!

Fix it!

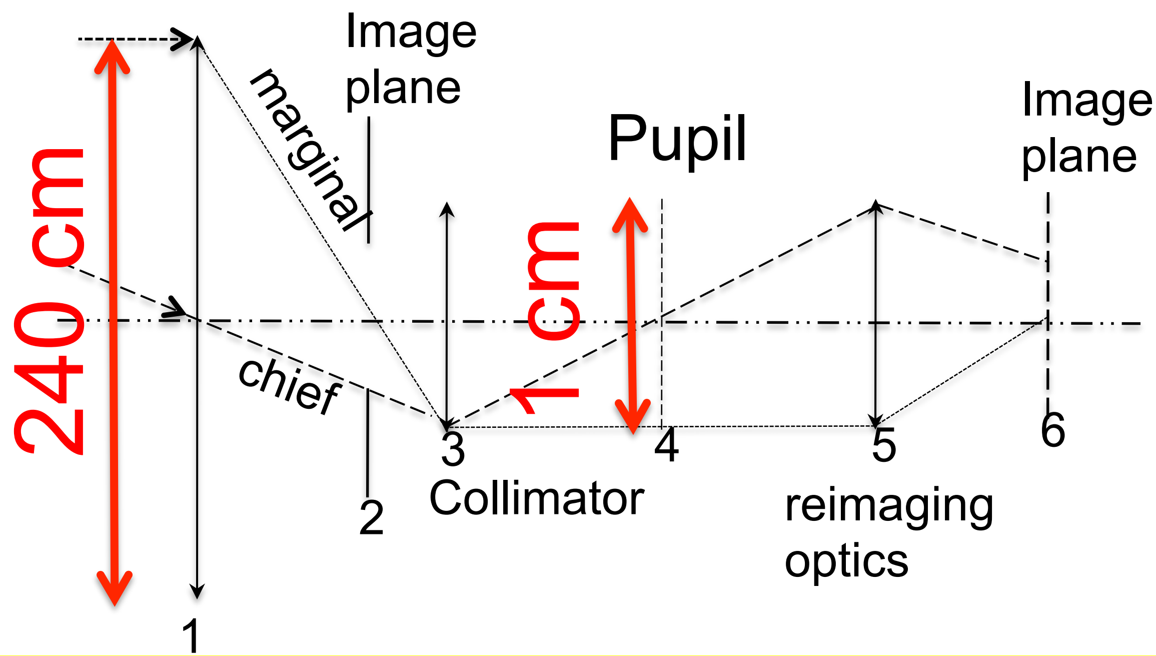
- NASA had given the go-ahead several months before original launch to build a second camera
- Hardware was ordered and some parts were in house
- The 36 month schedule became ~18 months
- Needed the correct magnitude and sign fast
  - But it had to be right!
- Challenge:
  - Correct the telescope error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

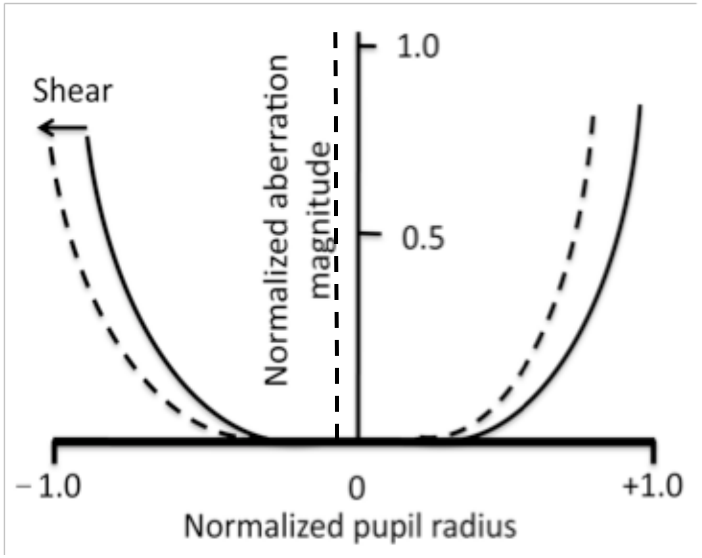


- Entrance pupil to internal pupil image distances in the x, y plane undergo a minification of 240 to 1

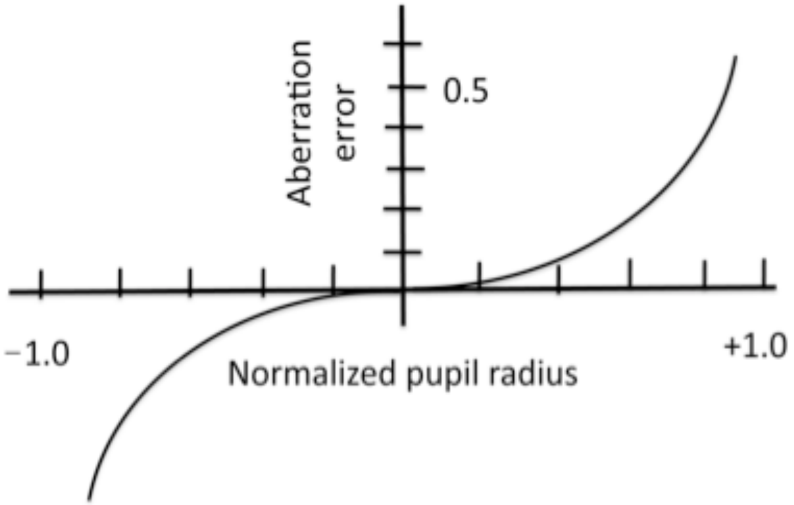
- Distances in the z direction (phase error) remains unchanged

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.

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

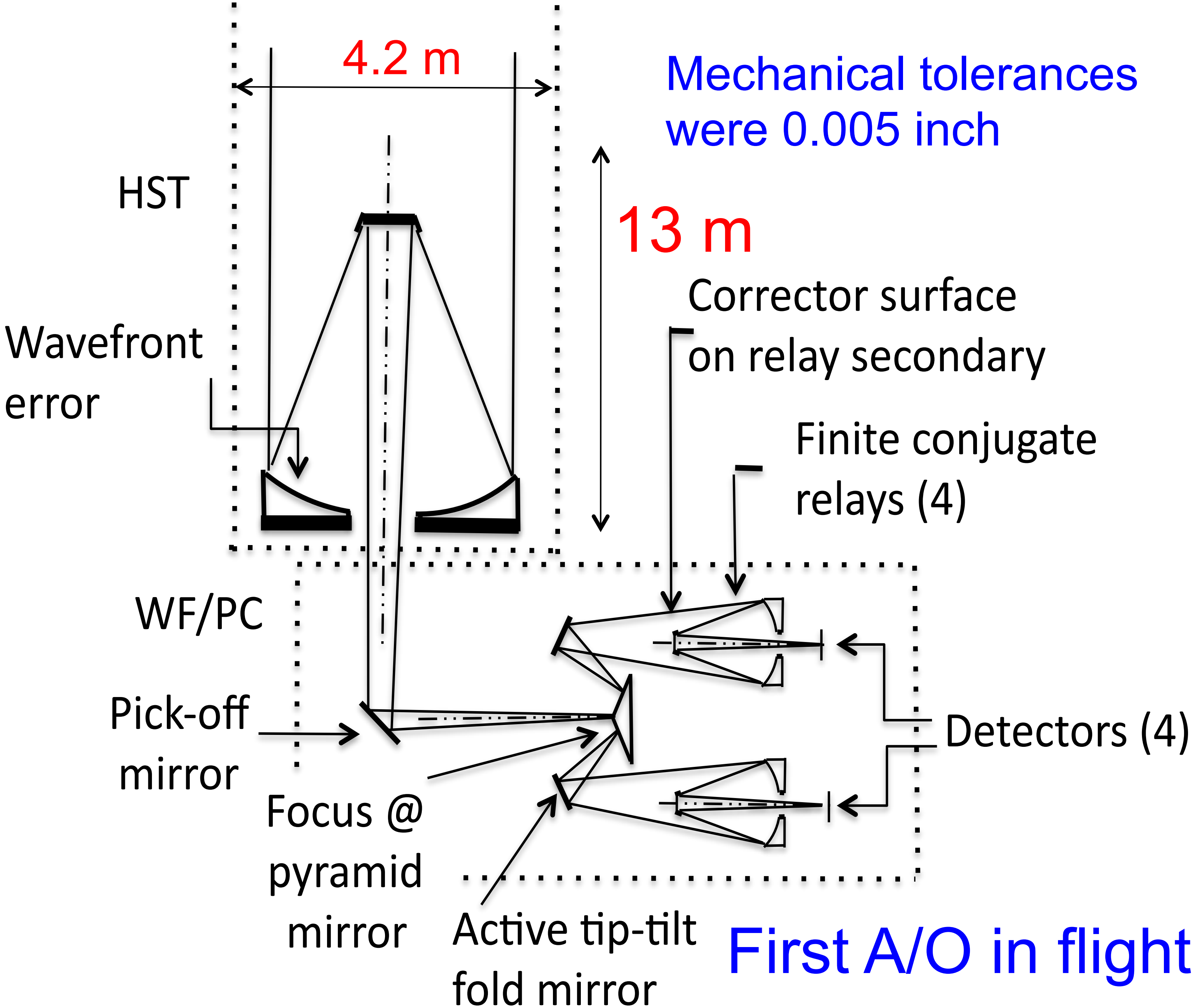
$$W_{131} = 0.2 \text{ waves (assumed tolerable)} \quad \Rightarrow \quad \Delta y = 28 \text{ microns}$$

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

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

Mechanical tolerances were 0.005 inch



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 optical prescription

JPL let 6 contracts & started several in house efforts

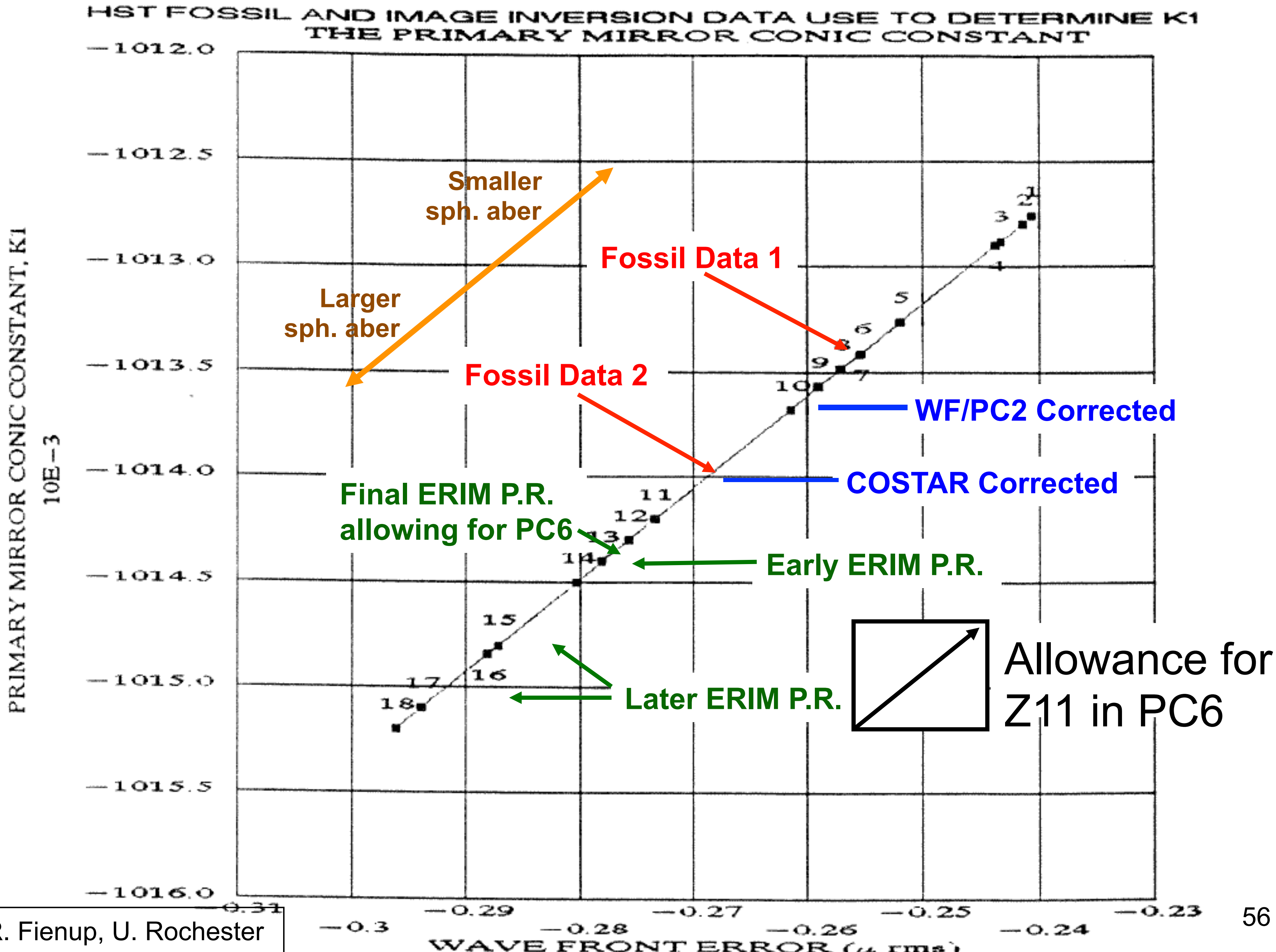
I was the CTM for these efforts

Investigator	Method
J. Fienup (ERIM)	Iterative transform algorithm and nonlinear least squares optimization
R. Gonsalves (Tufts)	Phase diversity iterative transform algorithms
C. Roddier (Hawaii)	Phase diversity iterative transform algorithms
M. Shao et. Al	Nonlinear least squares optimization
S. Brewer (PAGOS) D. Redding (Draper)	Diffraction propagation/ray trace with nonlinear, least squares optimization
D. Sandler (TTC)	Neural network image analysis
A. Vaughan (JPL)	Hartmann test
A. Meinel (JPL)	Geometric shadowing
C. Burrows (STScI)	Iterative Fourier transform algorithm
R. Lyon (HDOS)	Non-linear optimization

On-orbit data quantitative results

	DATA SOURCE	CONIC CONSTANT	ERROR BARS	WFE (µ rms)	ERROR BARS (µ rms)
	26-Feb-91				
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
WAVE FRONT ERROR (μ rms)
−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
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 with error built in
- Still fully operational after
  - 30 years since construction
  - 22 years on orbit
  - 4 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.

Oct 6, 1993 WSJ

U.S. in Settlement With Two Makers Of Space Telescope

By JOE DAVIDSON
Staff Reporter of THE WALL STREET JOURNAL

WASHINGTON – The federal government has reached a $25 million settlement with the makers of the troubled Hubble space telescope.

Launched three years ago, the Hubble has suffered a series of technological problems. The craft has a flawed mirror that stops it from doing some chores it was designed for and causes it to send some less-than-sharp images to Earth.

Under the settlement, **Perkin-Elmer** Corp., of Norwalk, Conn., will pay $15 million by Oct. 22. Another $3.5 million will be paid by Hughes Danbury Optical System, a subsidiary of Hughes Aircraft Corp., through a waiver of fees previously claimed by the company. Hughes will also forgo $6.5 million in fees for future work related to the telescope.

"The government contended that the

launched and five years after the telescope was delivered to NASA.

Hughes said it agreed to the settlement "to amicably resolve the matter by extending a goodwill economic benefit to its valued customer, NASA, as well as to avoid the time, expense and business disruption of a potential Hubble-related lawsuit."

A Hughes spokesman, Richard Dore, added in an interview that in many respects "the satellite is performing very well. It's just not up to the full expectations."

Gaynor Kelly, chairman and chief executive of Perkin-Elmer, said fighting a government lawsuit would have drained the company's resources for an unforeseeable period.

"Perkin-Elmer firmly believes that it acted responsibly in accordance with NASA's procedures during the manufacture of the Hubble telescope mirror and that a lawsuit would have been completely unwarranted," Mr. Kelly said.

To repair the telescope, the space agency said it is planning "perhaps the most difficult and challenging satellite servicing mission NASA has ever attempted" in December. Four astronauts are planning five, six-hour space walks to fix the crippled spacecraft.


WEBSHOTS

Thank you

Hardware repair

- The analysis of the
  - Interferograms & measurements on the residual hardware
  - Was not sufficient
  - To precisely determine the optical prescription to the accuracy & confidence we needed to build correctors
- Measure the on-orbit prescription

Hubble Testing Schedule

1-May-72	LST Phase A Studies	
15-Dec-78	Rough grinding begins	
1-Feb-81	Inverse null corrector interferogram of the reflective clamshell null	Shows spherical aberration
15-Apr-81	Polishing Completed	
1-May-81	Refractive Null Corrector Interferogram of the 2.4 m Primary	Used to measure focal length - fringe shapes ignored
31-Aug-81	Hindle sphere interferogram of secondary mirror	Shows no aberrations
1-Feb-82	Reflective Null Corrector Interferogram of the primary	Shows mirror figured exactly to match the reflective clamshell null error
15-Feb-82	Final Post coating test complete	
24-Apr-90	Launched	
21-Jun-90	Failure announced	
5-Jul-90	Investigations begin	
1-Dec-93	Repair Mission Launched	

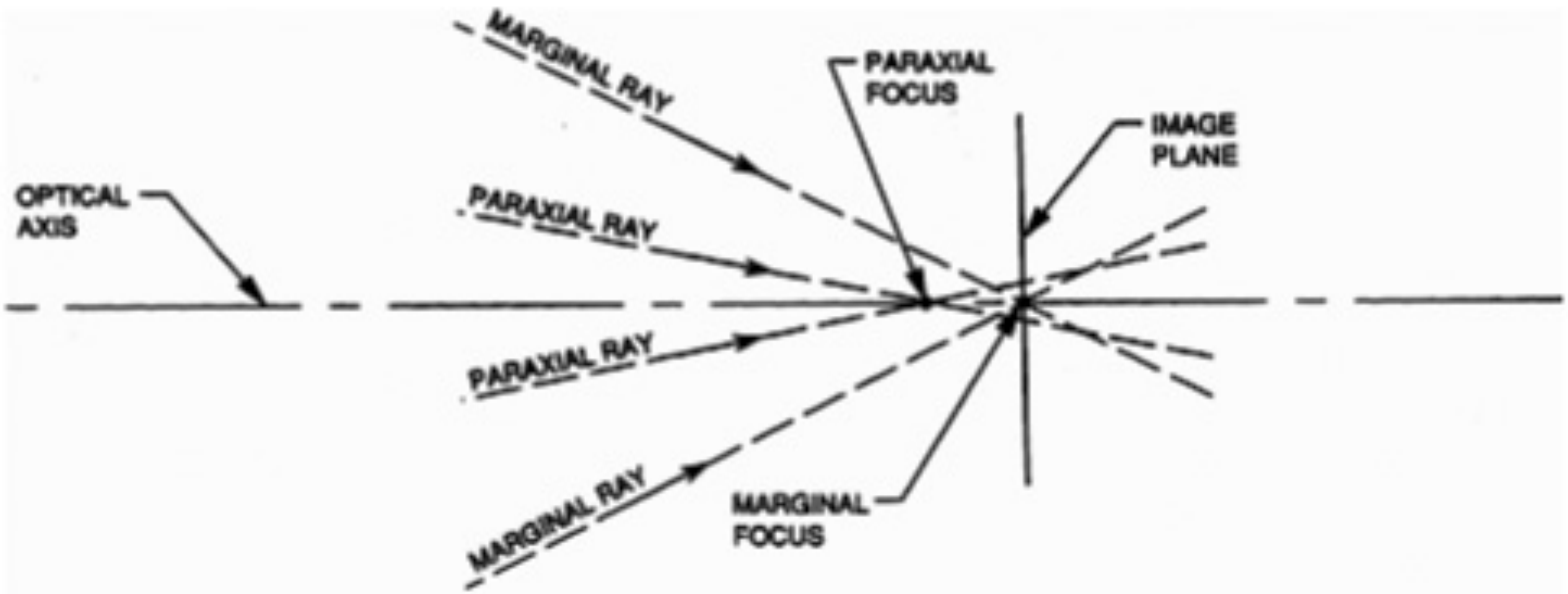
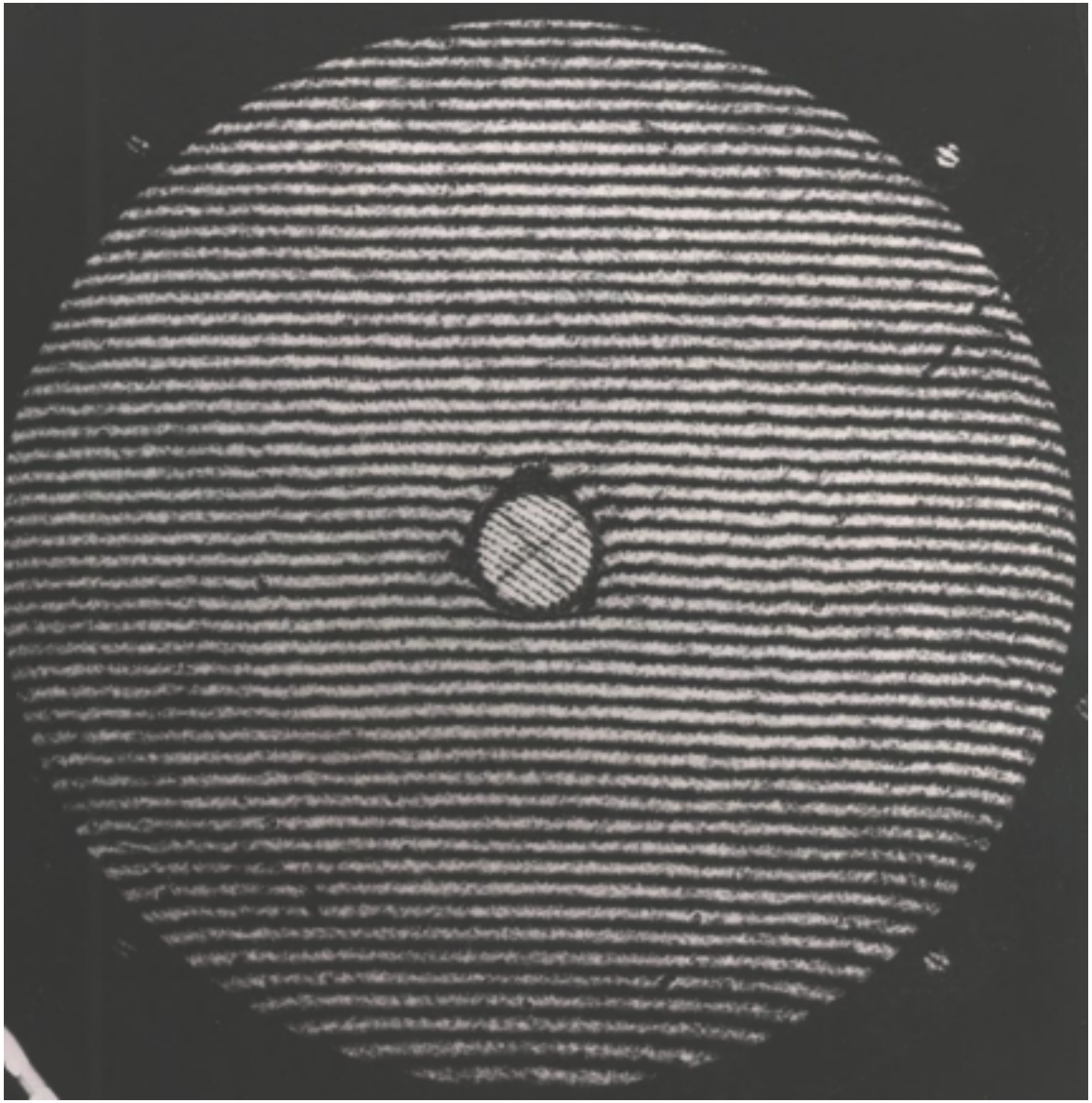


Figure C-4. Image-plane enlargement of the HST Ritchey-Chretien optical system. In the HST, too much material from the edges of the primary mirror was removed, and the marginal focus was moved past the paraxial focus. This is characteristic of an optical system overcorrected for spherical aberration.

HST Secondary Optical Interferogram

- The secondary
- Hindle sphere test configuration
- Recorded on August 31, 1981.
- Shows that the secondary was figured correctly.
- Therefore the cause was not the secondary mirror



Next

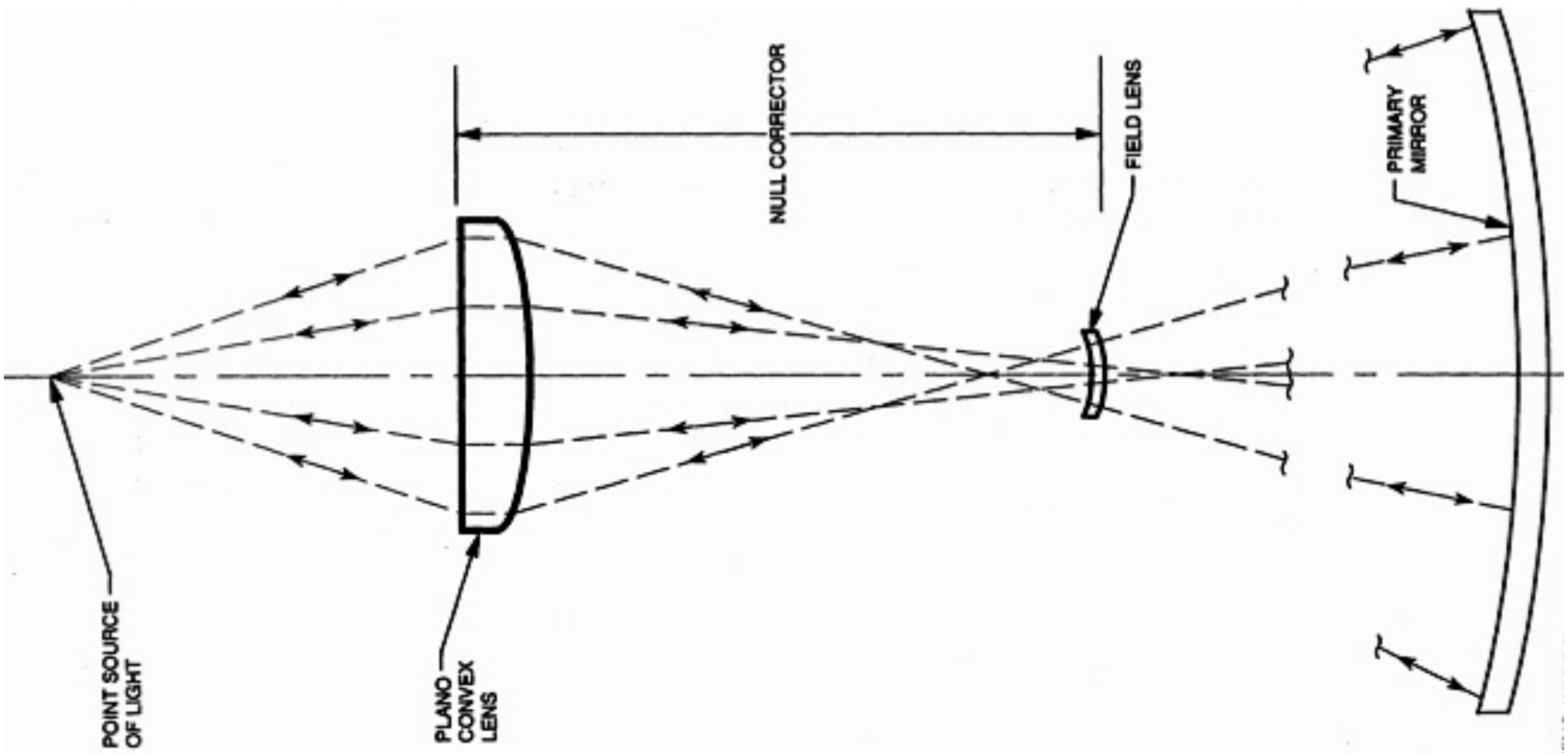
- Re-examine the mirror processing steps
- Determine, quantitatively the on-orbit prescription
- Identify a place in the WF/PC where the corrective element could be located & design the optic
- Design and build a test fixture to generate the same wavefront error as the telescope
  - Create a ground-based telescope/scene projector with exactly the same error as on the HST in orbit

Null correctors

- Used to generate reference wavefront so that
  - When used during the polishing & figuring of the mirror a “perfect” surface is fabricated the the fringes are fluffed out or “nulled”
- Refractive null correctors
- Reflective null correctors

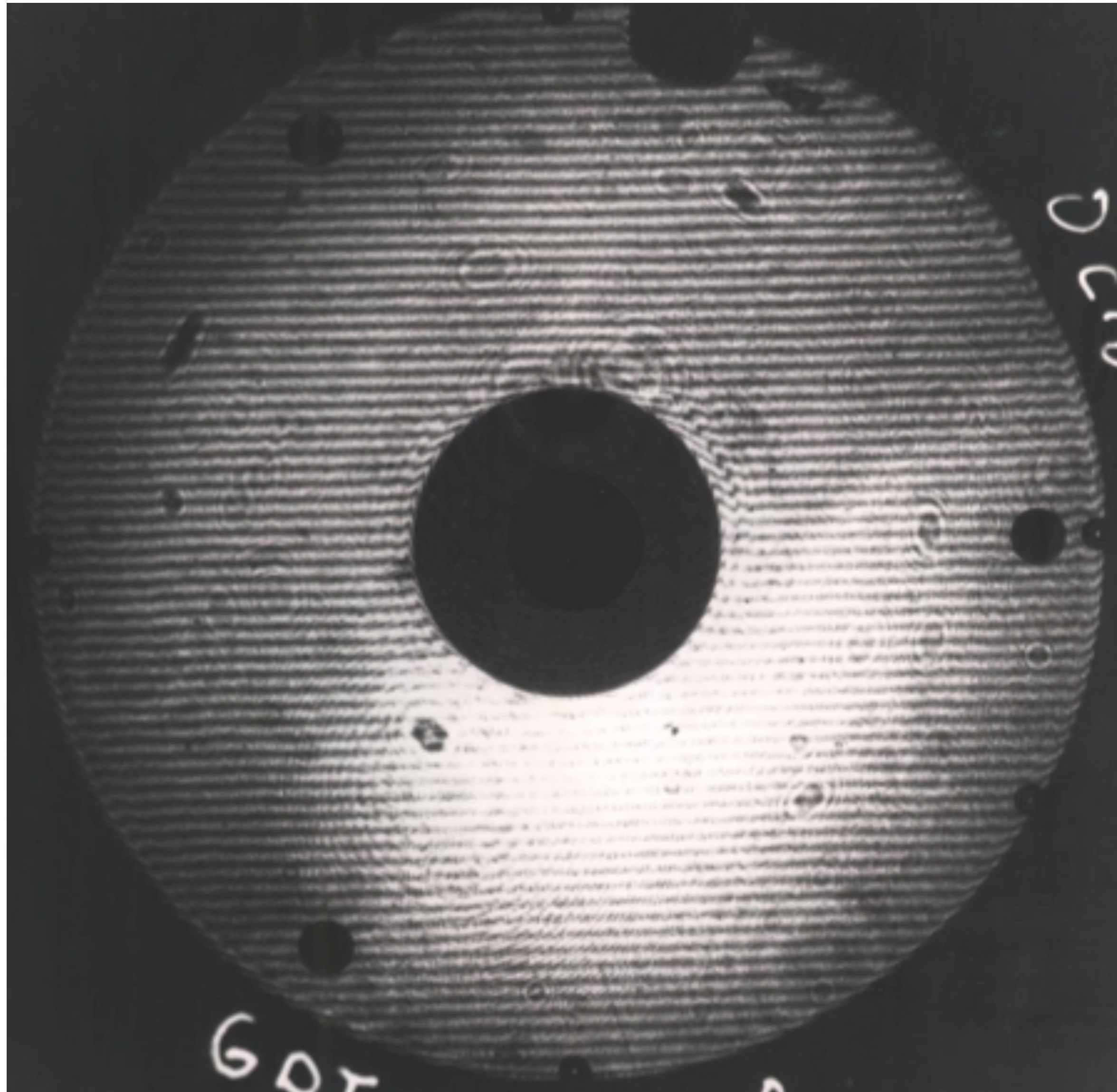
Refractive null corrector

Used at P-E Wilton to rough in the figure



HST Optical Surfaces Interferograms

- The primary mirror
- Refractive null corrector
- Recorded on February 1982.
- Shows that the primary was figured correctly in the rough grinding and polishing phase.
- Therefore the mirror was delivered from Wilton to Danbury with an accurate near-net shape.



Null correctors

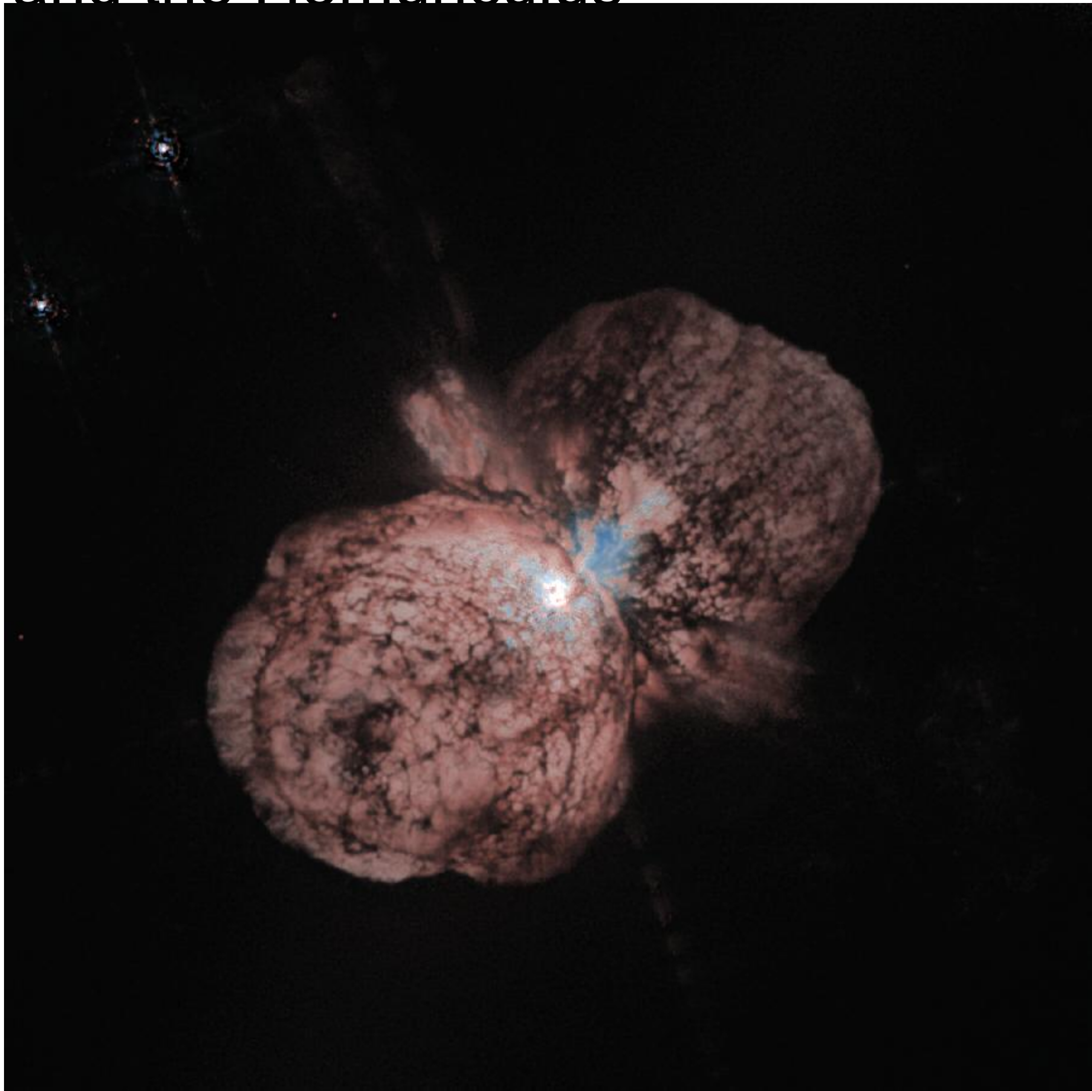
- Refractive null correctors have a performance limit given by the uniformity of the index of refraction in the bulk glass or refractive material
- Reflective null correctors are opto-mechanically more complex, but their performance limit is given only by surface smoothness (10 to 100 times better than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

Refractive Null Corrector

Figure D-2. RvNC interferogram of the primary mirror, taken in May 1981.

An example of what we have learned that is uniquely possible with HST/STIS:
Eta Carinae and the Homunculus

- Massive star with bipolar ejecta originating in the 19th century.
- N-rich, C-, O-depleted…
- Metals abound!



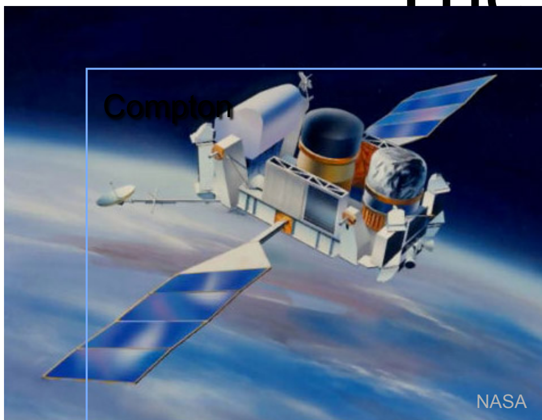
A Vision for Ground-Based Astronomy (1908)

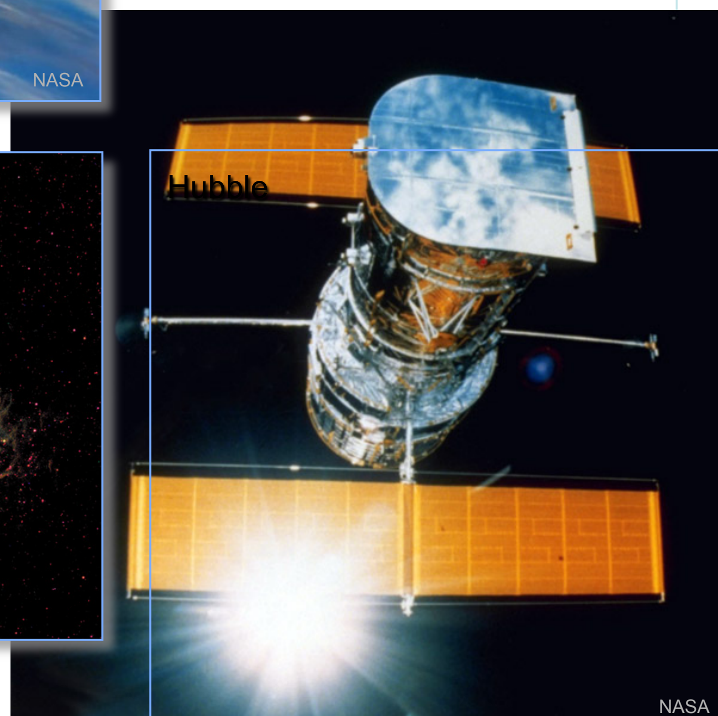
"It is impossible to predict the dimensions that reflectors will ultimately attain. Atmospheric disturbances, rather than mechanical or optical difficulties, seem most likely to stand in the way. But perhaps even these, by some process now unknown, may at last be swept aside. If so, the astronomer will secure results far surpassing his present expectations."

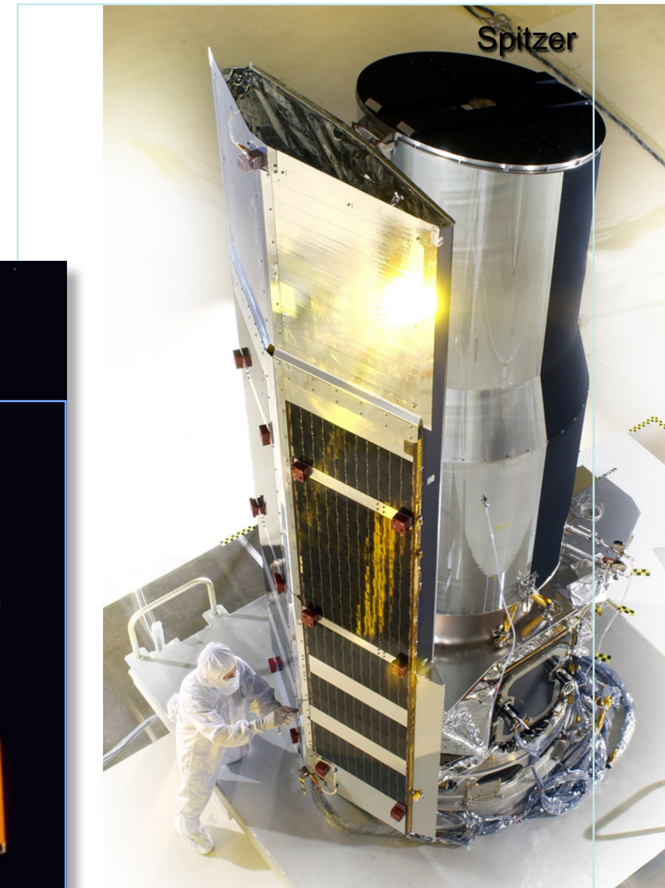
George Ellery Hale, *Study of Stellar Evolution*, 1908 (p. 242) writing about the future of the 100 inch.

The Great Observatories

- Compton
- Hubble
- Spitzer
- Chandra







New NASA Missions

- Constellation X
- James Webb Space Telescope
- LISA – Gravity Wave Experiment
- Joint Dark Energy Mission (JDEM)