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Phase-Retrieval Wave-Front Sensing for the Hubble and Future Space Telescopes

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Outline

- Hubble Space Telescope (HST)
  - Problem needs fixing
  - Phase retrieval algorithms
  - Effect of phase retrieval on the prescription
  - HST Repaired
- James Webb Space Telescope (JWST)
  - Background: foldable, segmented-aperture telescope
  - Phase retrieval will be used for wavefront sensing and control

Jim Fienup was at ERIM, Ann Arbor, MI, during the HST recovery period

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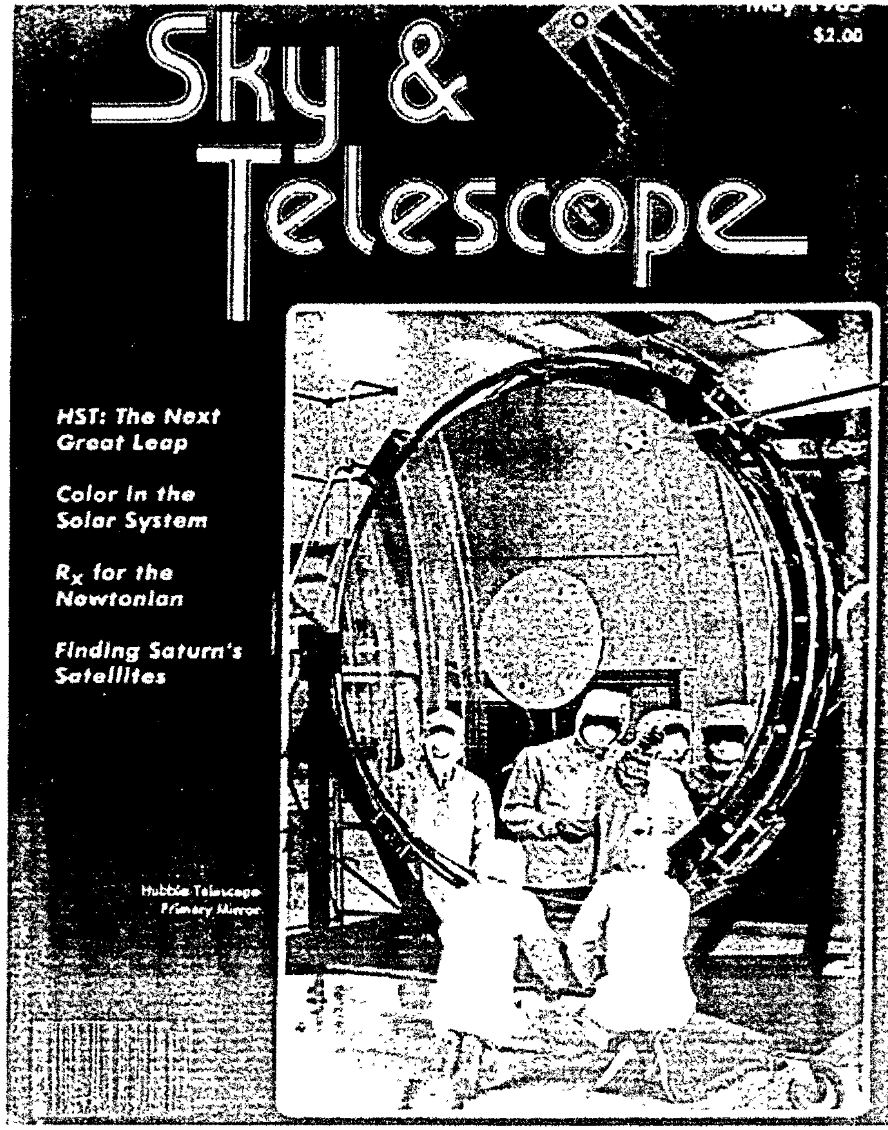
Hubble Space Telescope: Great Expectations, Pre-Launch



Note: Pads

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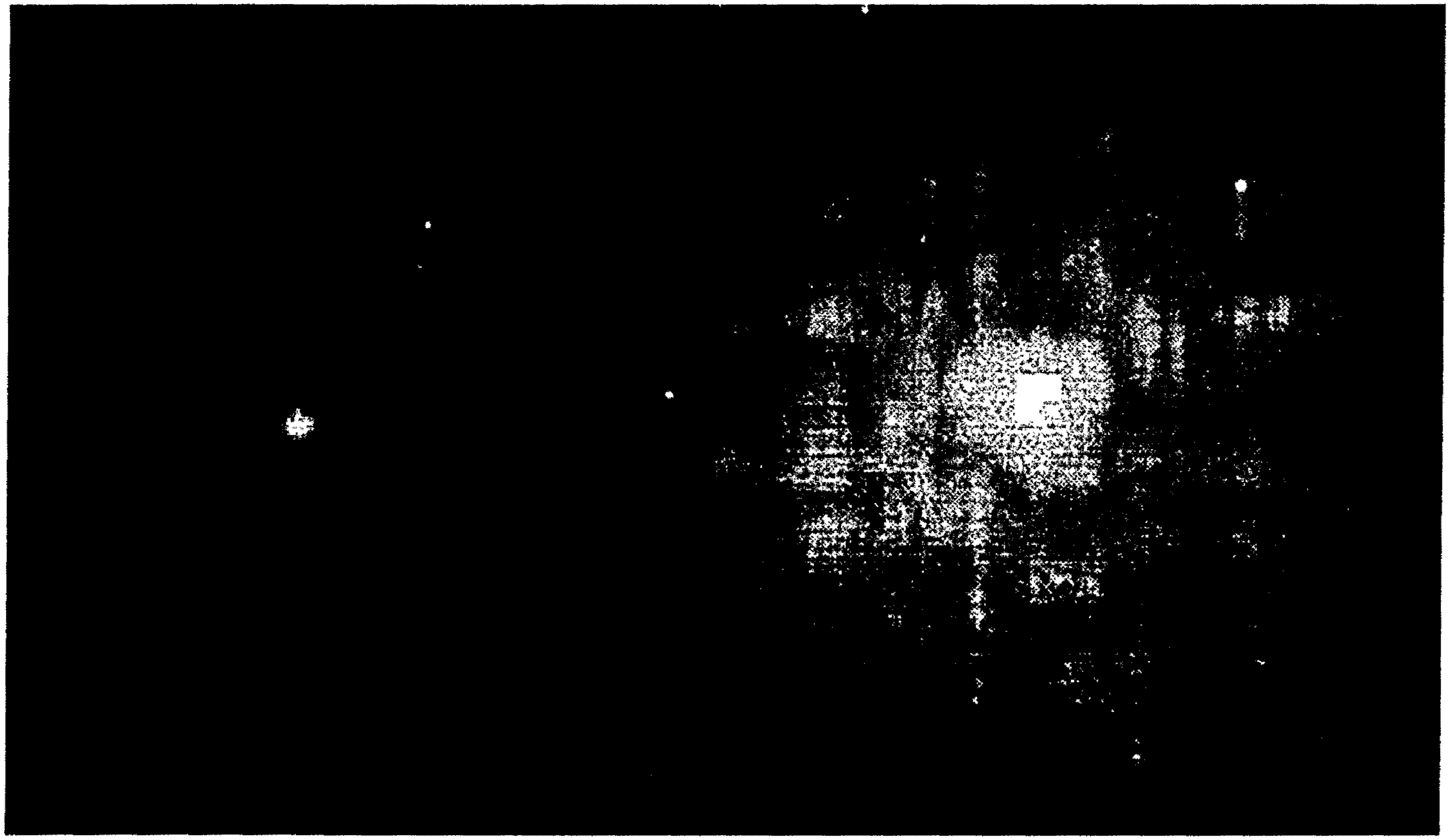
First HST Point-Spread Function, 1990



Expected   Actual

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Panels and Organizations
Characterizing and Fixing HST

HST Optical System Board of Investigation
(Lew Allen Committee)
How did it happen? Who was to blame?

HST Independent Optical Review Panel (HIORP)
Characterize error to fix WF/PC2
(JRF, IPWG representative)

HST Strategy Panel
How to fix HST in general

HST Image Processing Working Group (IPWG)
Improve imagery by post-detection processing
(JRF, member)

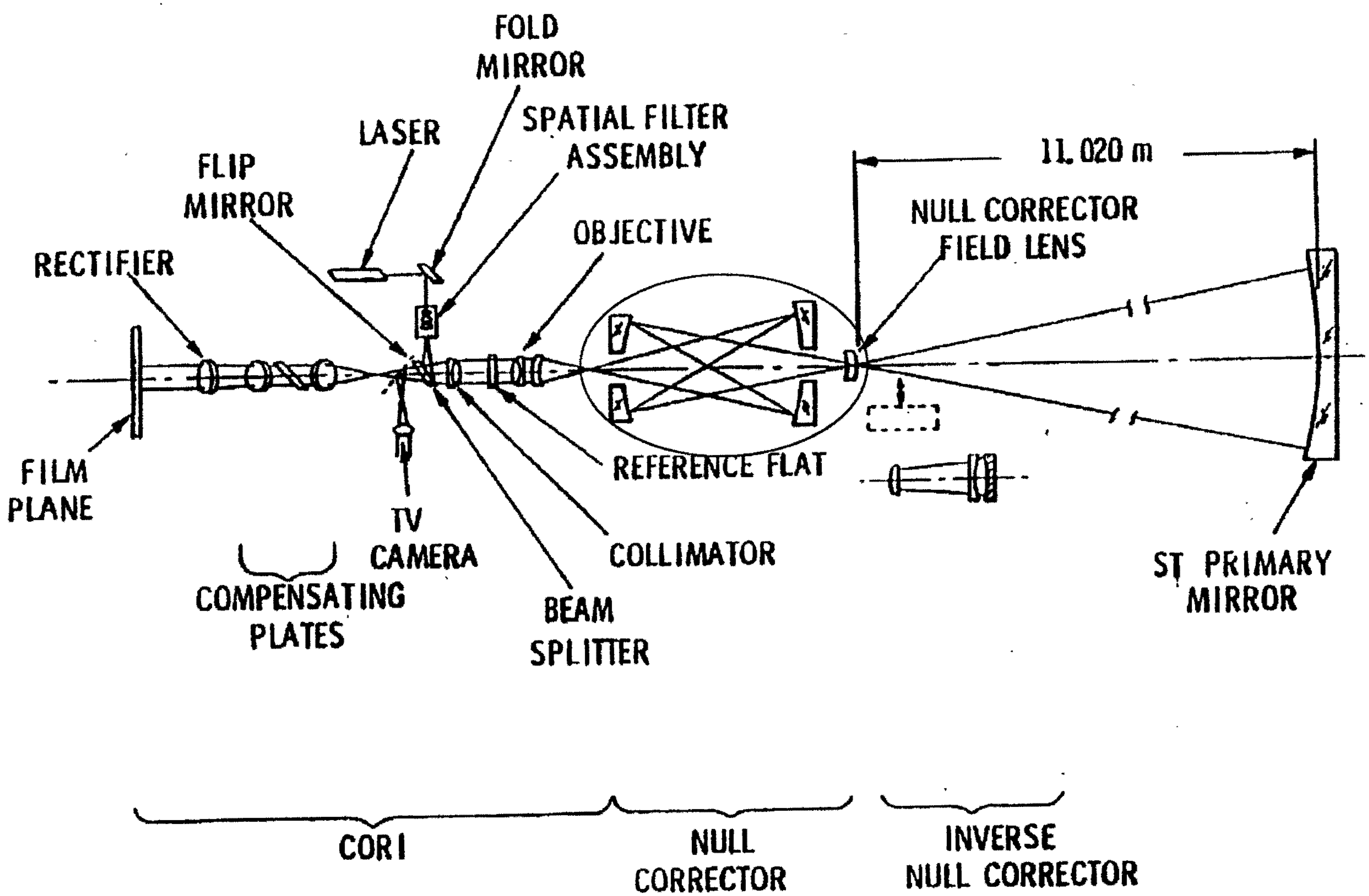
Instrument Teams:
WF/PC, FOC, HRS, FGS, ...
Vested interest

JPL WF/PC2 Team
Build camera and relay optics to fix problem
(JRF, subcontractor)

Space Telescope Science Institute
Process imagery

Hughes Danbury Optical System
Characterize problem, align system

HST Ground & Polished According to Interferometer Measurements



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1.3 mm Mistake in Null Corrector Spacing Causes 2 μm Mistake in Primary Mirror

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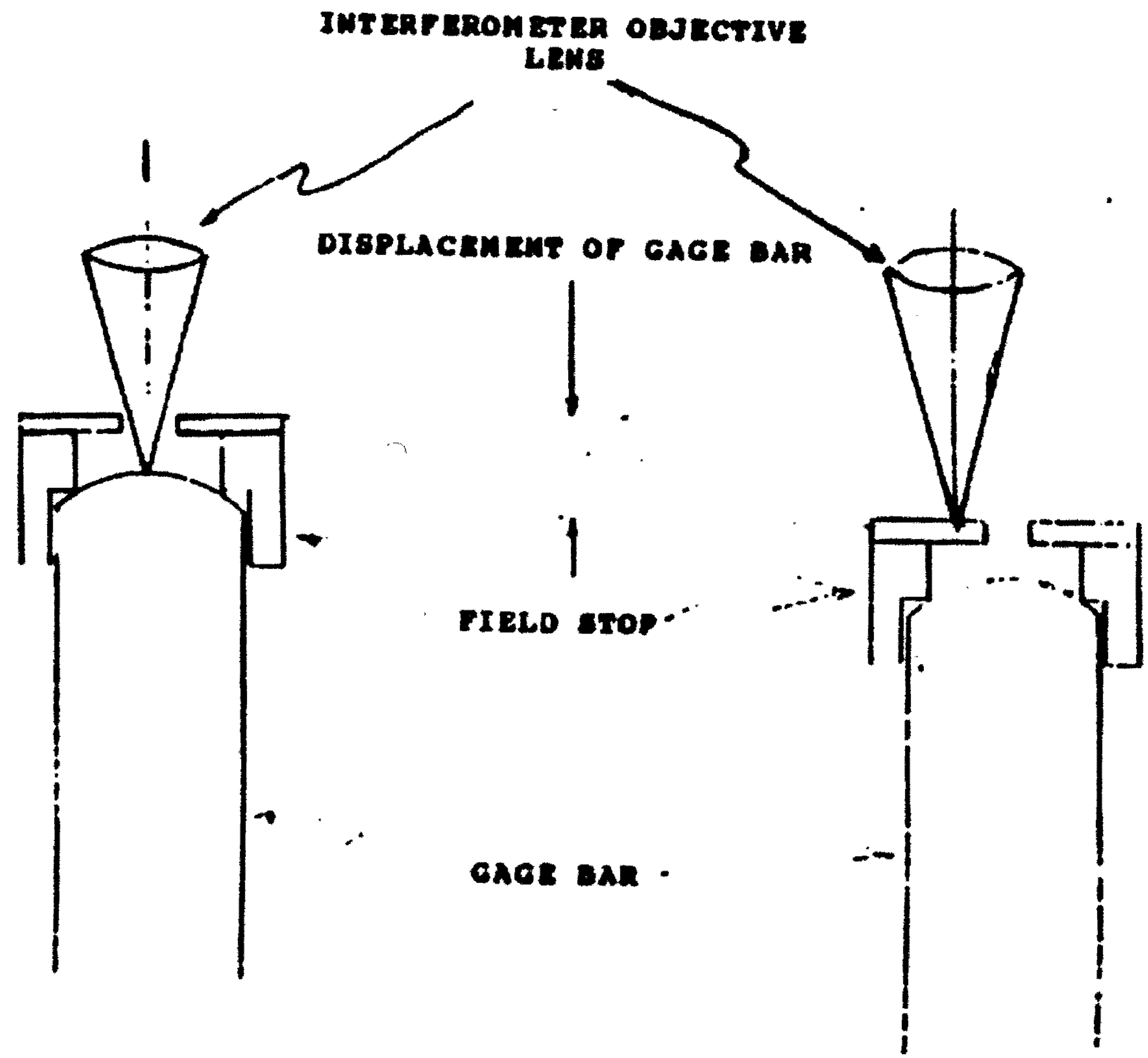

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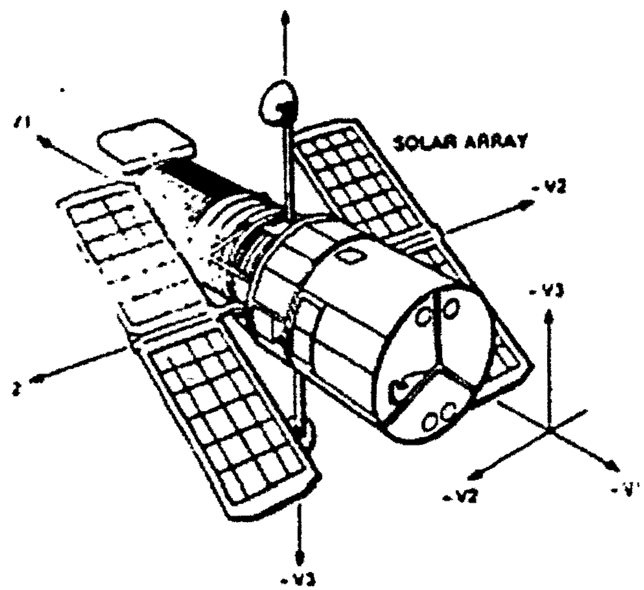
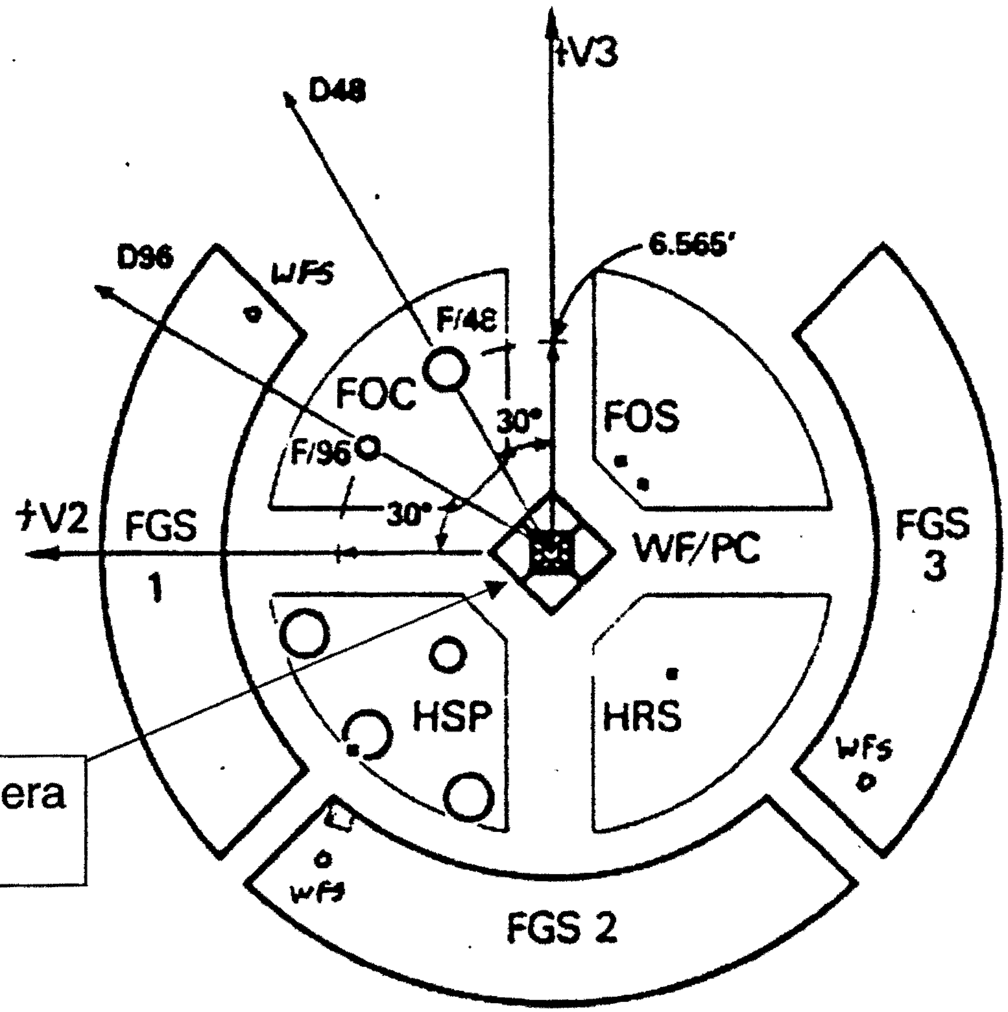
HST Focal Plane



Wide-Field/Planetary Camera
=WF/PC "wiff-pick"



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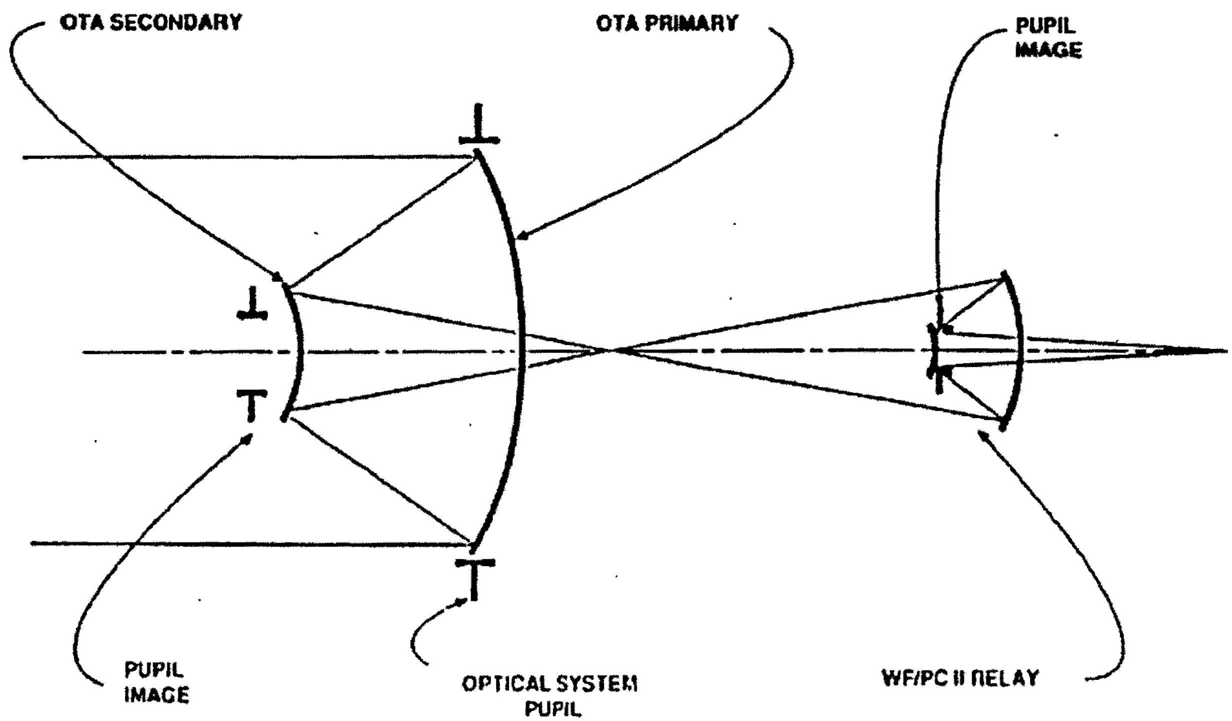
Can Correct Primary Mirror Error on Secondary of WF/PC2 Relay Telescope

K. LESCHLY

CORRECTION APPROACH



(Not to scale)

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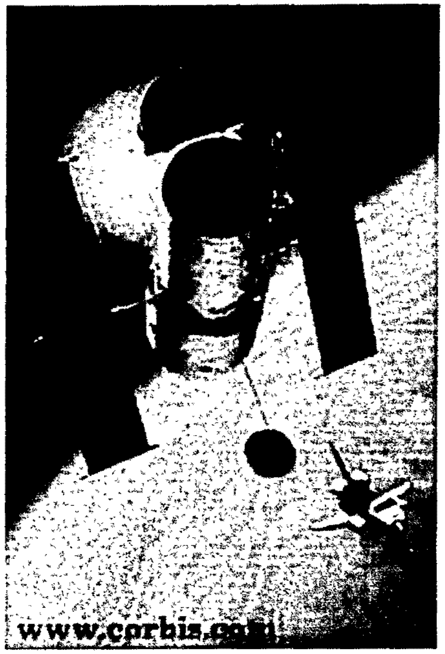
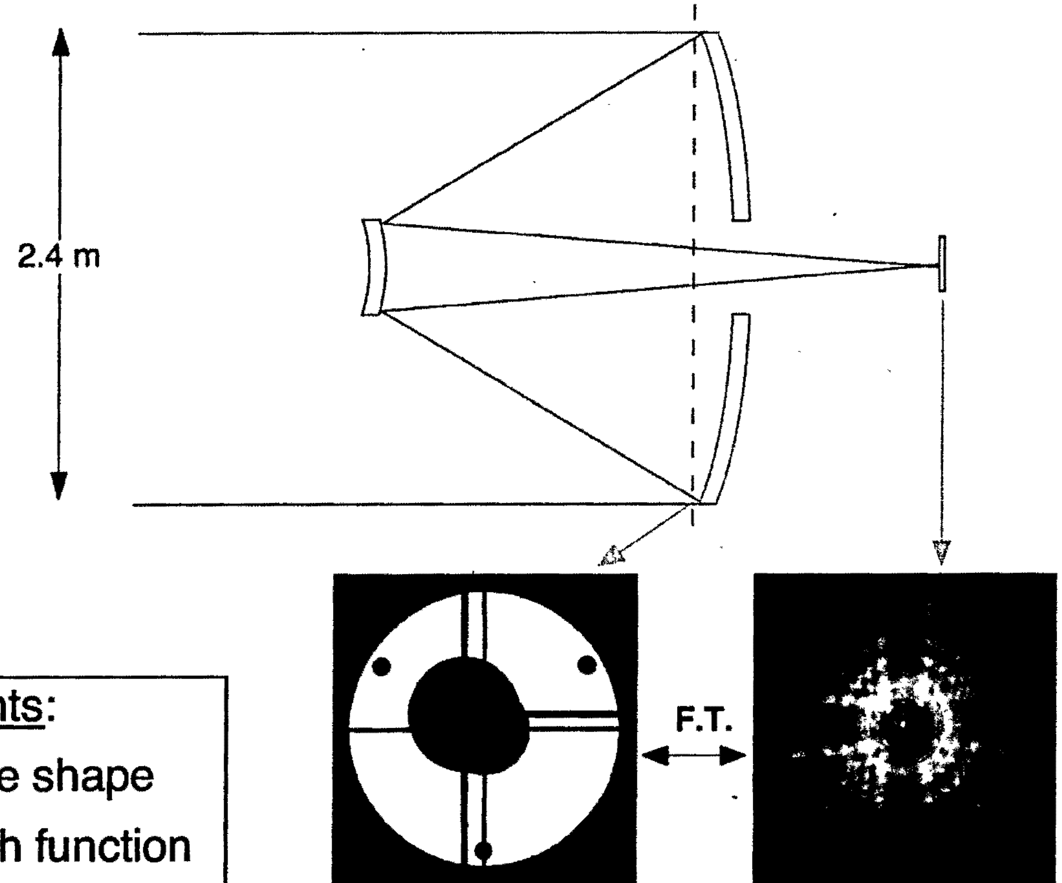
Determine HST Aberrations from PSF





(Hubble Space Telescope)

Measurements & Constraints:

Pupil plane: known aperture shape

phase error fairly smooth function

Focal plane: measured PSF intensity

Wavefronts in pupil plane and focal plane are related by a Fourier Transform

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Benefits of Phase Retrieval

Knowing aberrations precisely allows for:

- Design correction optics to fix the HST
  - WF/PC II
  - COSTAR
- Optimize alignment of secondary mirror of HST OTA
- Monitor telescope shrinkage (desorption) and focus
- Compute analytic point-spread functions for image deconvolution
  - Noise-free
  - Depends on λ, $\Delta\lambda$, camera, field position
  - Is highly space-variant for WF/PC
  - Eliminates requirement to measure numerous PSF's

In addition, reconstruction of pupil function allows determination of alignment between OTA and WF/PC

Phase Retrieval Basics

Focal plane field → $F(u,v)$; Pupil plane field → $f(x,y)$

Fourier transform: $$F(u,v) = \iint_{-\infty}^{\infty} f(x,y)e^{-i2\pi(ux+vy)}dx\,dy$$

$$= |F(u,v)|e^{i\psi(u,v)} = \mathcal{F}[f(x,y)]$$

Focal plane field magnitude = sqrt(intensity) → $|F(u,v)|$

Focal plane field phase → $\psi(u,v)$

Inverse transform: $$f(x,y) = \iint_{-\infty}^{\infty} F(u,v)e^{i2\pi(ux+vy)}du\,dv = \mathcal{F}^{-1}[F(u,v)]$$

Phase retrieval problem:

Given $|F(u,v)|$ and some constraints on $f(x,y)$,
Reconstruct $f(x,y)$, or equivalently retrieve $\psi(u,v)$

Equivalently, reconstruct field $f(x,y)$ in the pupil
— its phase is the phase error we wish to correct

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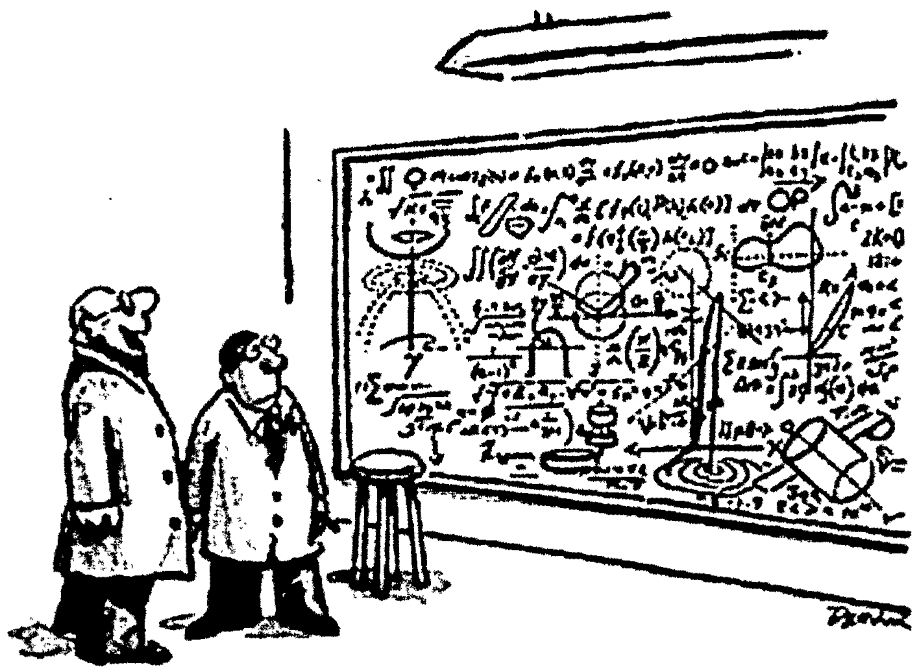
Is Phase Retrieval Possible?



"Hey, no problem!"

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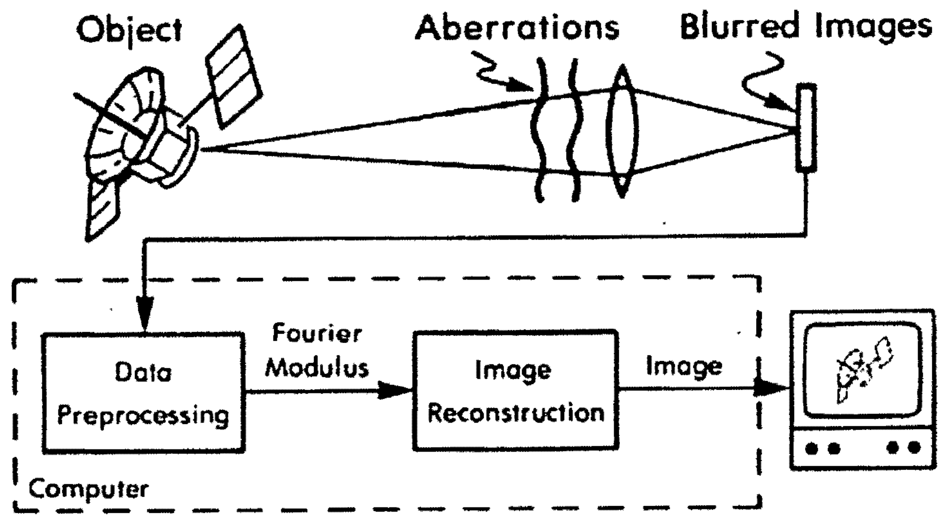
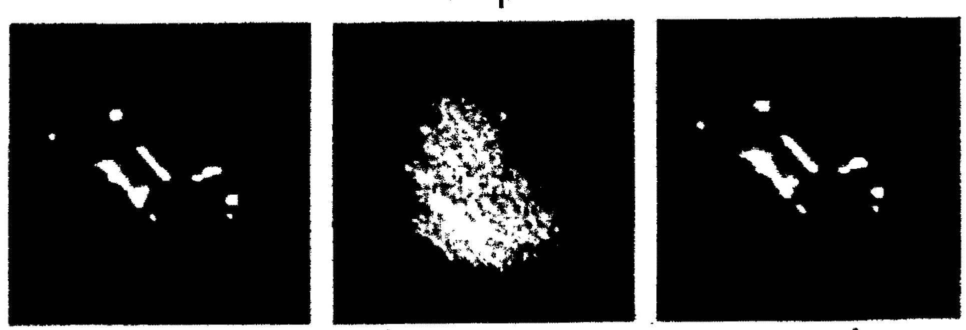
Phase Retrieval for Image Reconstruction from Stellar Speckle Interferometry Data

IMAGING WITH PHASE ERRORS



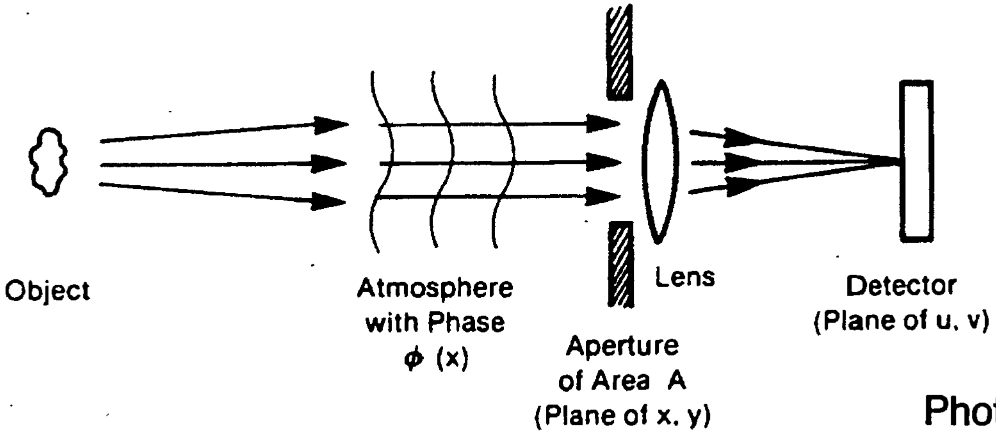
Example:



Object — Blurred Image — Reconstructed Image

J.R. Fienup, "Phase Retrieval Algorithms: A Comparison," Appl. Opt. 21, 2758-2769 (1982).

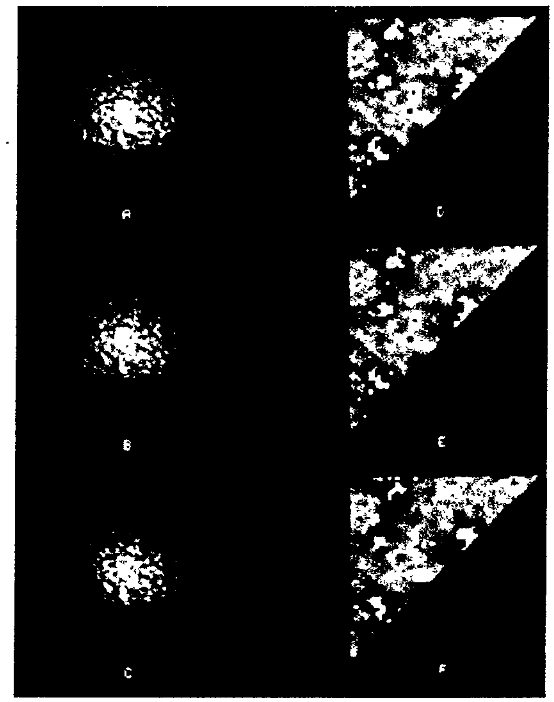
Fourier Intensity Wavefront Sensor



No Noise

1.1×10^5
Phot./Coh.Cell

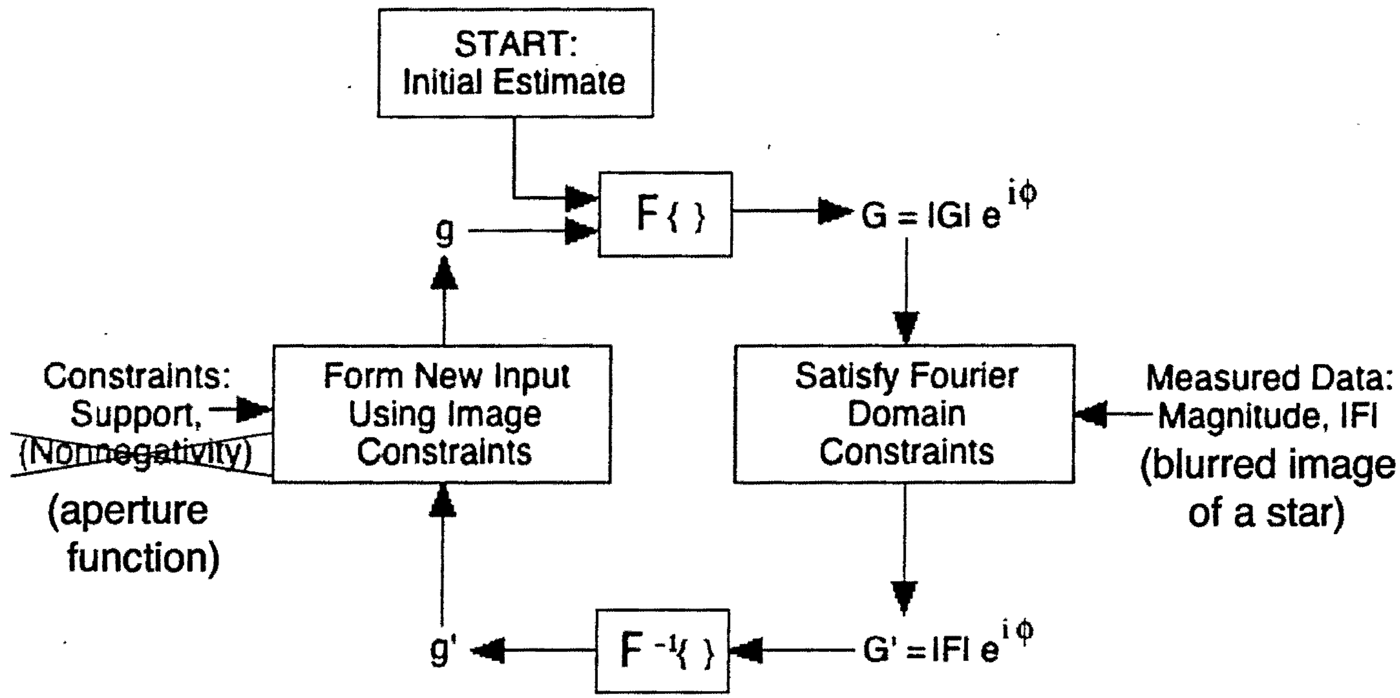
1.1×10^3
Phot./Coh.Cell



Focal Plane Intensity | Reconstructed Phase

J.N. Cederquist, J.R. Fienup, C.C. Wackerman, S.R. Robinson and D. Kryskowski, "Wave-Front Phase Estimation from Fourier Intensity Measurements," J. Opt. Soc. Am. A 6, 1020-1026 (1989).

Iterative Transform Algorithm



Enforcing magnitude constraints in both domains
is the "Gerchberg-Saxton" algorithm

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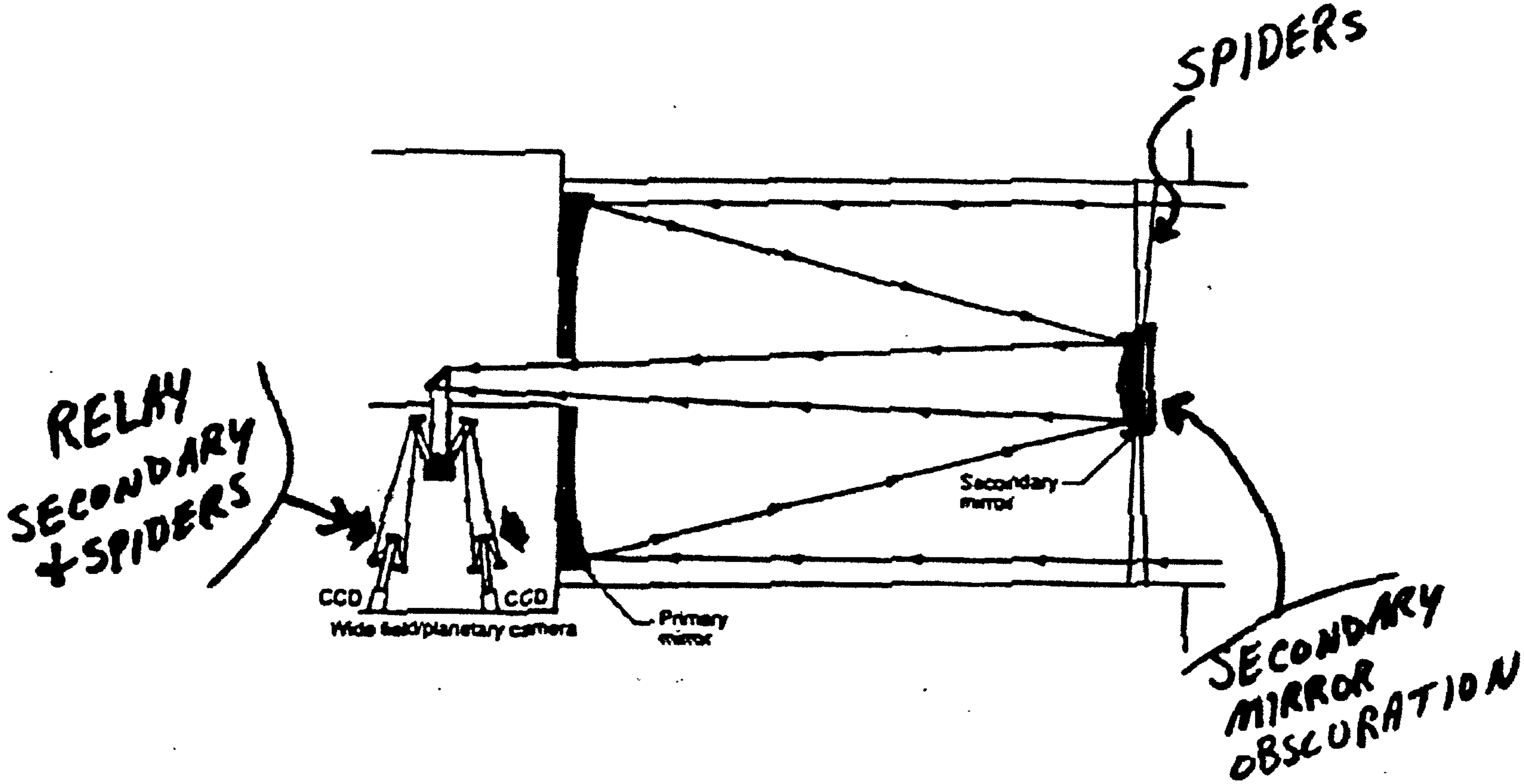
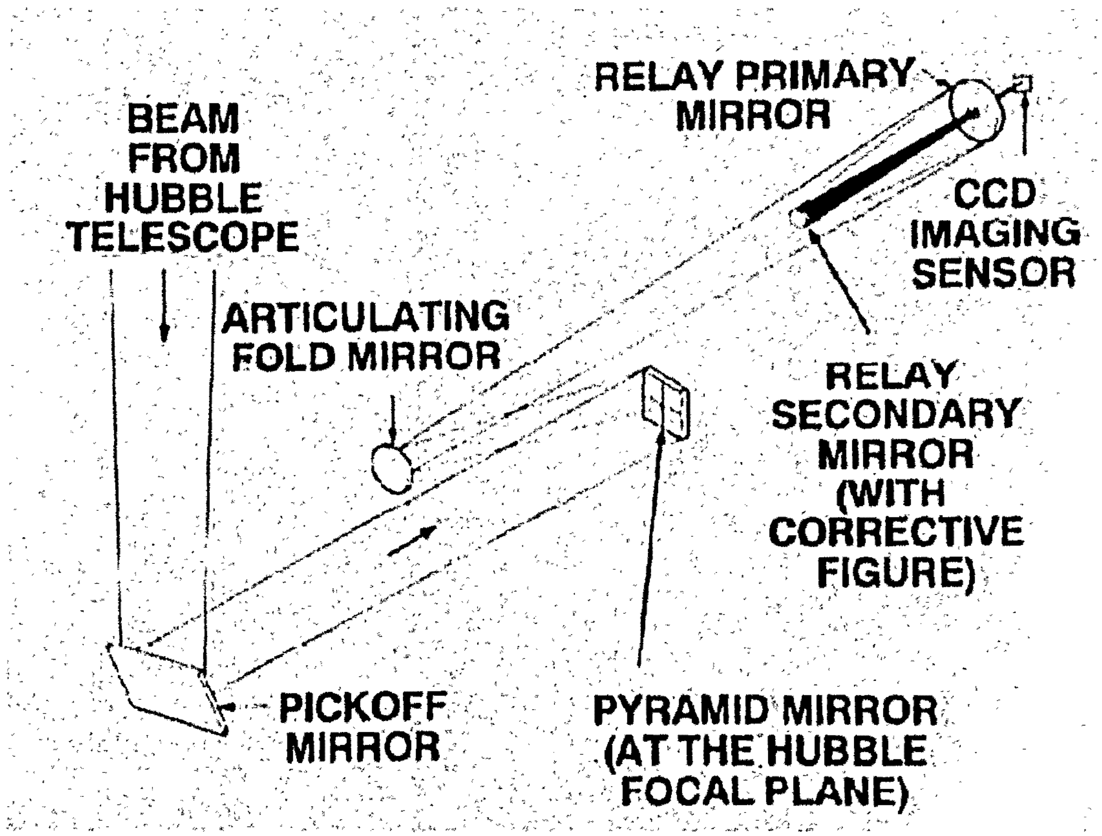
Sources of Obscurations in HST



WF/PC Camera Details



- Relay telescope secondary obscuration appears to translate vs. field angle

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Phase Retrieval Techniques

Minimize error metric by

- Cut & try [Jon Holtzman (Lowell Observatory)]
- Iterative transform algorithm (Gerchberg-Saxton/Misell/Fienup)
- Gradient search (steepest descent, conjugate gradient, . . .)
- Damped least squares (Newton-Raphson)
- Neural network [Todd Barrett & David Sandler (Thermo Electron)]
- Linear programming
- Prescription retrieval [David Redding (Draper Lab)]
- Phase diversity
- etc. (intensity transport, tracking zero sheets, simulated annealing, ...)

- Other groups doing phase retrieval
  - Rick Lyon *et al.* Hughes Danbury Optical Systems
  - Chris Burrows (Space Telescope Science Institute)
  - Mike Shao *et. al.* (JPL)
  - Francois Roddier (U. Hawaii), . . .

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Phase Retrieval by Optimization

- Model optical system
  - Known parameters (constraints)
  - Unknown parameters (to retrieve)
- Compute model of data
- Compare model of data with actual measured data
  - Compute error metric
- Minimize error metric over space of unknown parameters
  - Using nonlinear optimization algorithms

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Error Metrics

Detector plane: Computed, Measured

$$E_1^2 = \sum_u W(u)\left[\left|G(u)\right| - \left|F(u)\right|\right]^2$$

$$E_2^2 = \sum_u W(u)\left[\left|G(u)\right|^2 - \left|F(u)\right|^2\right]^2$$

Maximum likelihood for additive Gaussian noise

$$E_3^2 = \sum_u W(u)\left\{\left|G(u)\right| - \left|F(u)\right| - \left|G(u)\right| \ln\left[\left|F(u)\right| / \left|G(u)\right|\right]\right\}^2$$

$$L = -\sum_u W(u)\left|G(u)\right|^2 + \sum_u W(u)\left|F(u)\right|^2 \ln\left[\left|G(u)\right|^2\right]$$

Maximum likelihood for Poisson noise

Aperture plane:

— Treating detector-plane phase as optimization parameters

$$E_{ap}^2 = \sum_x \left[\left|g(x)\right| - \left|f(x)\right|\right]^2$$

etc.

Computed, Known Pupil

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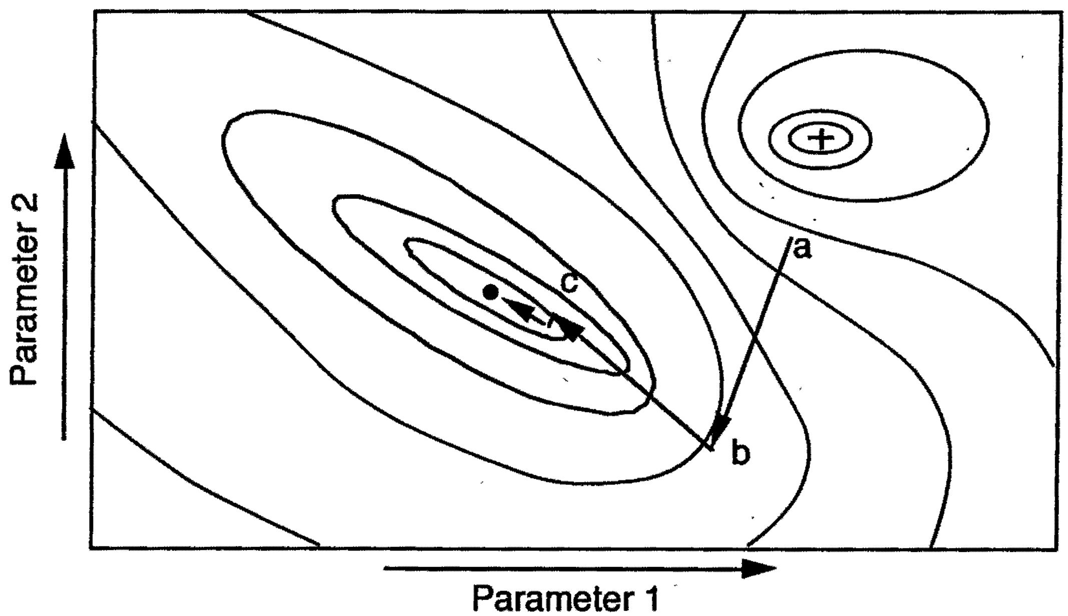
Techniques Employing Gradients

Minimize Error Metric, e.g.: $E = \sum_{u} W(u)[|G(u)| - |F(u)|]^2$

Contour Plot of Error Metric



Repeat three steps:

1. Compute gradient: $\frac{\partial E}{\partial p_1}, \frac{\partial E}{\partial p_2}, \ldots$
2. Compute direction of search
3. Perform line search

Gradient methods:

(Steepest Descent)
Conjugate Gradient
BFGS/Quasi-Newton
...

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Analytic Gradients of $E = \sum_u W(u)\left[|G(u)| - |F(u)|\right]^2$

<u>Pupil</u>: <u>Detector plane</u>:

$$g(x) = m_o(x) e^{i\theta(x)} \longrightarrow G(u) = P[g(x)]$$

$$\downarrow$$

$$g^W(x) = P^\dagger\left[G^W(u)\right] \longleftarrow G^W(u) = W(u)\left[|F(u)|\frac{G(u)}{|G(u)|} - G(u)\right]$$

Derivative w.r.t. general parameter: $\frac{\partial E}{\partial p} = -2\,\mathrm{Re}\left[\sum_x \frac{\partial g(x)}{\partial p} g^{W*}(x)\right]$

For point-by-point phase map, $\theta(x)$, $\frac{\partial E}{\partial \theta(x)} = 2\,\mathrm{Im}\left\{g(x)\, g^{W*}(x)\right\}$

For Zernike polynomial coefficients, $\frac{\partial E}{\partial a_j} = 2\,\mathrm{Im}\left\{\sum_x g(x)\, g^{W*}(x)\, Z_j(x)\right\}$

where $\theta(x) = \sum_{j=1}^{J} a_j Z_j(x)$

Propagator P[•] can be single FFT or multiple-plane Fresnel transforms with phase factors and obscurations

Analytic gradients very fast compared with finite differences

J.R. Fienup, "Phase-Retrieval Algorithms for a Complicated Optical System," Appl. Opt. <u>32</u>, 1737-1746 (1993).

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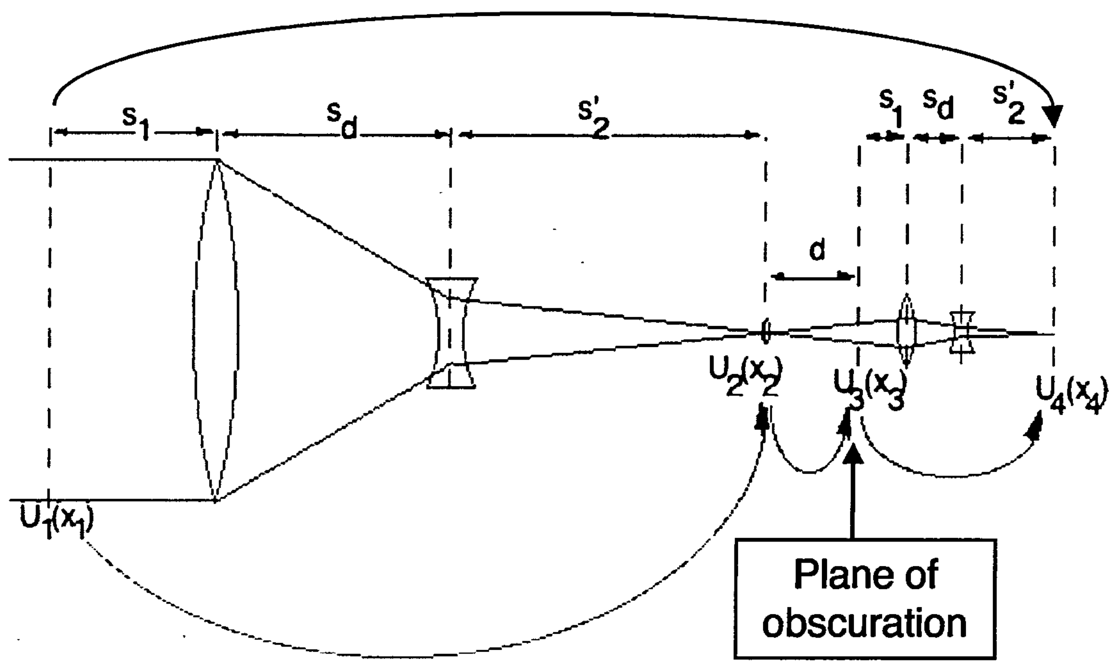
System Modeling — Propagation

- Simple Fourier propagation
  - All obscurations, phase errors in same plane
  - Phase errors in two mirrors, wavefront translates with field angle



Thin lens model of HST + PC

- Fresnel propagation, using multiple planes of diffraction
  - Obscurations planes, phase error planes

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More System Modeling Considerations

- Multi-plane propagation including vignetting or multiple aberration planes
- Jitter in telescope pointing during exposure time
- Exclude bad pixels from error metric (dust/saturation/cosmic rays)
- Finite spectral bandwidth
- Shifted WF/PC obscurations vs. field position
- Correct plate scale (depends on field position)
- CCD pixel integration, sampling (undersampling/aliasing)
- Include model of noise (photon, readout)
- Higher-order Zernike's and micro-roughness
- Effect of aberrations in OTA secondary, in WF/PC cameras
- Design aberrations versus field position
- Possibility of non-point-like star

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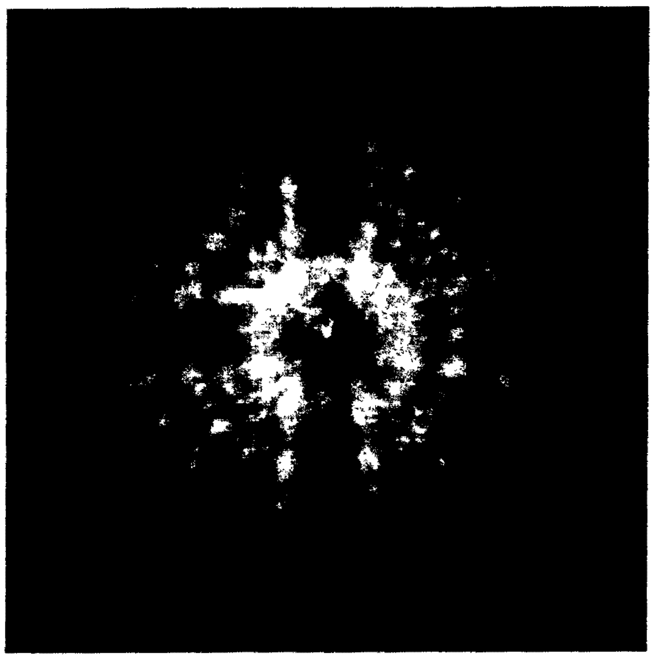
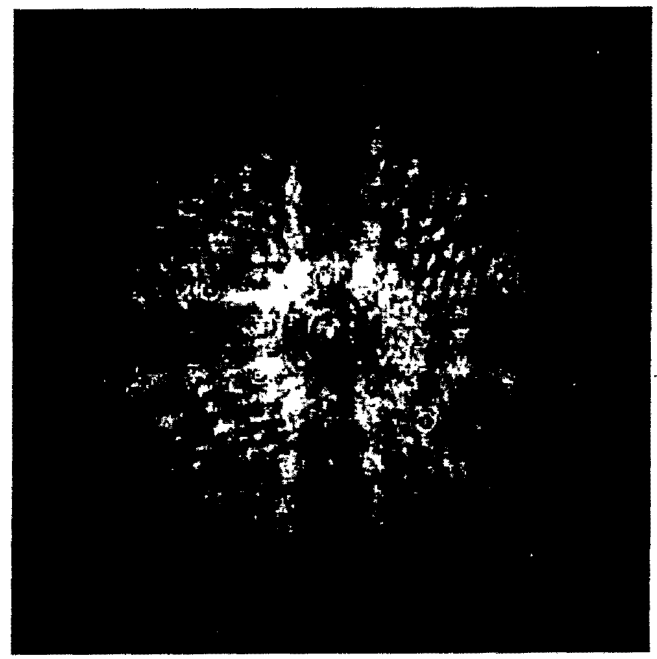
Dust Artifacts and Glitches in WF/PC Images



Raw image (point source)

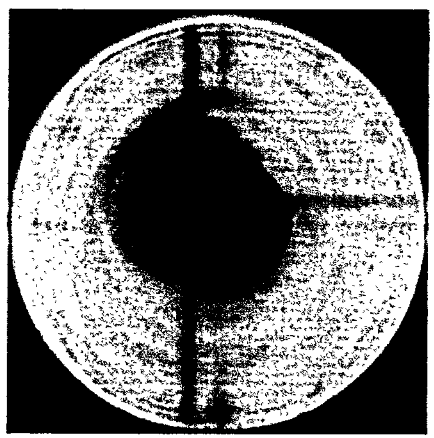


Sharpened image

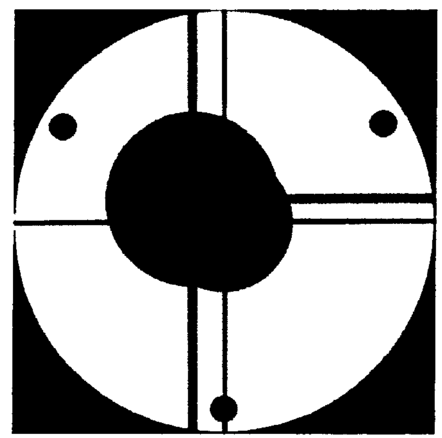
Hubble Telescope Retrieval Approach

- Pupil (support constraint) was known imperfectly
- Phase was relatively smooth and dominated by low-order Zernike's
  - — Use boot-strapping approach

1. With initial guess for pupil, fit Zernike polynomial coefficients
2. With initial guess for Zernike polynomials, estimate pupil by ITA



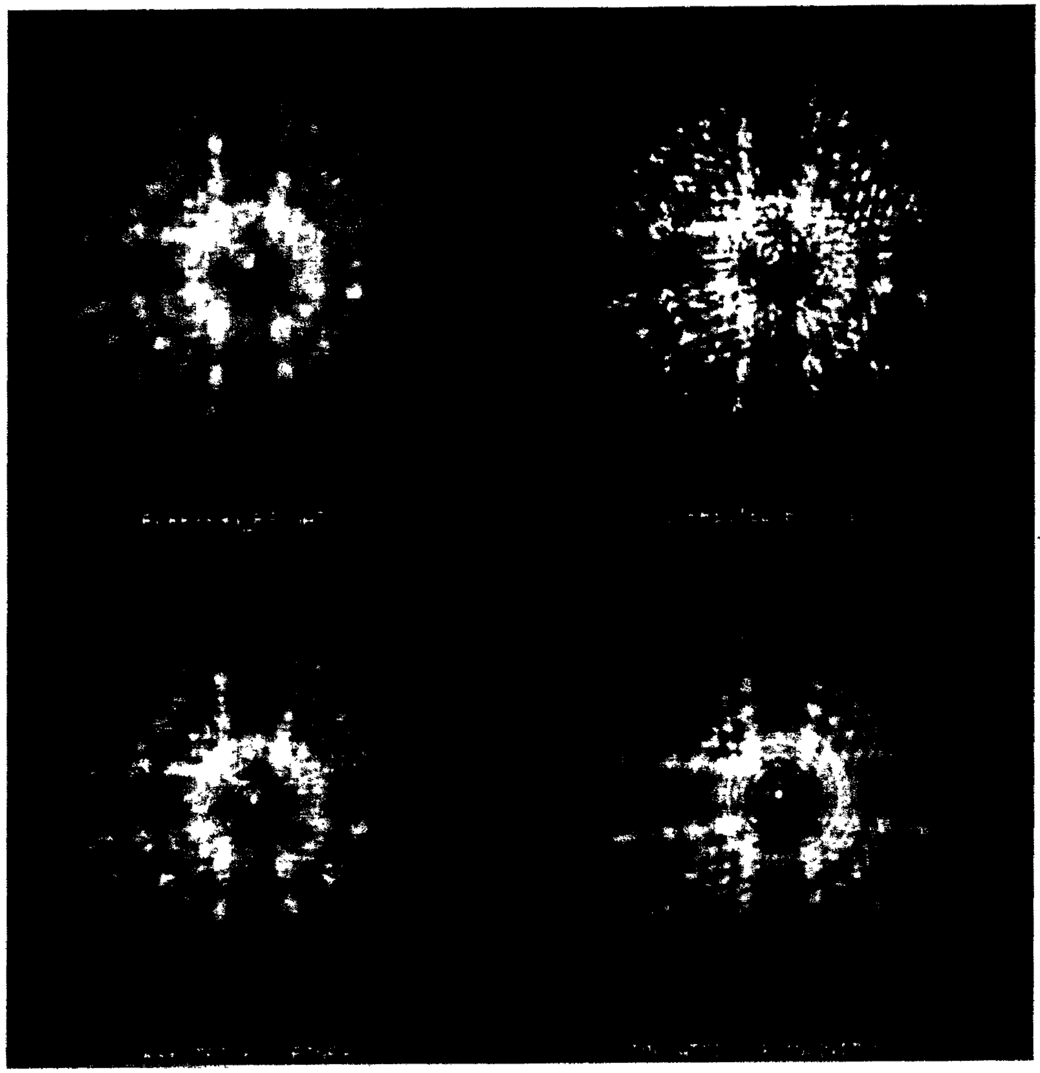
Pupil Reconstructed by ITA



Inferred Model of Pupil

3. Redo steps 1 and 2 until convergence (2 iterations)

Comparison of Actual and Simulated HST Image of a Point Star



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ERIM Phase Retrieval Results
Greater Accuracy --> Larger Z11 Values

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- **Results -- PC6 F889N_P2 data (Δz = -260):**

Zernike Coefficients (microns rms of wavefront error):

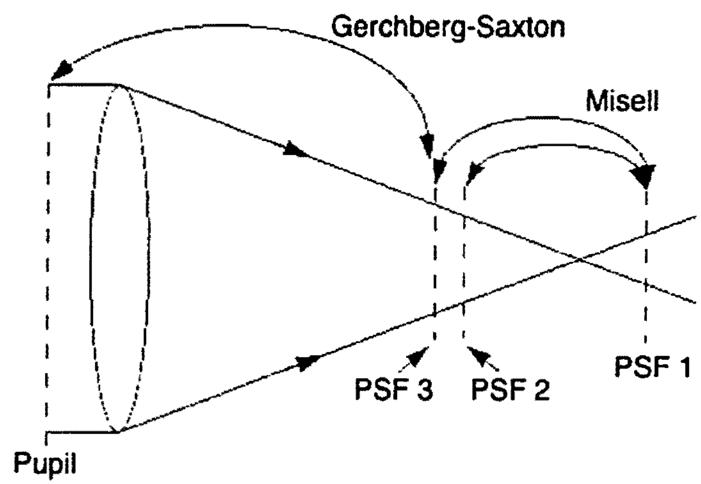
Zernike Coefficient	Single	Multi(11)	Multi(22)	New Param. Multi(11)
4	-2.212	-2.227	-2.223	-2.303
5	-0.018	-0.003	0.006	-0.003
6	-0.025	0.025	0.026	0.031
7	0.004	0.001	0.005	-0.001
8	0.017	0.010	0.009	0.013
9	-0.022	-0.020	-0.009	-0.021
10	0.002	0.008	0.010	0.005
11	**-0.280**	**-0.292**	**-0.295**	**-0.300**
12	0.008			
16	-0.009		-0.004	
20	0.006			
22	0.005	0.006	0.007	0.008
conic κ =	-1.0144	-1.0151	-1.0152	-1.01545
rms err =	0.1583	0.1352	0.1353	

New parameters: Plate scale = 0.0442 arcsec/pixel, bq = -0.000059

Other Phase Retrieval Approaches

John Holtzman (Lowell Observatory)
"Cut and Try" = compare images with various computed spherical

Francoise & Claude Roddier
Miselle algorithm



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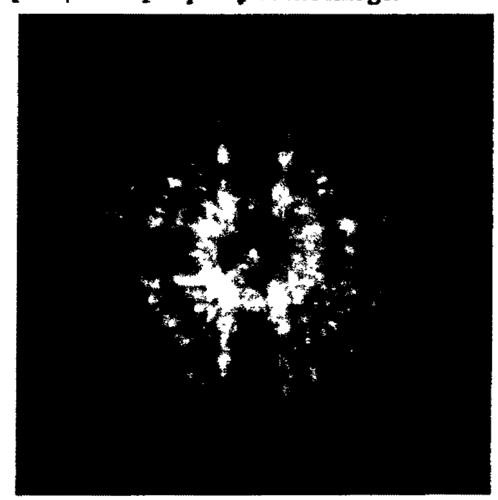
Tracking Pupil Features with Defocus

Aden B. Meinel, Marjorie P. Meinel, and Daniel H. Schulte, "Determination of the Hubble Space Telescope effective conic-constant error from direct image measurements," Appl. Opt. 32, 1715-1719 (1993).

Fig. 2. Typical PC-6 image showing the points defining the center of the pad diffraction spot and the periphery of the image.



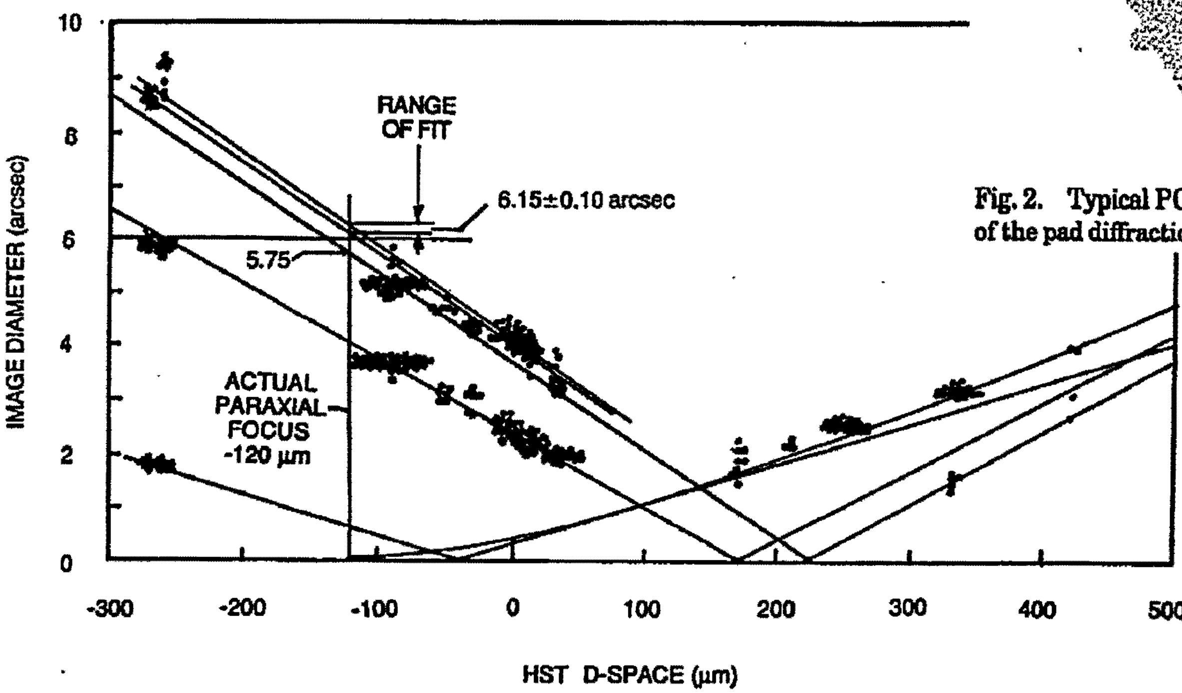


Fig. 5. Best fit of measured points to the Schulte lines defines the paraxial focus as being at −120 μm and the rim image diameter as being 6.15 ± 0.1 arcsec. This leads to an apparent conic constant of −1.01429 ± 0.0002.

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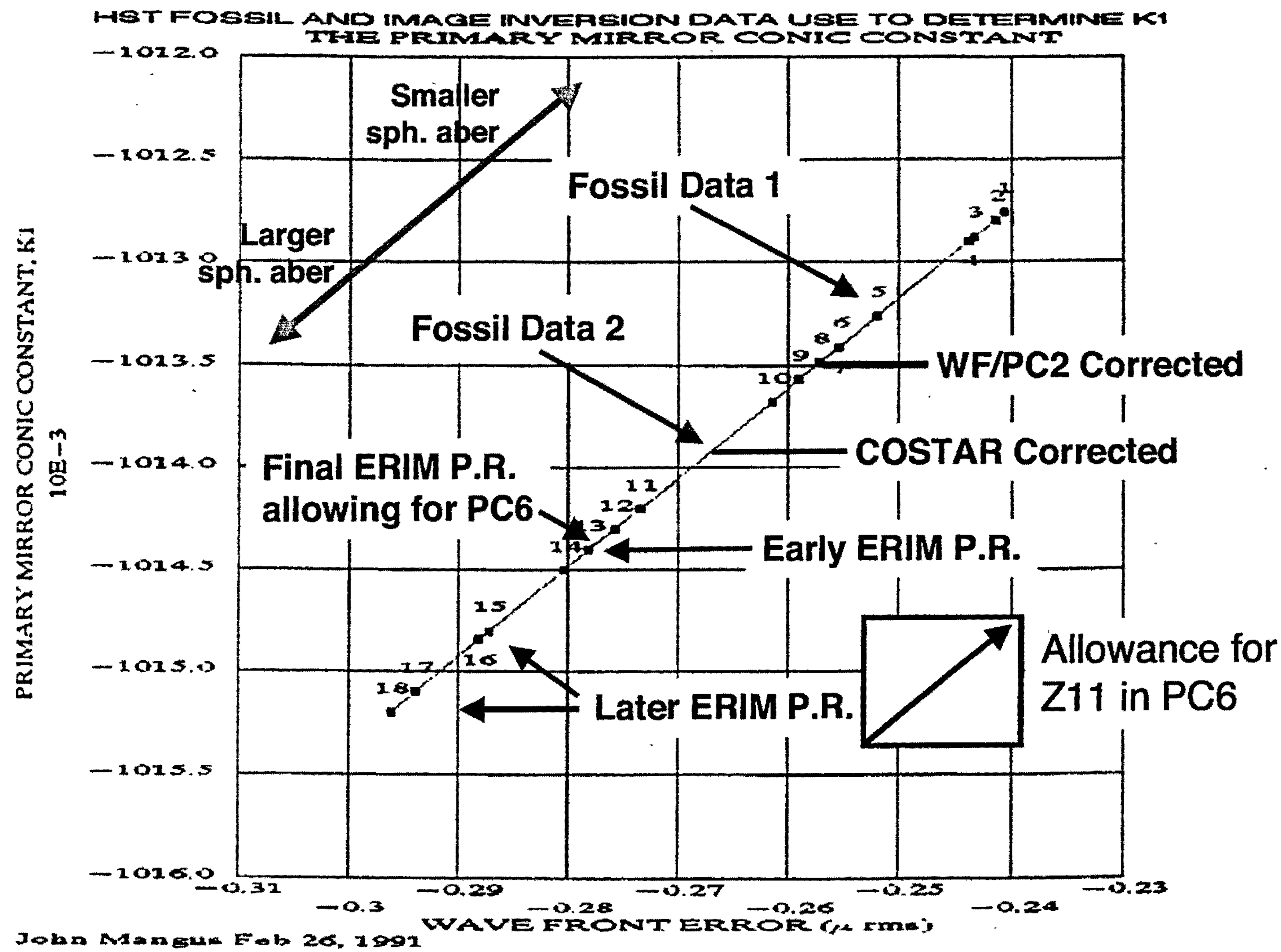
Discrepancy with Phase Retrieval Caused NASA to Look for Additional Errors



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Sources of Estimates of Spherical Aberration

	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

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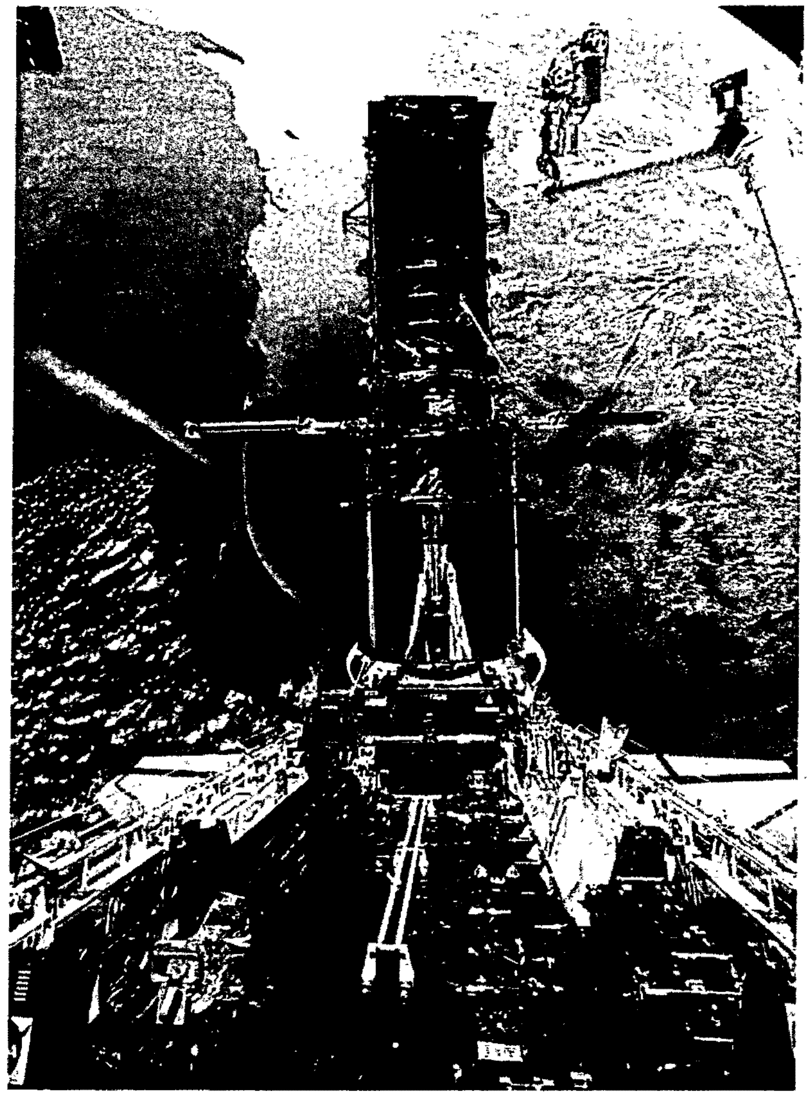
Hubble Fixed



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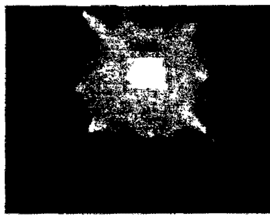
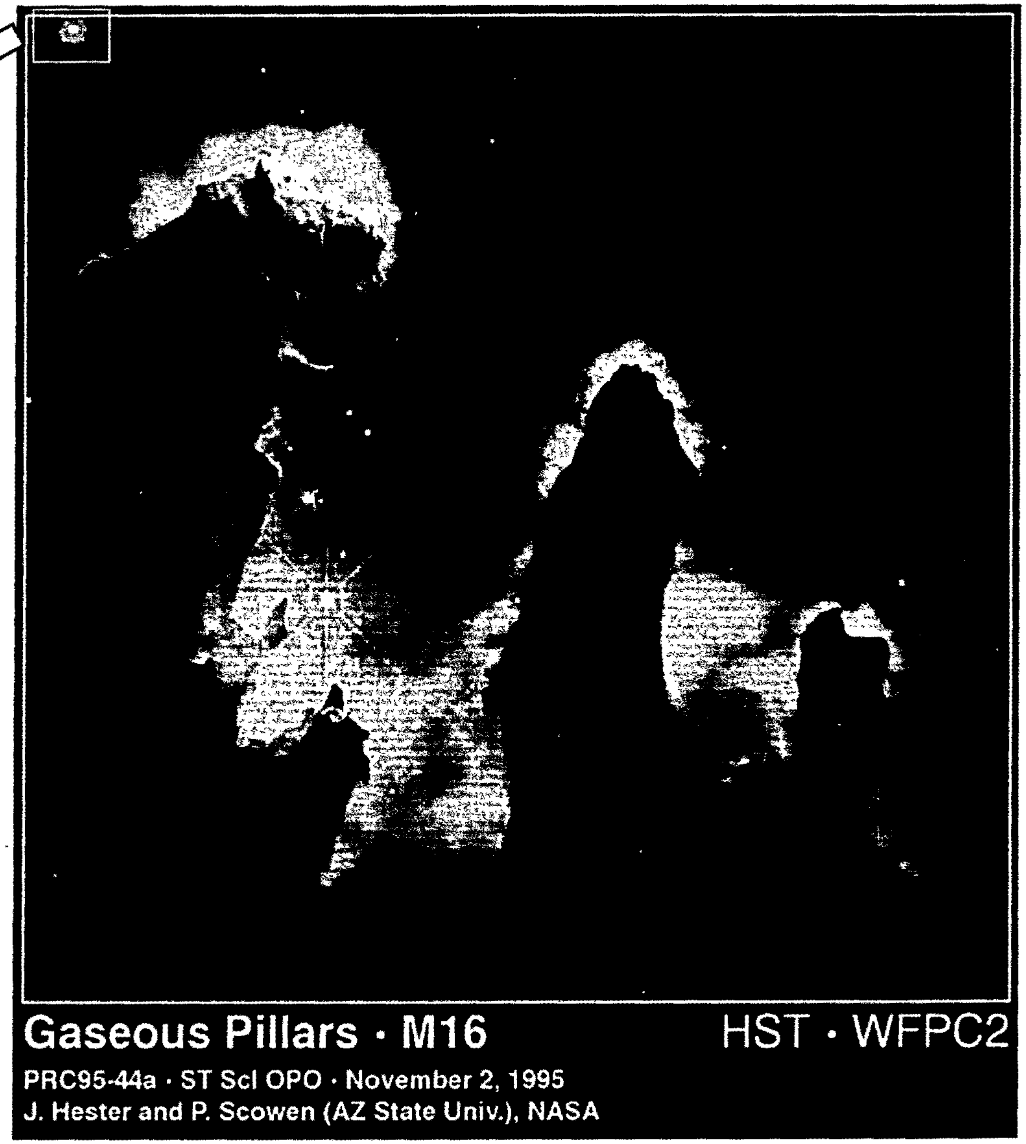
Greatly Improved Imagery



Small residual blurring noticeable only for bright point sources



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Accuracy of 1991 Phase Retrieval Estimates Verified

Phase-retrieval analysis of pre- and post-repair Hubble Space Telescope images

John E. Krist and Christopher J. Burrows

Phase-retrieval measurements of point-spread functions from the pre- and post-repair Hubble Space Telescope are presented. The primary goal was to determine the aberrations present in the second wide-field and planetary camera (WFPC2) to align and validate its corrective optics. With both parametric model-fitting techniques and iterative (Gerchberg–Saxton) methods, accurate measurements have been obtained of the WFPC2 and Hubble Space Telescope optics, including improved maps of the zonal errors in the mirrors. Additional phase-retrieval results were obtained for the aberrated, prerepair cameras and the corrected faint-object camera. The information has been used to improve models produced by point-spread-function simulation programs. On the basis of the measurements a conic constant for the primary mirror of $\kappa = -1.0144$ has been derived.

1 August 1995 / Vol. 34, No. 22 / APPLIED OPTICS 4951

Our results for WFPC2 indicated that the compromise conic constant derived by the HIORP underestimated the spherical aberration by a small but measurable amount.

WF/PC2 corrected to
$\kappa = -1.0135$ ($Z_{11} = -0.254$ μm)
COSTAR corrected to
$\kappa = -1.0139$ ($Z_{11} = -0.263$ μm)
Fienup 1991 (after -0.013 μm PC)
$\kappa = -1.0144$ ($Z_{11} = -0.276$ μm)
Krist & Burrows 1995 agrees

↔

"Hubble Space Telescope Characterized by using Phase-Retrieval Algorithms, J.R. Fienup, J.C. Marron, T.J. Schulz, and J.H. Seldin, Appl. Opt. 32, 1747-1767 (1993).

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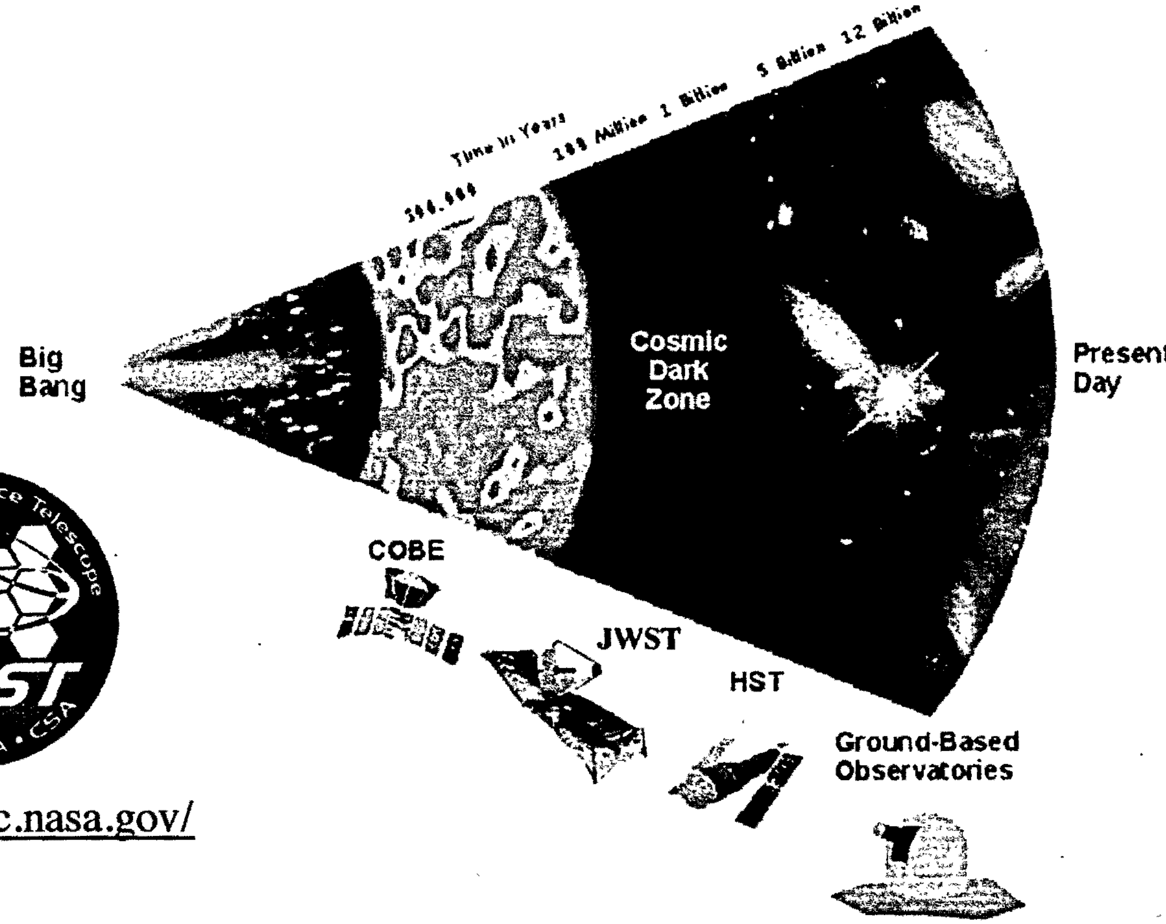
James Webb Space Telescope

(Next Generation Space Telescope)



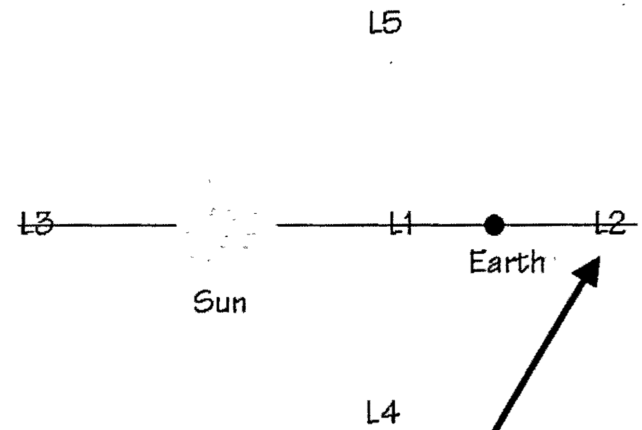
http://ngst.gsfc.nasa.gov/

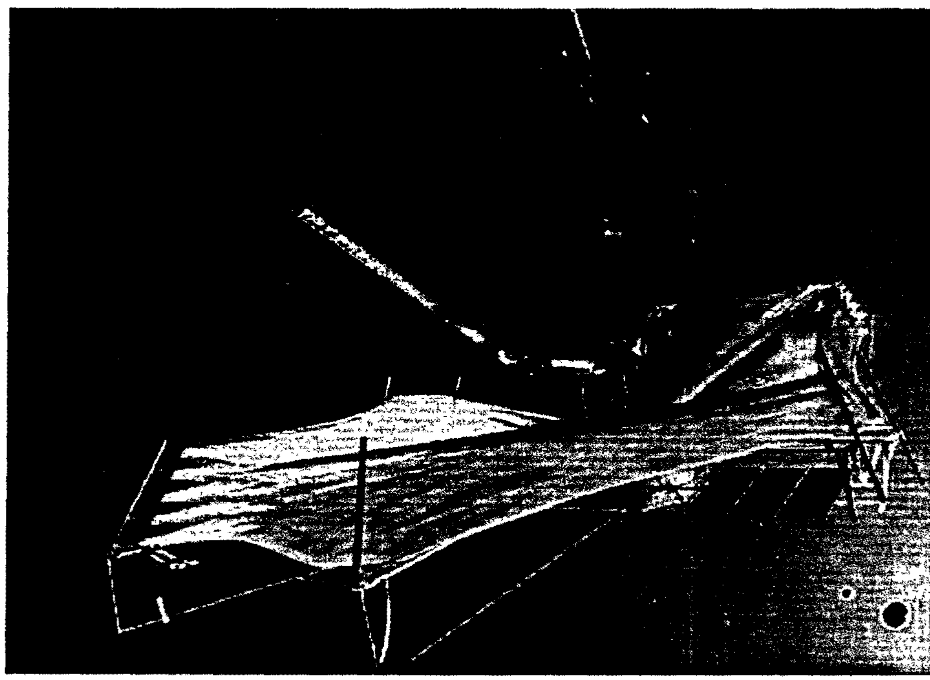
See farther back towards the beginnings of the universe

Light is red-shifted into infrared

James Webb Space Telescope (JWST)

- See red-shifted light from early universe
  - 0.6 μm to 28 μm
  - L2 orbit for passive cooling, avoiding light from sun and earth
  - 6.6 m diameter primary mirror
    - Deployable, segmented optics
    - Phase retrieval to align segments





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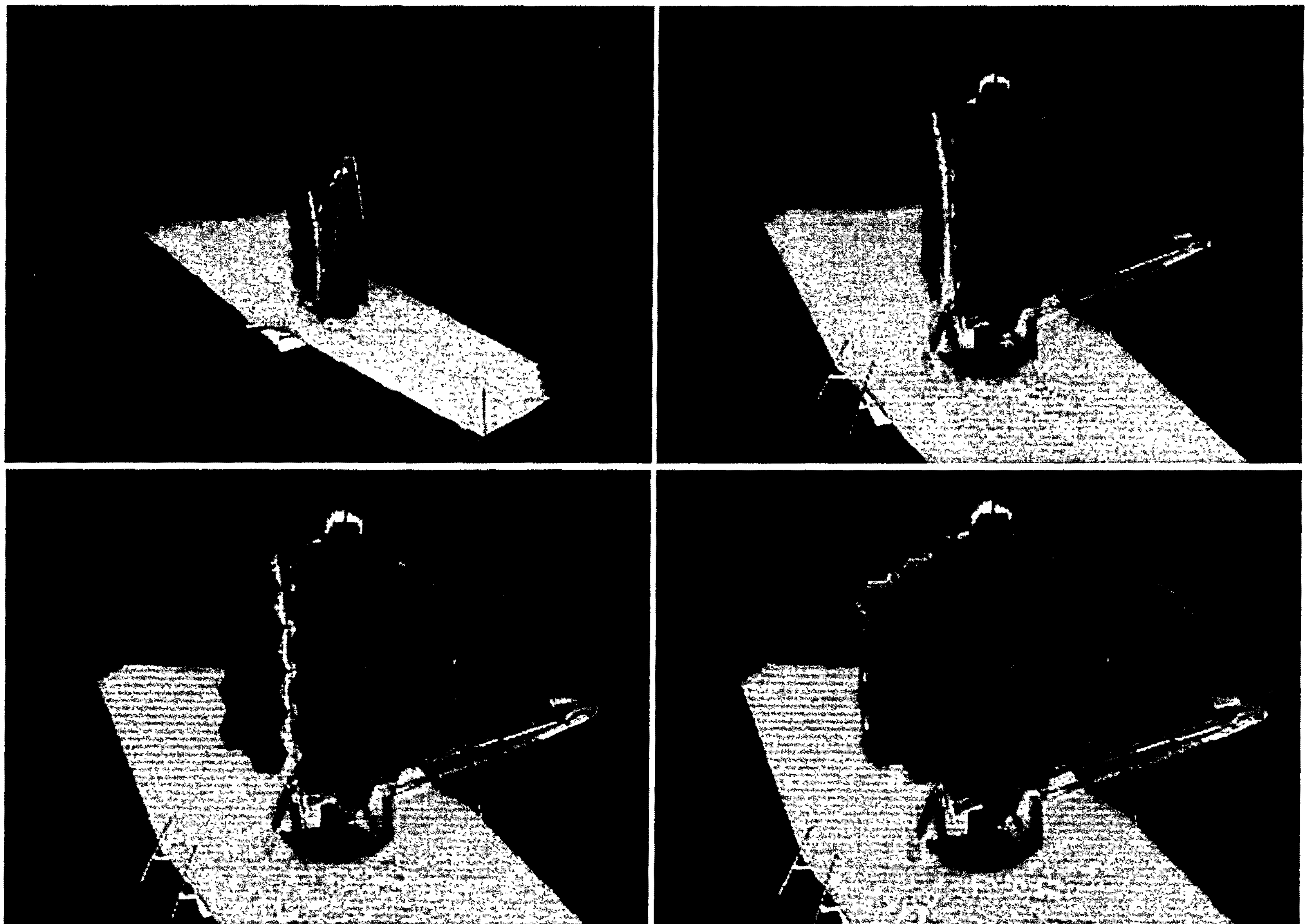
Segmented-Mirror Deployment



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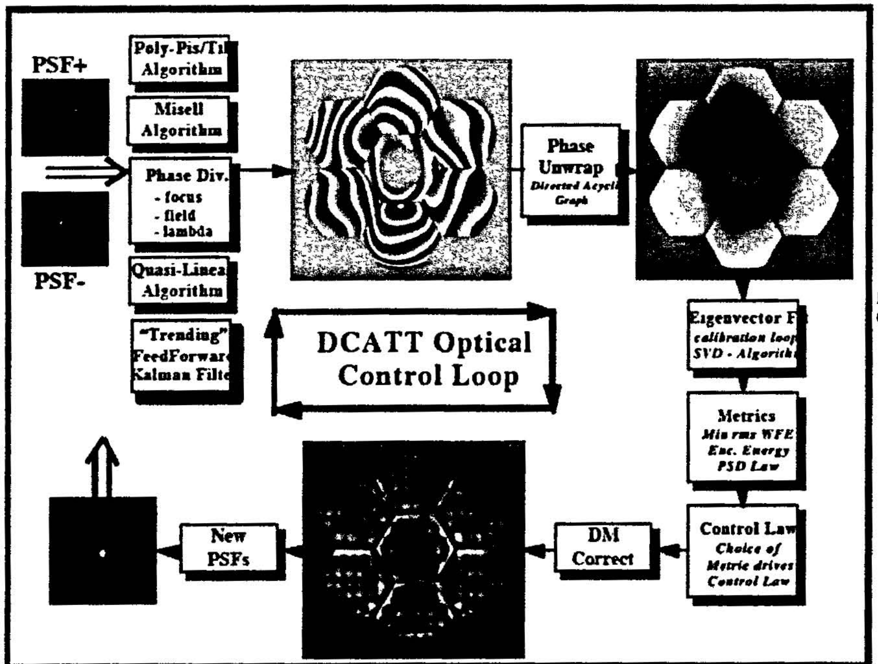
Phase Retrieval for JWST



R. Lyon et *al.*, (GSFC)

Figure 3: Estimates of the JWST OPD from the ±2 wave defocus PSF pair (left) and the ±8 wave pair (right). As in Figure 1, the OPDs are shown with a linear intensity scale stretched over ±200nm

J. Green (JPL), B. Dean (GSFC) *et al.*, Proc. SPIE (Glasgow 2004)

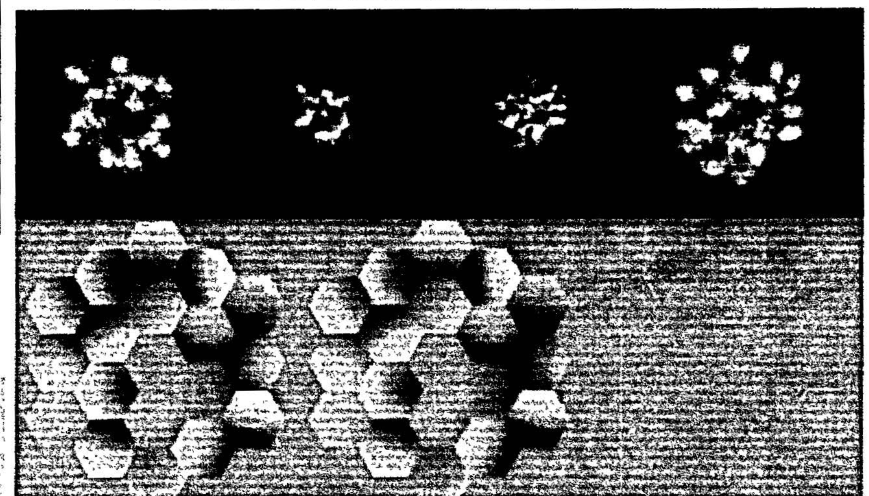


Figure 7. Fine phasing example. Top: simulated images with defocus values of −6, -3, 3, 6 waves PTV (log display). Lower left: the actual phase map (~250 nm rms). Lower center: estimated phase. Lower right: difference (~10 nm rms).

D.S Acton et *al.*(Ball Aerospace), Proc. SPIE (Glasgow 2004)

NASA has chosen phase retrieval as the fine phasing approach for JWST.

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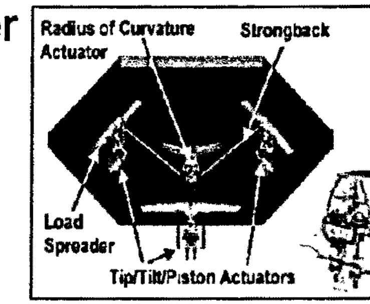
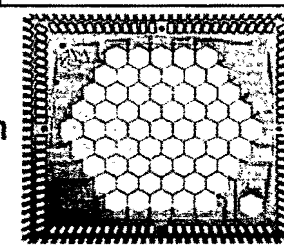
WFS at U of R
WaveFront Sensing Improvements

- Develop improved WFS (phase retrieval) algorithms
  - Faster, converge more reliably, less sensitive to noise, 2π jumps
  - Work with larger aberrations, broadband illumination, jitter
    - Refining iterative transform, gradient search algorithms
    - Increase robustness and accuracy
  - Extended objects
    - Phase diversity
    - Phase retrieval performance

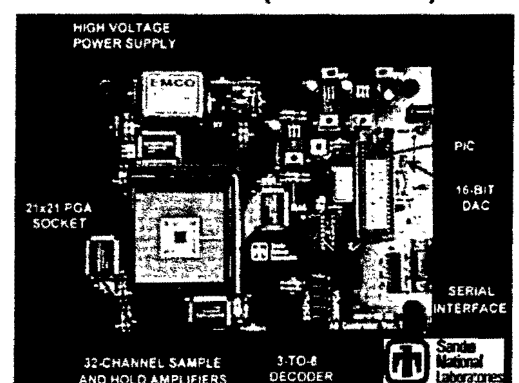


- Experiments with U of R telescope laboratory simulator
  - Adaptive optics MEMS deformable mirror
  - Interferometer measure wavefront independently
  - Put in misalignment, reconstruct wavefronts, compare with interferometer "truth"

4 mm



(metallized)



- 61 piston/tip/tilt hexagonal mirrors
- 497 μm diam. (polysilicon), 500 μm center-center
- 27 μm stroke
- 99% fill factor (polysilicon), 96% (metal)

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Conclusion

- Phase Retrieval found the correct prescription for HST
  - Getting all the physics into the algorithm key to accuracy
  - Was not fully trusted by NASA
  - Hubble repair successful

- NASA has chosen phase retrieval for fine phasing of JWST
  - Key component in the system operational concept

Questions?