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NGST Wavefront Control: Lessons Learned from DCATT and Nexus

Wood's Hole Meeting

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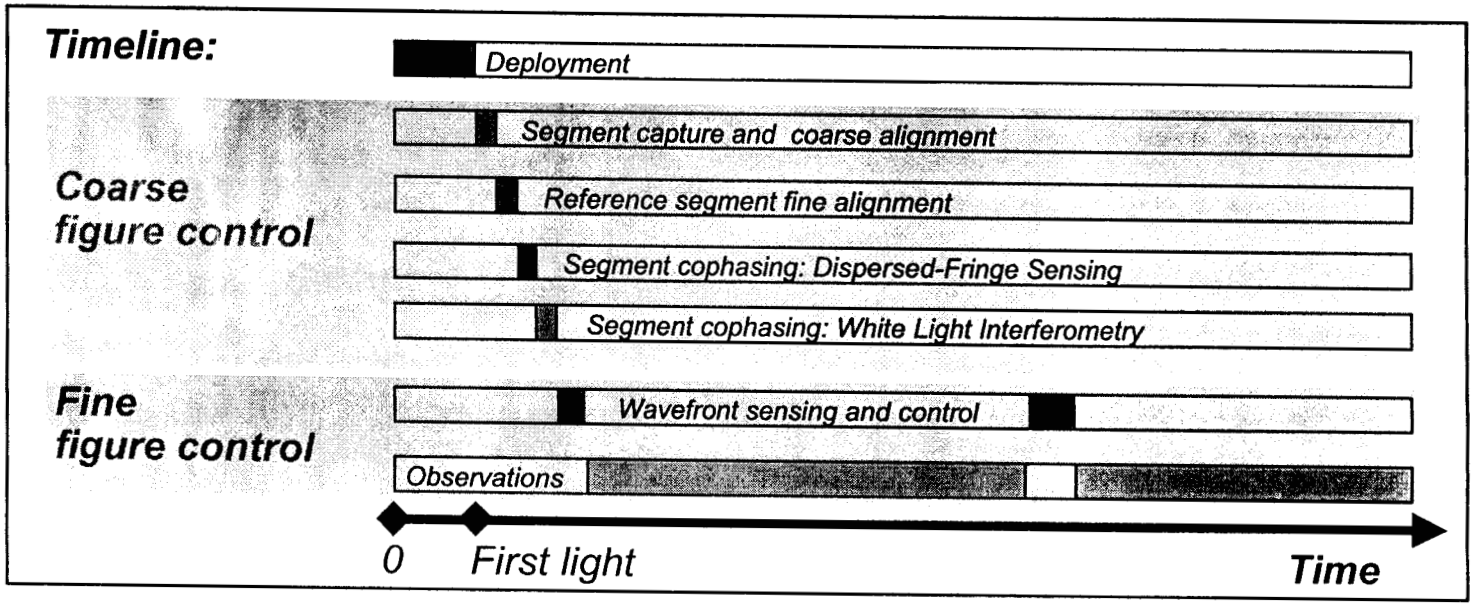
NGST Baseline WFC Summary

- WFC functions are performed using the science cameras
- Control is split into distinct phases:
  - Initial Capture, Coarse Align and Coarse Phasing control follows deployment
    - *WFE goes from cm to um*
  - Fine Phasing follows initial phasing
    - *WFE goes from um to nm*
  - Fine Phasing is repeated throughout the mission
    - Dedicated observations or simultaneous with science observations, using other camera
- Benign environment, thermally-controlled structure, vibration isolation provide required stability during observations w/o active WFC



Changes...

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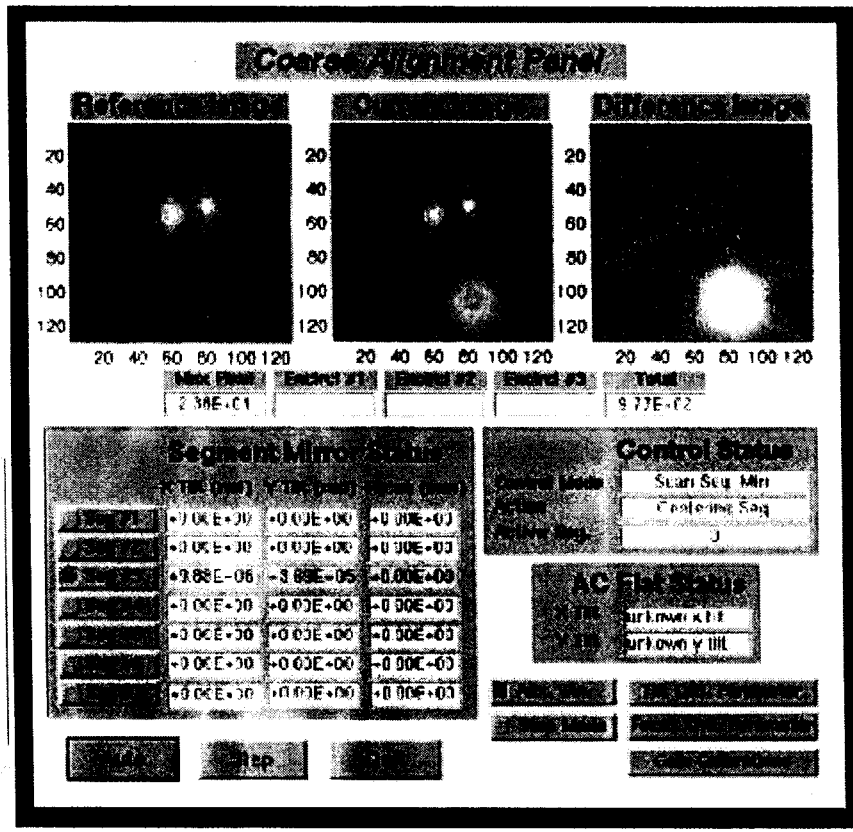
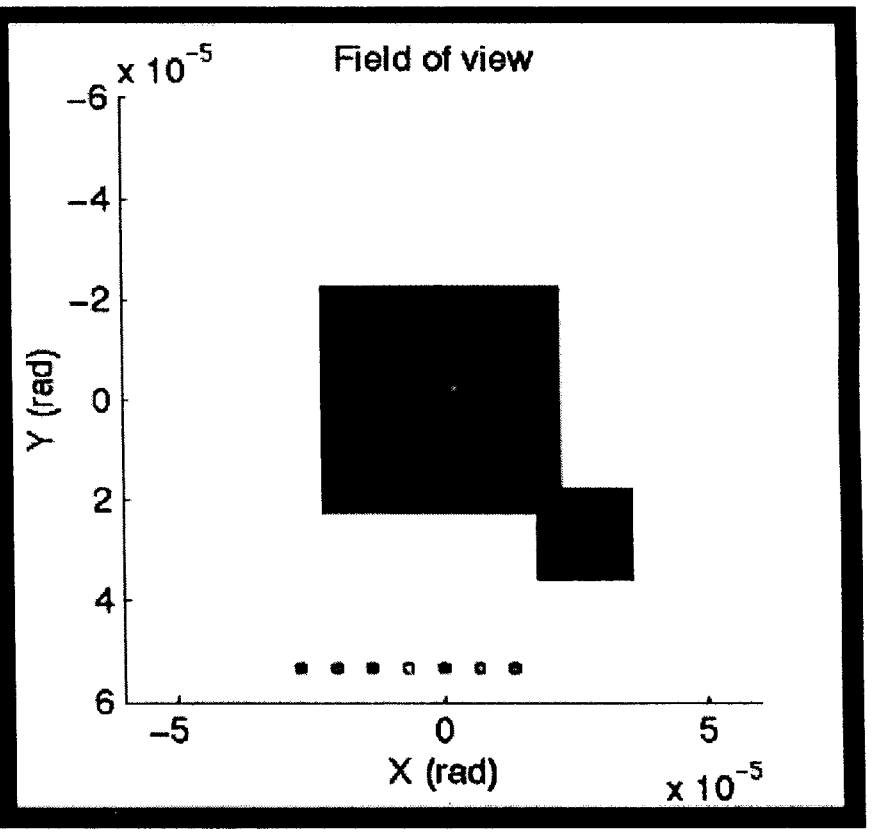
- DCATT has provided some interesting lessons...
  - Good: Fine Phasing using phase retrieval works well!
  - Bad: have had hardware problems…
    - Open-loop actuator precision and repeatability problems
      - Sequential vs. pair-wise Coarse Phasing
    - Larger-than-expected PM figure errors
      - Phase retrieval dynamic range
- Nexus/Horizon proposal has forced some issues…
  - Ground vs. on-board processing
    - Batch vs. serial operation during Capture, Coarse Phasing

Initial Capture

- While observing a bright, isolated star...
  - Segment is tilted slightly, frames differenced, and difference frame is thresholded
  - If difference exceeds threshold, spot is centroided, and the spot is driven to the center of the field
  - Otherwise, scan segment to next (4 amin) FOV and repeat





DCATT Coarse Alignment control panel*. Shows previous (reference) image, current image, and the difference frame. During Capture, the difference image is thresholded to detect the segment, and then centroided to find segment location. Segment is then driven to middle of the FOV.*

Aux Window*, shows FP (red) and segment spots (small squares). The focal plane is shown to move as the segments are scanned during Capture.*

WFE goes from 1 cm to 100's of um

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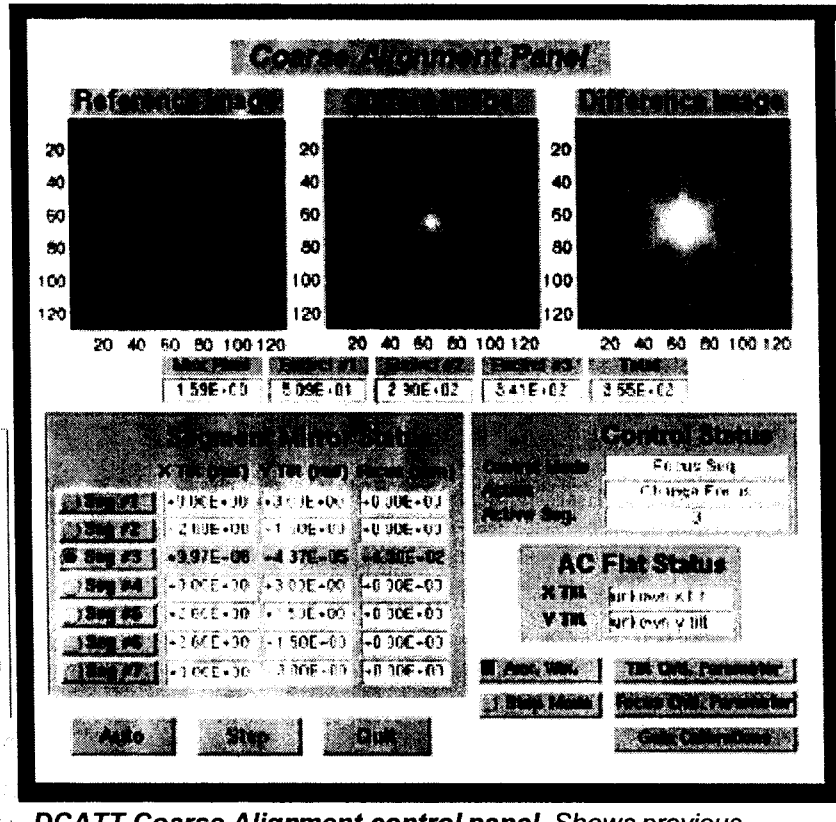
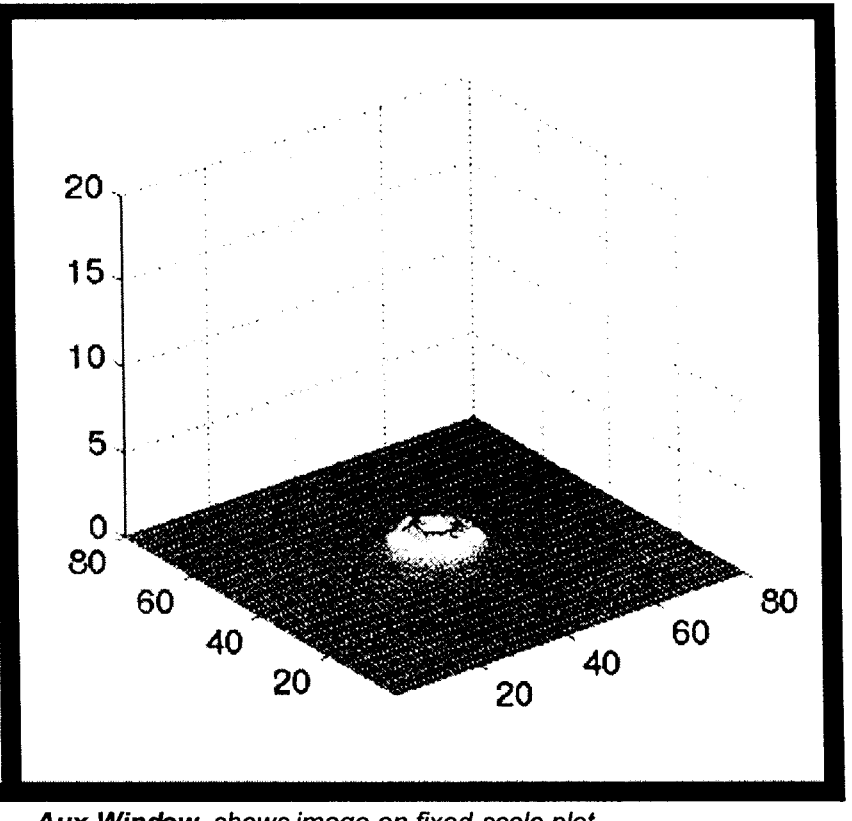
Coarse Alignment

- Align and focus each single segment
  - Segment is scanned in focus and encircled energy is recorded
  - Realigned as necessary to keep spot centered
  - Segment placed at best focus, then tilted away
  - Repeat for each segment



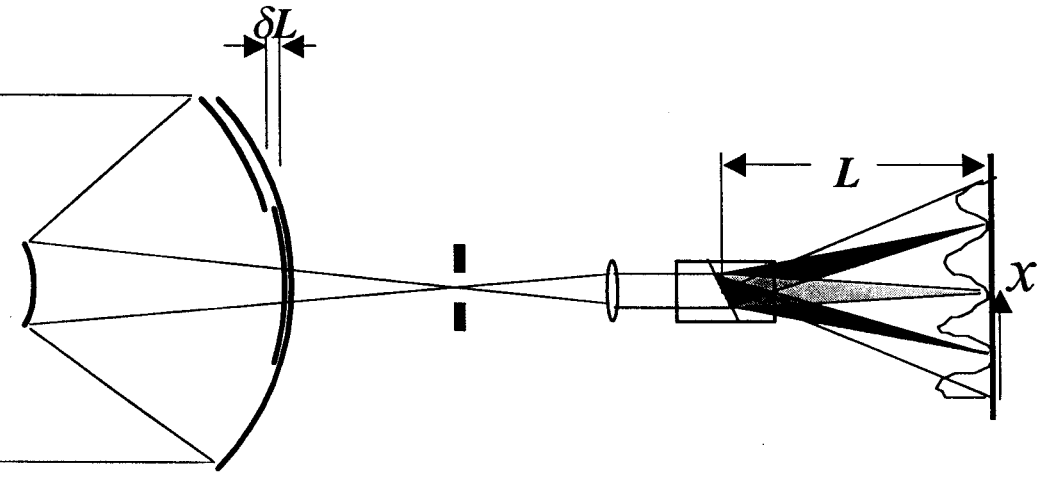


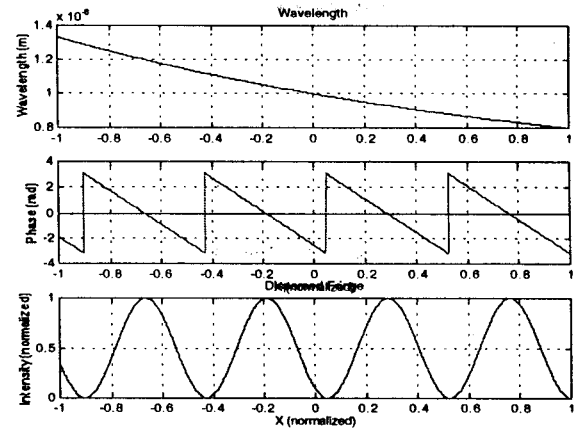
DCATT Coarse Alignment control panel. *Shows previous (reference) image, current image, and the difference frame. During Coarse Alignment, shows segment spot during focus and tilt scans. Status windows show amount segments are moved, control action, etc.*

Aux Window*, shows image on fixed-scale plot.*

WFE goes from 100's of um to 10 um

Dispersed-Fringe Sensor





GRISM interferometry...

- **Begin by coaligning 2 segment spots**
- **Then rotate grism into beam to form Dispersed Fringe Sensor (DFS)**
- **Phase difference δL is modulated by wavelength (which varies with x), causing dispersed spots to interfere**
- **Field at any x on detector sums contribution from 2 dephased segments:**

$$E = E_0 \exp(i\,(2\pi/\lambda(x))\,L)\;\;(1 + \exp(i(2\pi/\lambda(x)\;\delta L)$$

- **Fringe spacing along x is inversely proportional to δL**
- **DFS in operation at Palomar Testbed Interferometer**

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Coarse Phasing: Dispersed Fringe Sensor

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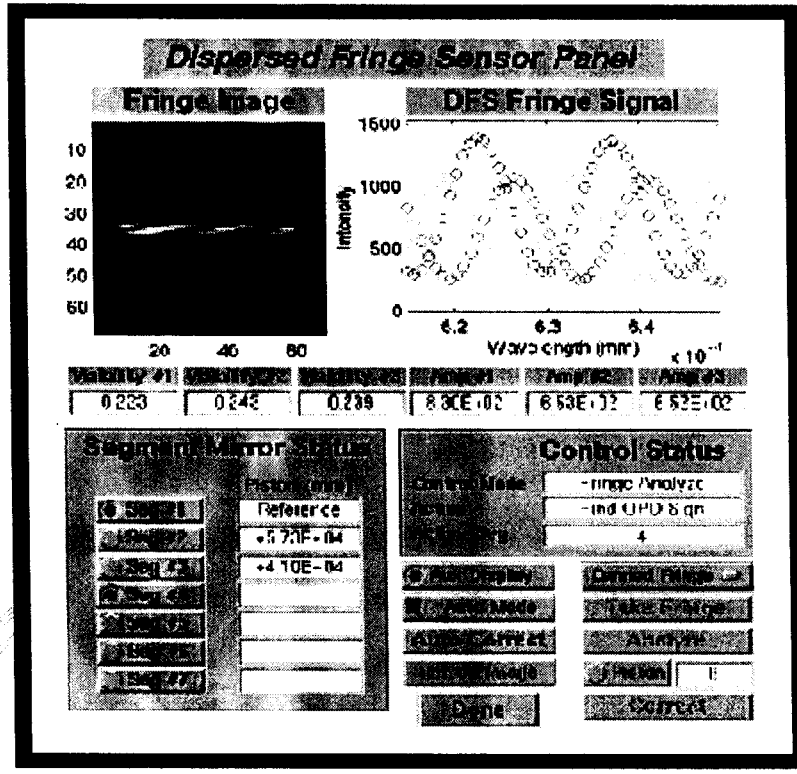
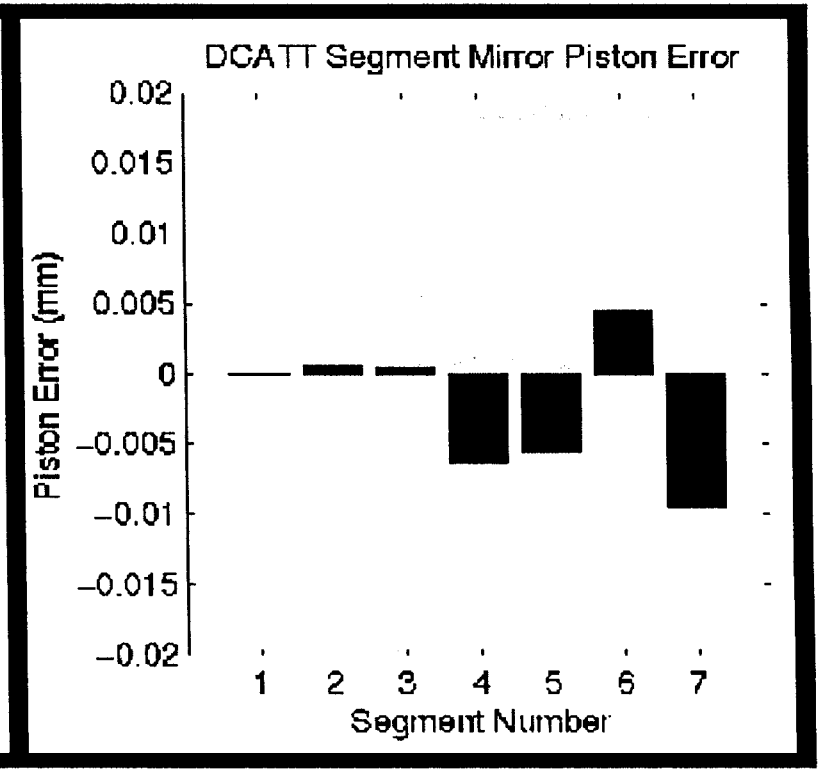
- Coarse phasing using the Dispersed Fringe Sensor puts the light from 2 segments (reference segment and an outer segment) through a grism, which modulates the optical pathlength difference by varying wavelength, producing interference fringes
  - Fringes are analyzed to find spacing, compute piston control
  - Sign of piston determined from angle of fringes
  - If fringes are faint, segment is pistoned to improve visibility, then controlled



DCATT DFS Panel. Shows fringe images taken using science camera with grism in place and 2 segments aligned to interfere. Also shows results of fringe analysis (sine curves). Status windows show amount segments are moved, control action, etc.



***Aux Window**, shows true piston error. Updates as segments are moved.*

WFE goes from 500 um to 0.5 um

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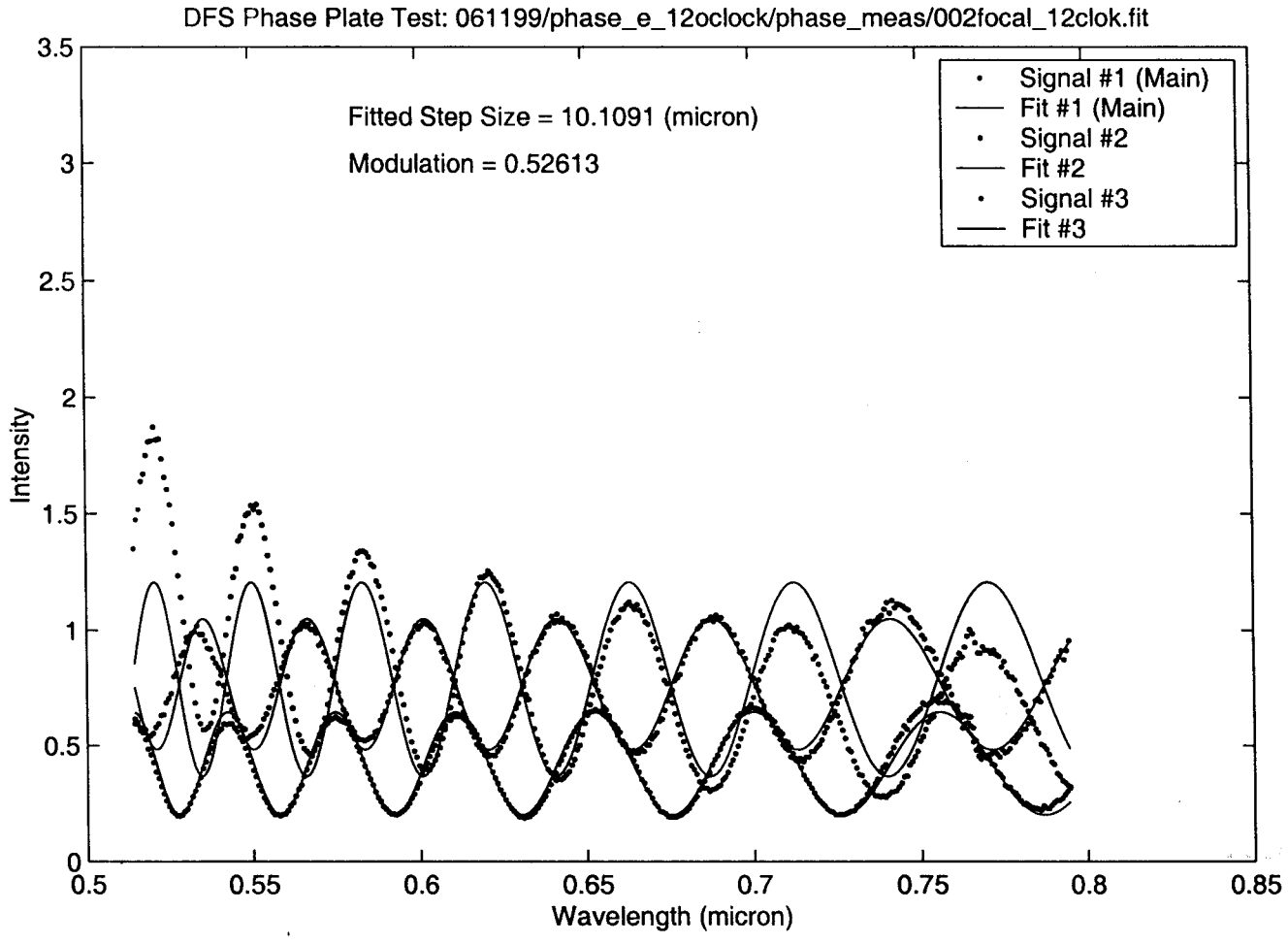
DCATT DFS Data



- DCATT DFS using transmissive phaseplate
- Manufactured step size: 10.0 um
- Measured step size: 10.11 um
- Modulation: 0.53

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Coarse Phasing: White Light Interferometry

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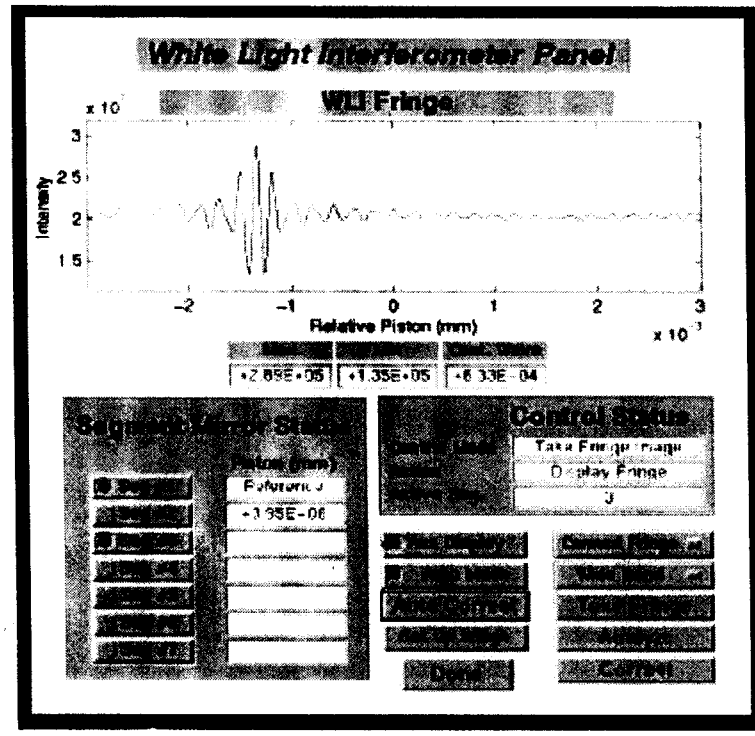
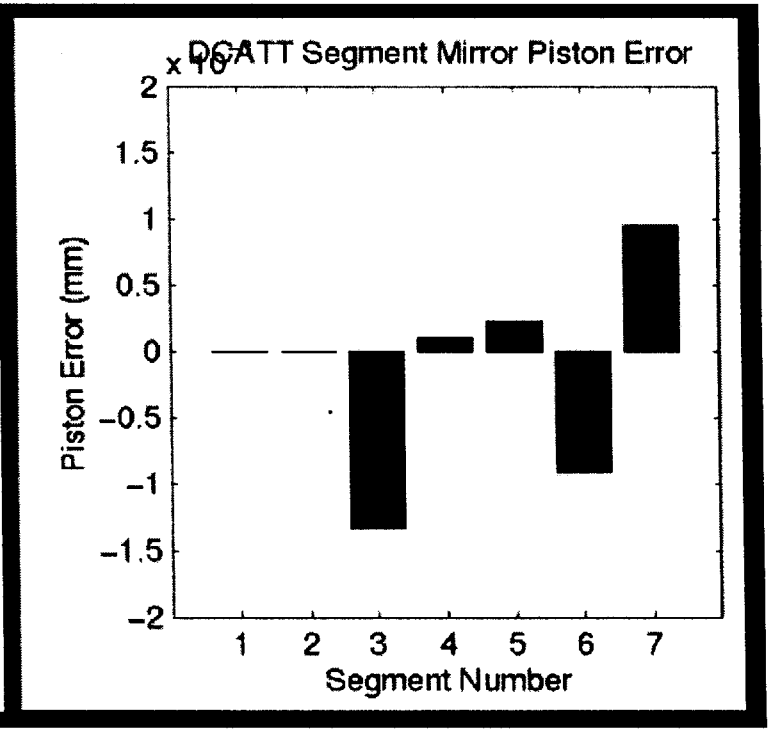
- Coarse phasing using White Light Interferometry follows DFS
  - Coalign center and 1 outer segment
  - Scan outer segment in piston, record peak intensity as a function of position to generate fringes
  - Peak of fringe occurs at co-phased position, and is identified by correlation filter
  - Segment is driven to position determined by correlation
  - Process is repeated for each segment



Shows fringe taken by scanning outer segment relative to fixed center reference segment and recording peak value. Also shows results of fringe analysis. Status windows show segment position, current control mode and action, etc.



Aux Window, shows true piston error. Updates as segments are moved.

WFE goes from 20 um to 0.1 um

Fine Phasing: Phase Retrieval WF Sensing

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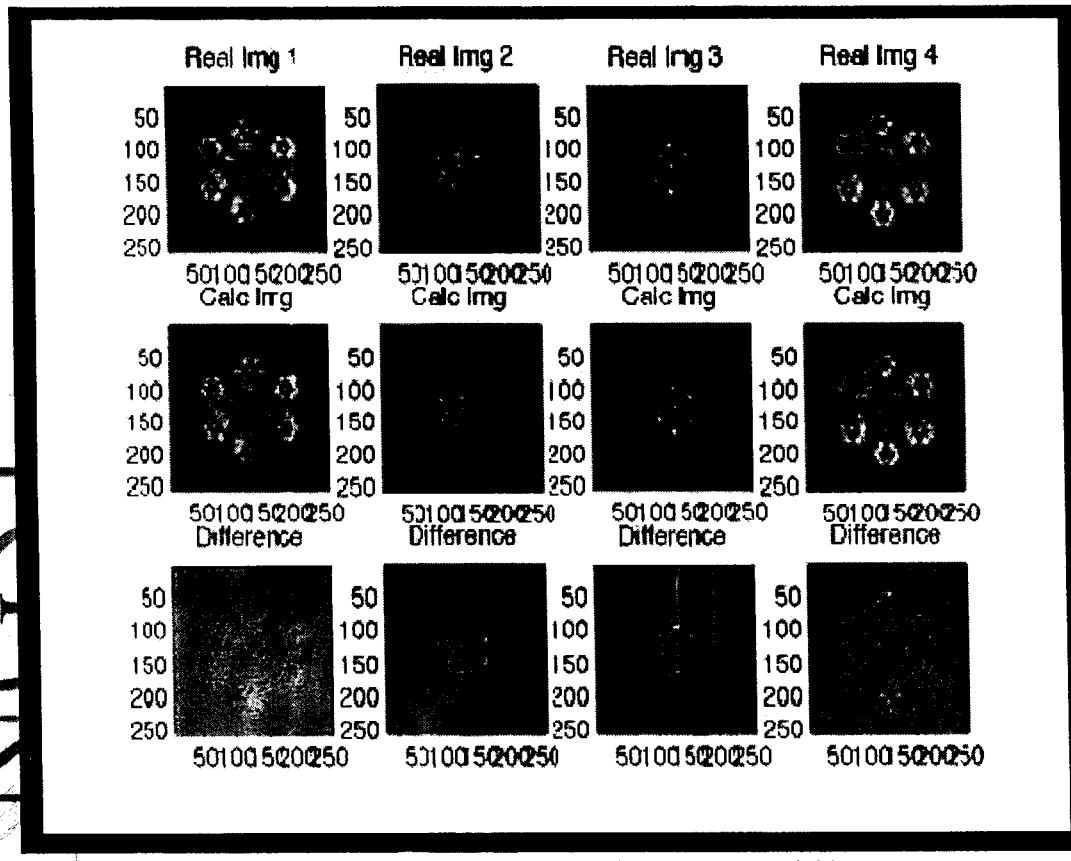
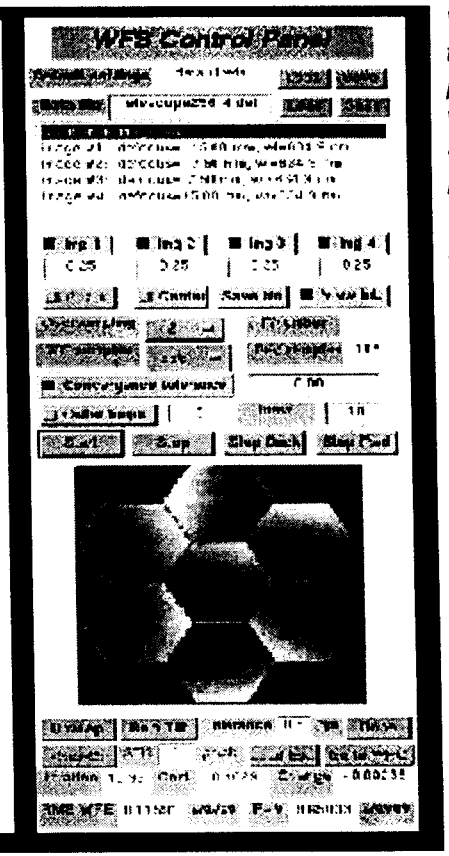
- After coarse phasing at the beginning of the mission, and then periodically during the rest of the mission:
  - Fine phasing uses phase retrieval WF sensing to estimate WFE at thousands of points across the pupil
  - Phase retrieval analyzes defocussed star images
  - On completion of WF estimate, next step is WF Control (next slide)





WFS Panel is used to select images for processing, set weights and other algorithmic parameters, and run the phase retrieval processing. The evolving pupil estimate is updated in the picture frame. It starts with a random guess, but quickly converges to correct estimate.

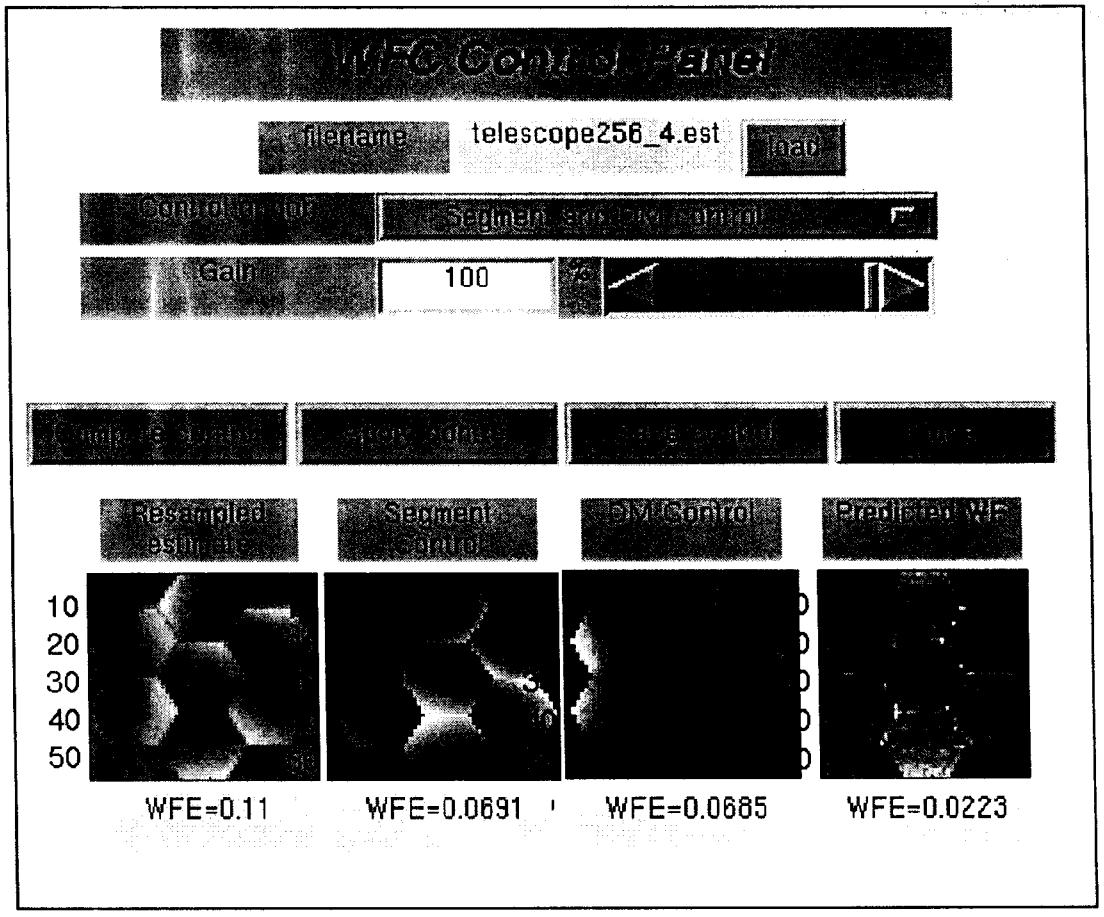
Aux Window, shows data images (top row), evolving model images on which estimate is based (middle row), and the difference frames (bottom row).

Fine Phasing: WF Control

- **Following WF sensing...**
  - **WF estimate is used to compute optimal segment and DM controls**
  - **Segment and DM are actuated settings to minimize final WF error**

WFC Panel is used to select control option, set weights and other algorithmic parameters, compute the new segment and/or DM settings, and apply them. Selection of control type is made in the "Control option" pull-down menu; predicted results are displayed in the pupil OPD frames. When all is as desired, the "Apply" button is pushed.

The movie shows controls for several different settings, of which the first (Segment and DM simultaneous control) is the best.



WFE goes from 2 um to 20 nm

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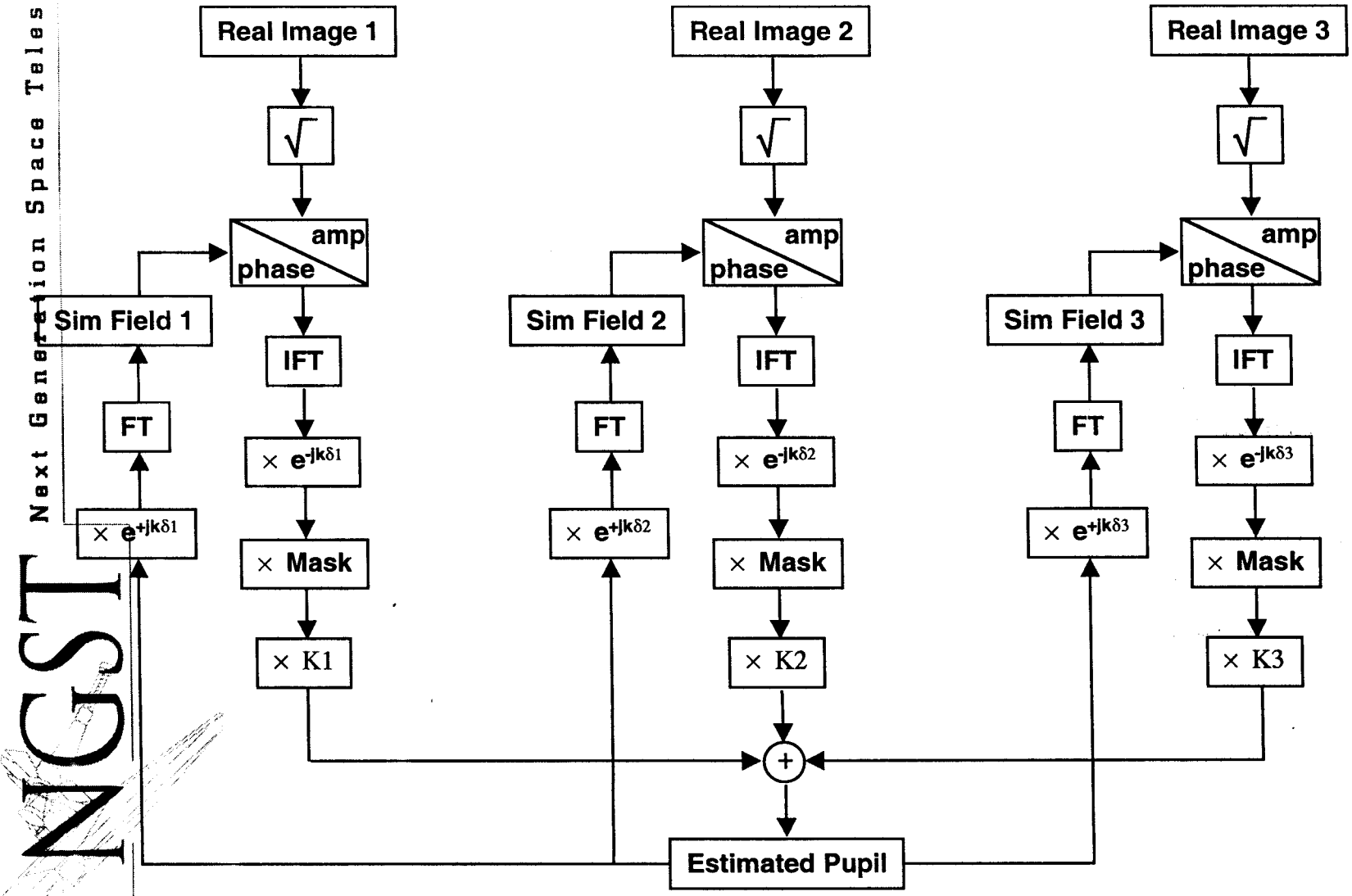
Focus-diverse iterative-transform phase retrieval



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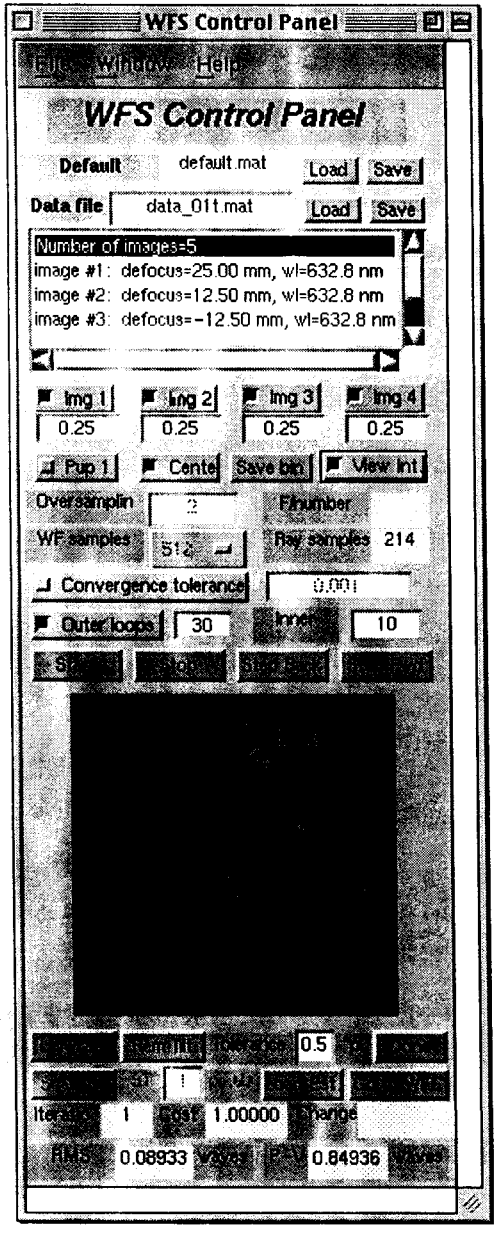
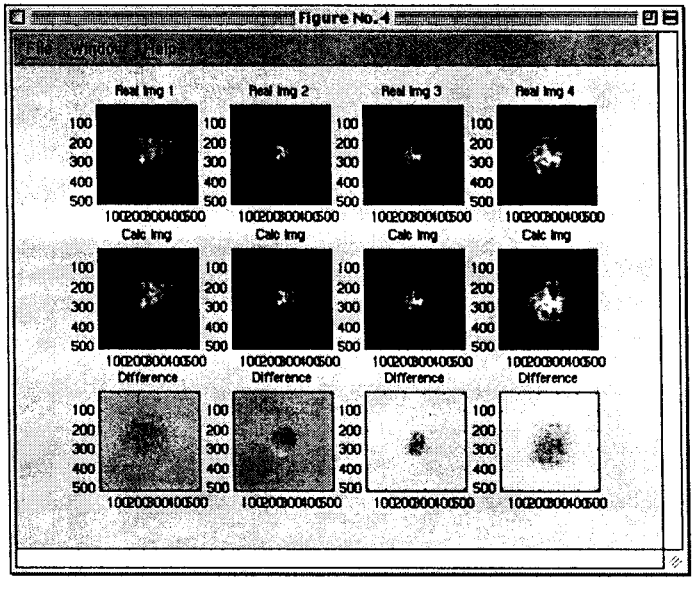
DCATT WFS Performance Summary





- Low WF sensing error
  - RMS for 10 estimates < $\lambda/110$ at $\lambda = 6328$ Å, 3 nm bandwidth
  - Comparison to Zygo within Zygo error bar
- Low wavelength sensitivity
  - Δ RMS < 6 nm, $\lambda = 5140, 6328, 7945$ Å
- Low bandwidth sensitivity
- Low jitter sensitivity
- Insensitive to pupil intensity profile variations when pupil image used in processing

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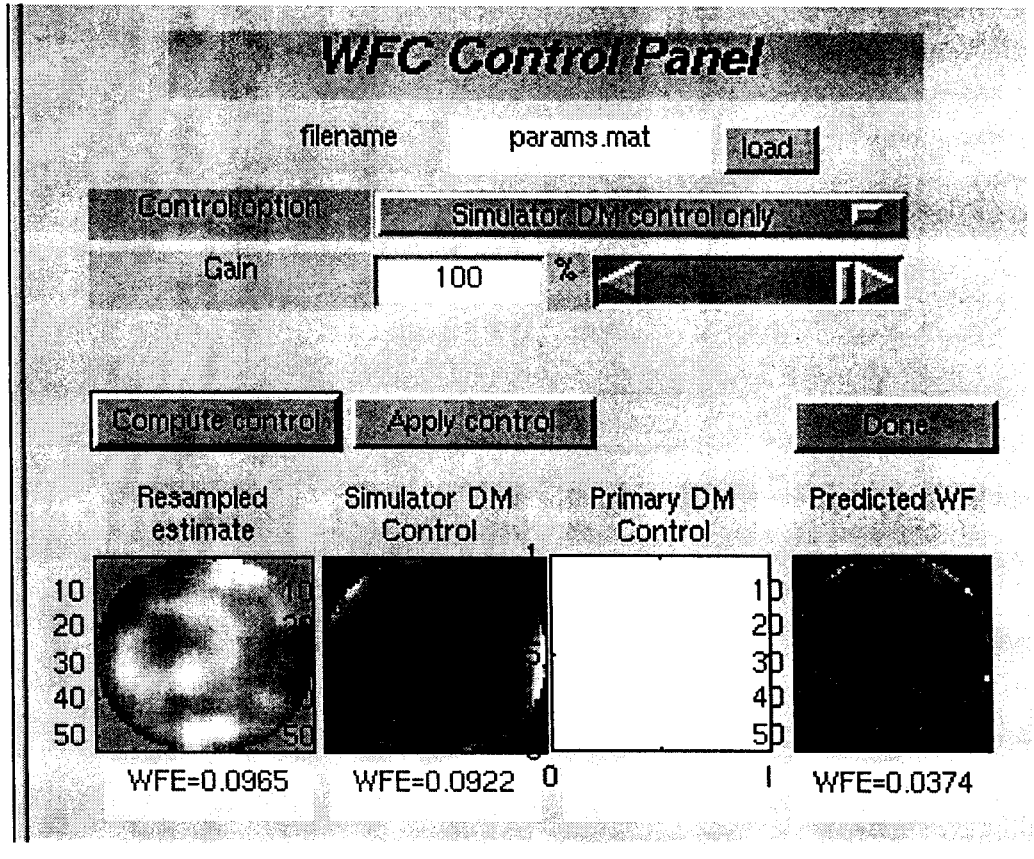
DCATT WFC Performance Summary



- Actuation-limited WF control performance
  - WFE = $\lambda/36$ at $\lambda = 6328$ Å
  - Remaining OAP figure errors beyond DM spatial frequency cutoff

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Data and Computation Requirements

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- Approximate numbers of images and floating-point operations required for various WFC operations

Operation	Images Needed	MFLOPS
Capture and Coarse Alignment	300	150
Coarse Phasing		
Cophase using DFS	30	40
Cophase using WLI	800	50
Fine Phasing		
Phase Retrieval WF Sensing	16	1,000
WF Control	0	10