Design and Manufacture of a Large Aperture Wavefront Sensor (LAWS)

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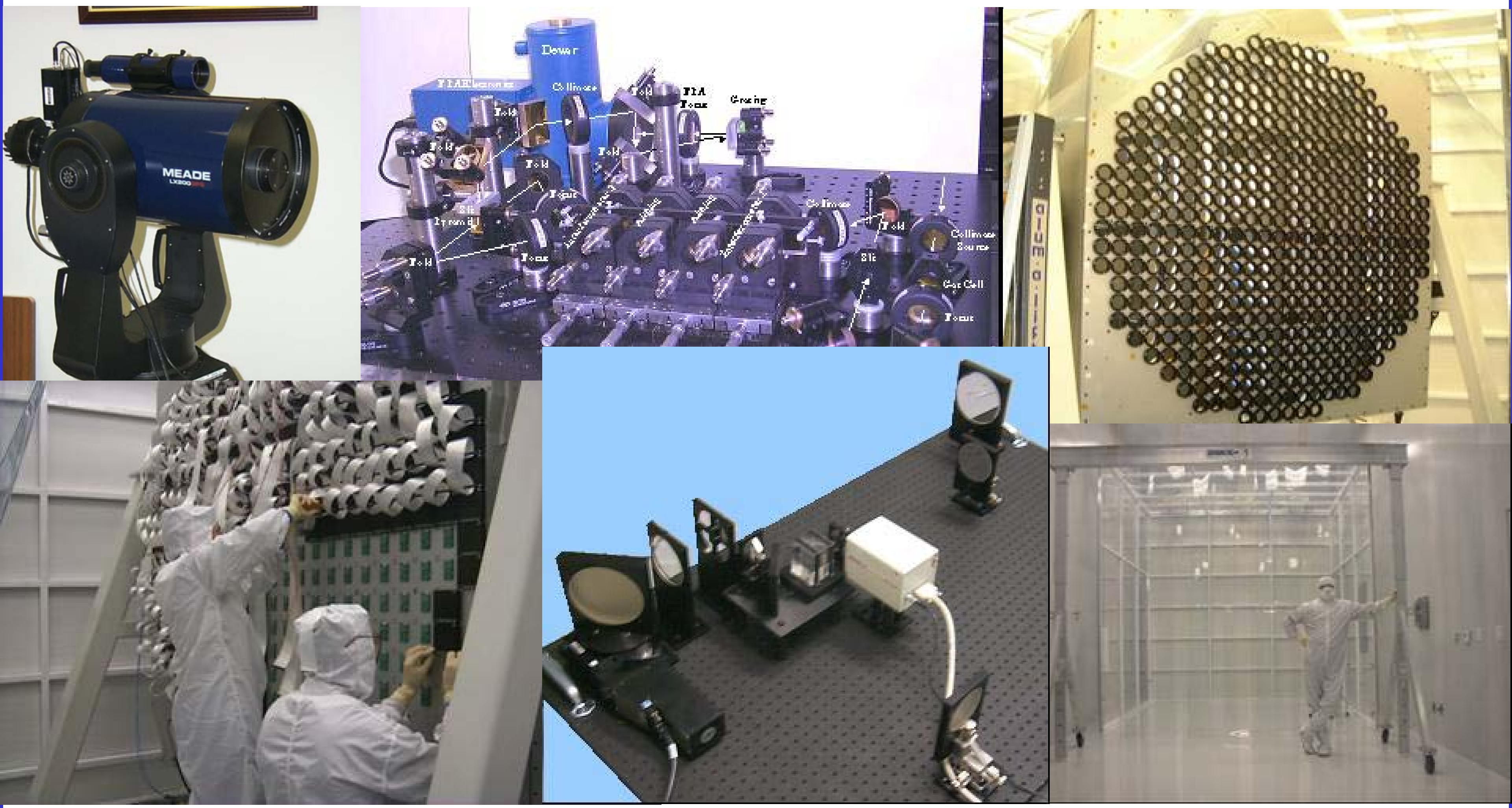
Large Aperture Testing

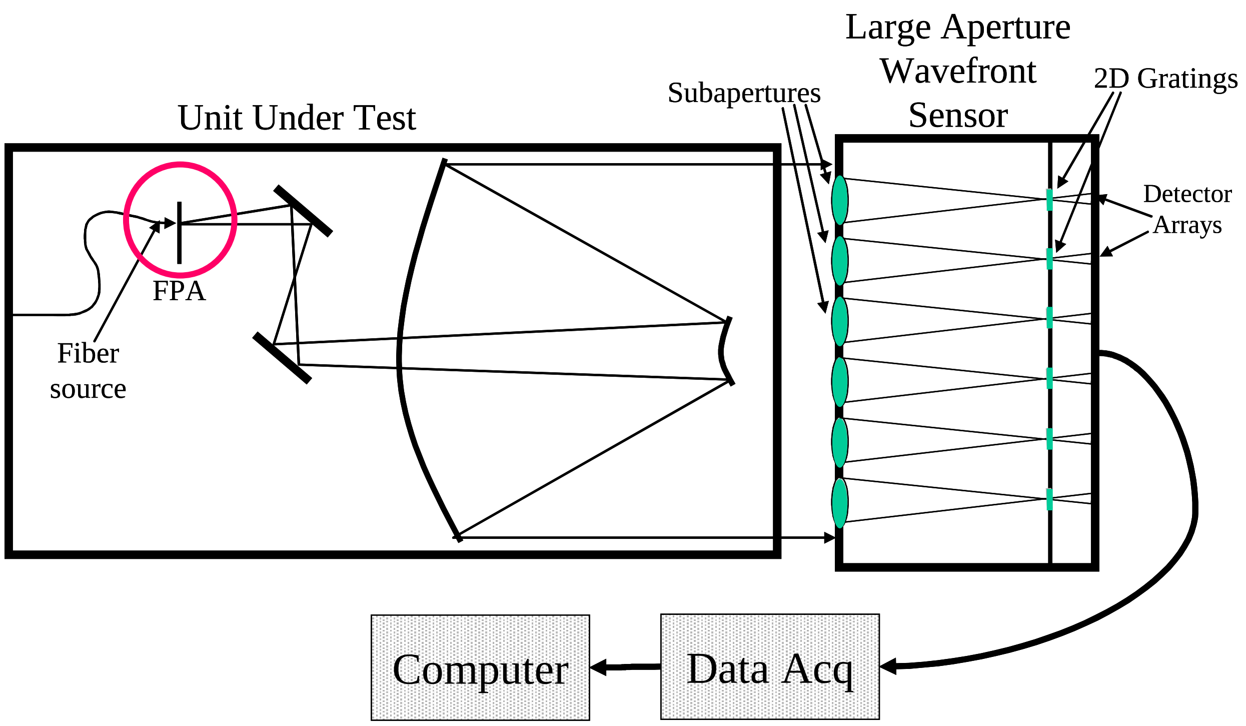
- There is an evolving requirement for ground testing large aperture optical systems
  - James Webb Space Telescope – 6.5 meters
  - Space-Based Lasers – 5-10 meters
  - Phased ground telescopes – 8-30 meters
- Should measure wavefront tilts and phasing errors
- Such large aperture test equipment can be extremely expensive and large to build
- OPC has developed a compact, cost-saving alternative
- Modular design for 2-10 meter systems

Seeing the world in thousands of colors

HyperSpectral Sensors and Large Wavefront Sensors



Hartmann Sensor with 5 millirad FOV

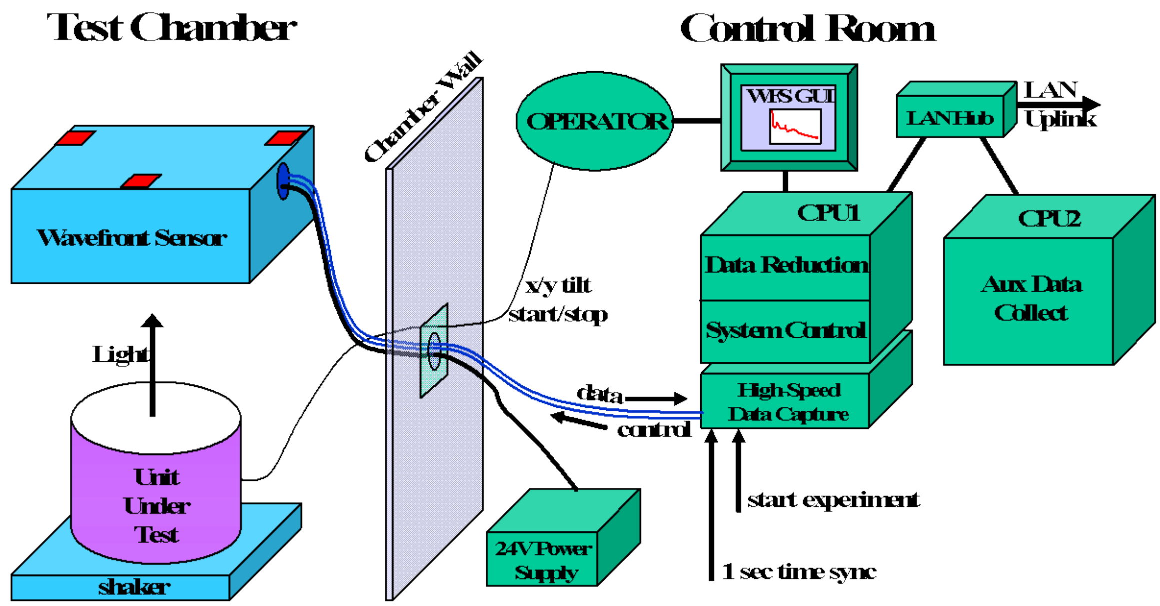


- The tilt of each subaperture is measured with a shearing interferometer (also measures phasing error)
- Just add a fiber source near the system FPA and the sensor can measure end-to-end wavefront

LAWS Specifications – First Module

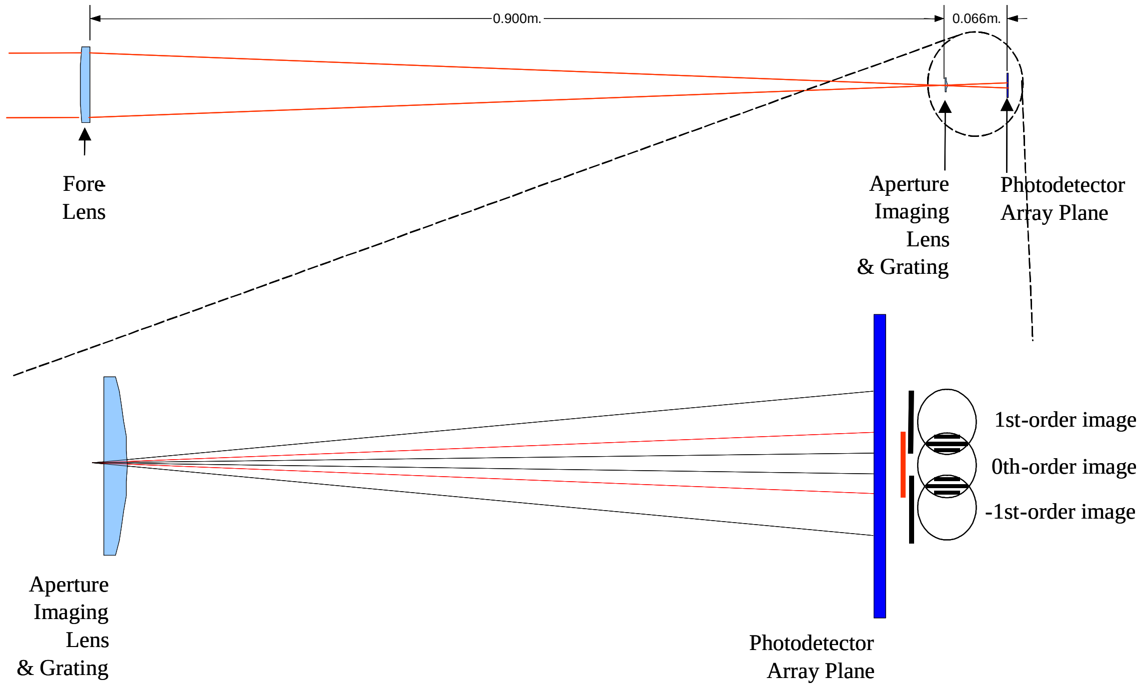
- 2.4 meter diameter aperture
- 448 subapertures (every 10 cm)
- 3.5 nanoradians rms subaperture noise at 4 kHz frame rate
  - Median noise 1.7 nanoradians rms
  - Phasing noise 0.12 nanometers rms
- Measure wavefront disturbances up to 2 kHz at a level of 1/1800 waves rms at 0.65 μm
  - Achieved 1/3800 waves rms at 0.65 microns
- Linear dynamic range of 5 milliradians for ease of alignment
- Second Generation Enhancement: Absolute wavefront to lambda/300 rms

LAWS System



- LAWS system includes the WFS, cabling, GUI control system, high speed data storage, processing software and external synchronization
- System is space clean and vacuum compatible

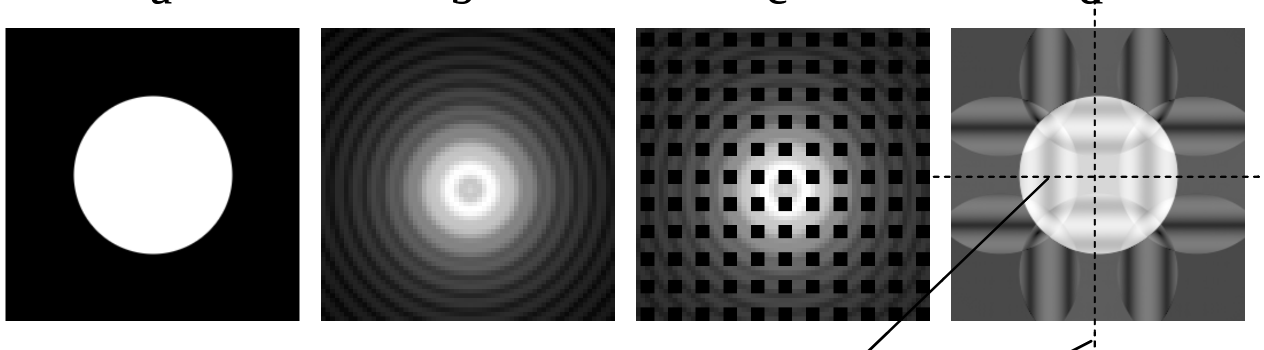
NanoTracker Sensor Design



- Subaperture tracker is a shearing interferometer for linearity and huge field of view (patent pending)
- Grating is on a plano-convex lens which re-images the fore lens onto the detector plane

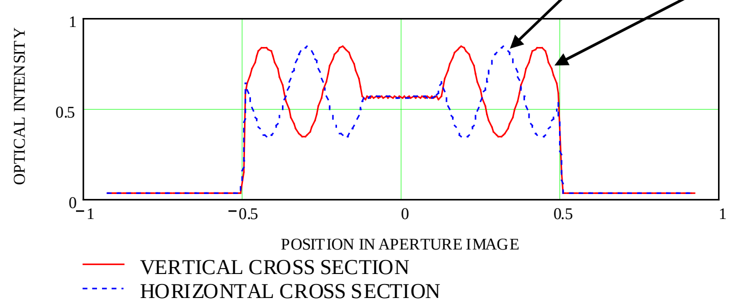
Shearing Interferometer Signals

a b c d



Aperture of Sensor Lens | Aperture focus at P-V defocus | 2D Rectangular Ronchi Grating at P-V defocus | Aperture Image with interfering orders

$$\gamma = \frac{\left((\mathrm{eff}_0)^{\frac{1}{2}} + (\mathrm{eff}_1)^{\frac{1}{2}}\right)^2 - \left((\mathrm{eff}_0)^{\frac{1}{2}} - (\mathrm{eff}_1)^{\frac{1}{2}}\right)^2}{\left((\mathrm{eff}_0)^{\frac{1}{2}} + (\mathrm{eff}_1)^{\frac{1}{2}}\right)^2 + \left((\mathrm{eff}_0)^{\frac{1}{2}} - (\mathrm{eff}_1)^{\frac{1}{2}}\right)^2} \approx 0.40$$



Amp(j,k) = 0.75 if j = k = 0

Amp(j,k) = $1/(\pi^2 jk)$ if both j and k are odd

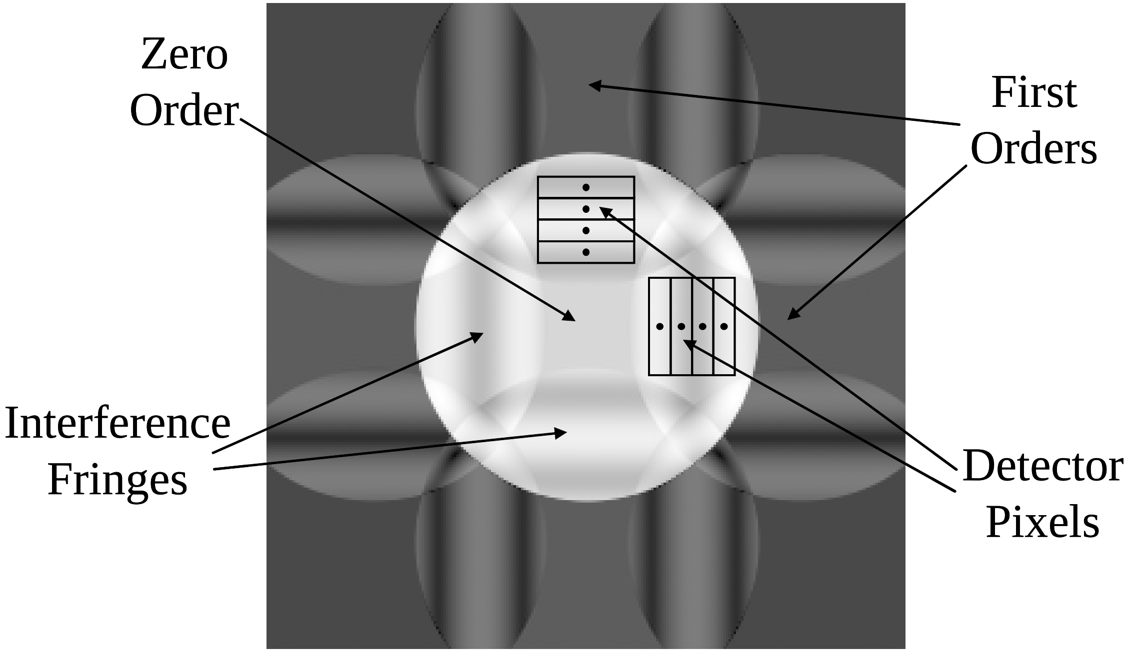
Amp(j,k) = $1/(2\pi j)$ if j is odd and k = 0

Amp(j,k) = $1/(2\pi k)$ if k is odd and j = 0

Amp(j,k) = 0 for all other values of j and k

- Subaperture beam passes through 2D grating about one wave out of focus
- Detector array is at image of fore lens
- 0 order interferes with +/- first orders for sinusoidal fringes

NanoTracker Phase Processing



$$\phi_{tilt} = \arg\left[\sum_{j=0}^{3}\left(Wt_j \cdot S_j\right)\right]$$

- Each axis has four photodiodes
- The phase of the sine wave is found using sum of the four intensities with complex weights
- Exact values of the weights are determined by a simple calibration operation where beam is scanned 25-100 μrads

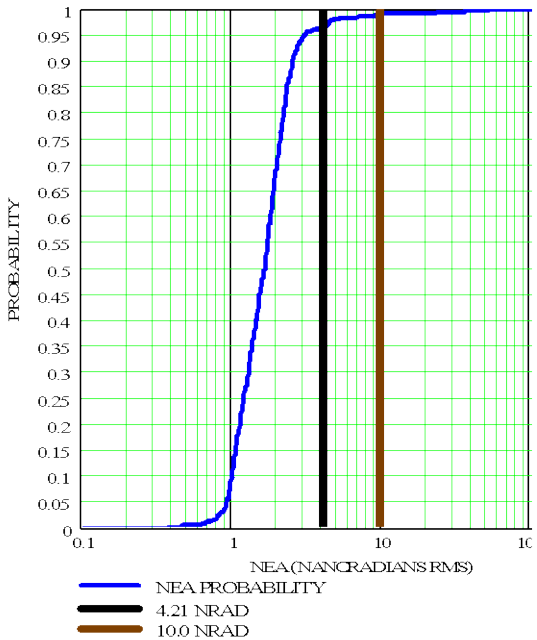
LAWS Calibration

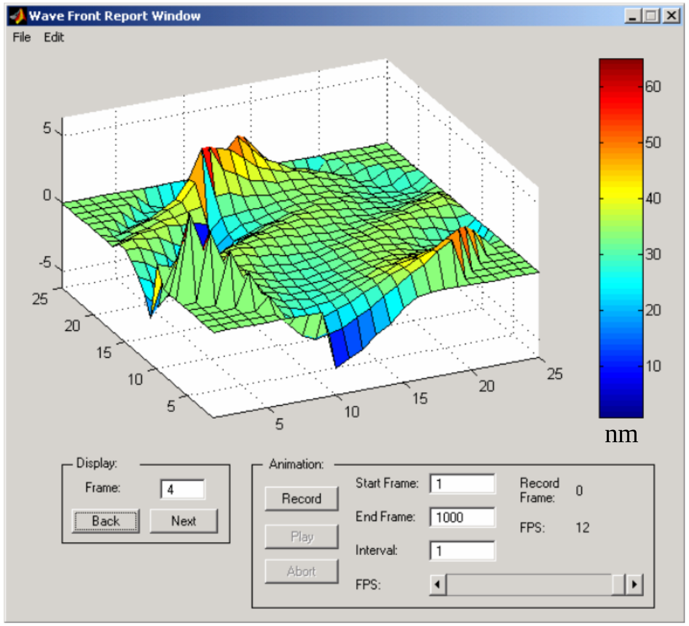
$$E = \sum_{j=1}^{4} \left(\left| \mathrm{Wt}_j \right| \right)^2 - \mu \cdot \sum_{j=1}^{4} \mathrm{Wt}_j \cdot \mathrm{DC}_j - \nu \cdot \left(\sum_{j=1}^{4} \mathrm{Wt}_j \cdot \mathrm{M}_j \cdot e^{\mathrm{li} \cdot \phi_j} - e^{\mathrm{li} \cdot \phi_2} \right)$$

$$\mathrm{Wt}_k = \frac{ - \left(\sum_{j=1}^{4} \mathrm{DC}_j \cdot \mathrm{M}_j \cdot e^{-\mathrm{li} \cdot \phi_j} \right) \cdot e^{\mathrm{li} \cdot \phi_2} \cdot \mathrm{DC}_k + \left[\sum_{j=1}^{4} \left(\mathrm{DC}_j \right)^2 \right] \cdot e^{\mathrm{li} \cdot (\phi_2 - \phi_k)} \cdot \mathrm{M}_k }{ \left[\sum_{j=1}^{4} \left(\mathrm{DC}_j \right)^2 \right] \cdot \left[\sum_{j=1}^{4} \left(\mathrm{M}_j \right)^2 \right] - \left(\sum_{j=1}^{4} \mathrm{DC}_j \cdot \mathrm{M}_j \cdot e^{-\mathrm{li} \cdot \phi_j} \right)^2 }$$

- Pixel dark calibration
  - Turn off source and average 100 frames
- Pixel phase calibration
  - Scan beam 25-200 μrads in each axis and solve for weights as shown above
- Gain calibration of the NanoTracker
  - Tell the processor how many microradians were scanned
  - No gain calibration is necessary for the phasing measurements
- Rotation calibration of the NanoTracker
  - Scan in the X and Y axes of the Unit Under Test
  - All data will then be presented in those axes

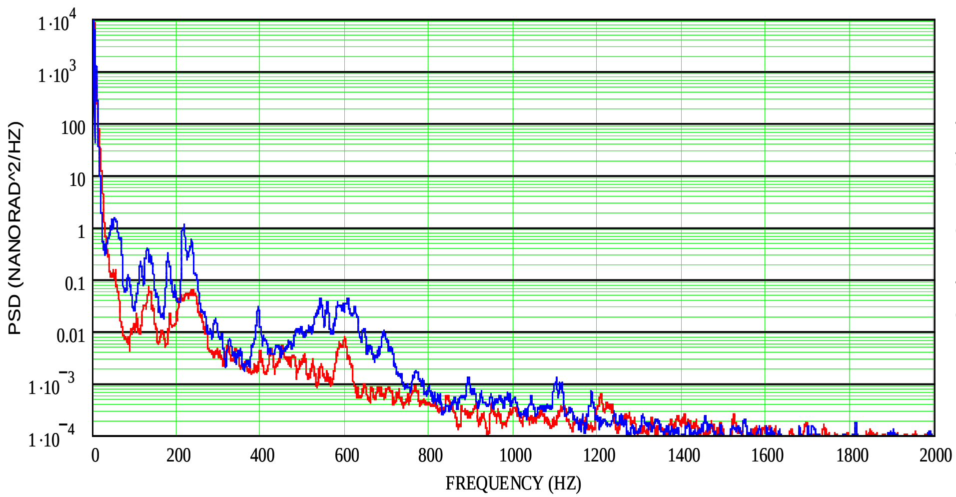
LAWS Test Results



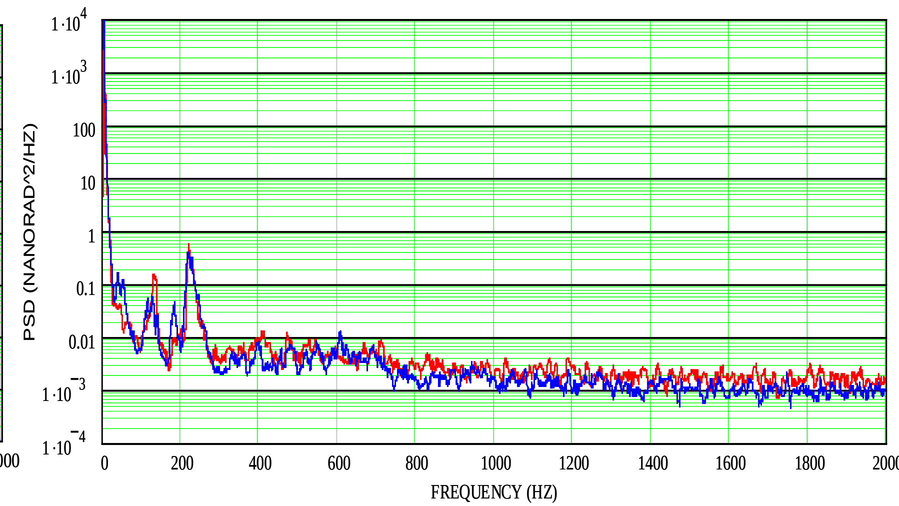


- Median subaperture noise was 1.7 nanoradians rms
- The sensor comes with a “flying carpet” display to show the dynamic wavefront

Sample Subaperture Tilt PSD's



Rush Hour in Calabasas with High Light Level



Night time in Calabasas with Low Light Level

- Sample PSD's are shown here taken under different seismic conditions
- LAWS resonances around 125 and 200 Hz are visible
- Noise floors are clear

LAWS Summary

- Modular WFS has been designed for 2-10 meter apertures
- First module has been built and tested for Kodak
  - 2.4 meter diameter, 448 subaperture
- 1.7 nanoradians rms mean noise at 4 KHz
- 0.1 nanometers rms phasing at 4 KHz
- 1/3800 waves rms wavefront accuracy at 4 KHz
- Second generation will have absolute wavefront accuracy of 1/300 wave rms
- Goal: Low cost, compact option for testing large optical systems