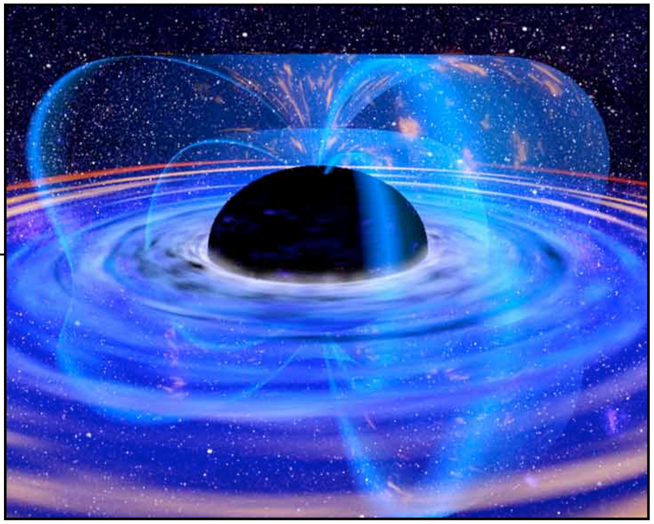
Suspension Mount and Alignment of IXO Mirror Segments



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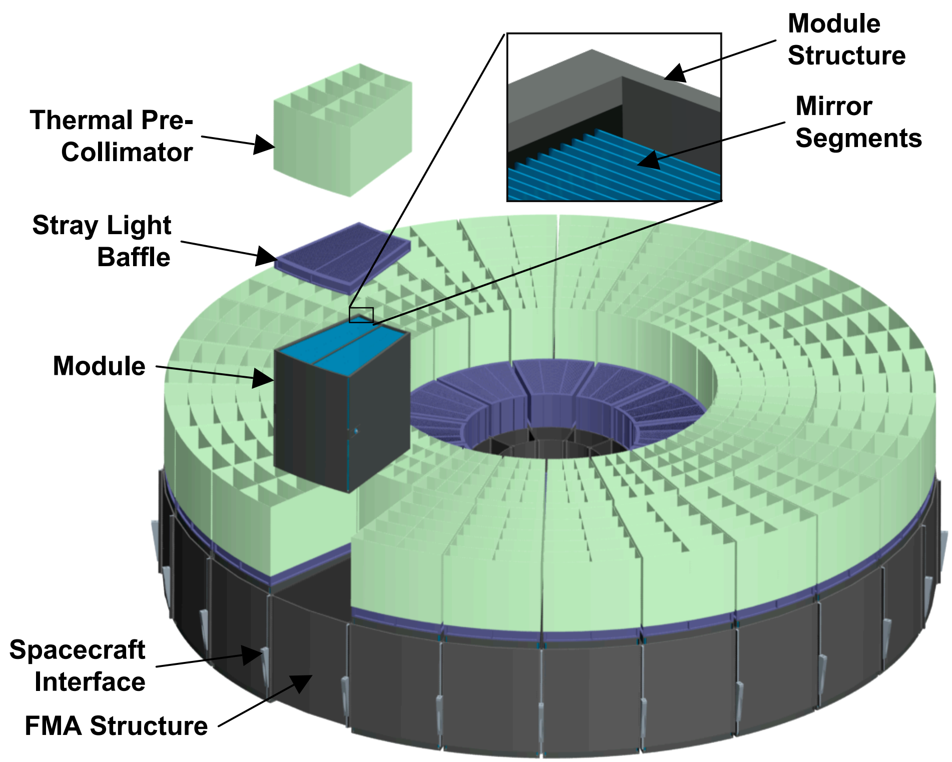
IXO Flight Mirror Assembly & Mirror Segments



The Flight Mirror Assembly as envisioned at NASA

- Telescope: Wolter-I
- Diameter: 3.3 m
- Modular/Segmented design: 30° (inner), 15° (middle, outer) modules

Mirror segments

- Material: glass
- Axial length/Height: 200 mm
- Radius = up to 1600 mm; azimuthal width 200 - 400 mm
- Thickness = 0.4 mm [Area density requirement ~ 1 kg/m^2, glass density ~ 2.5 g/cm^3]

Mirror Mounting

Major Sources of Mirror Segment Distortions

- Stress from thermal forming
- Surface stress from coating metallic film
- **Mechanical distortion from mounting of mirrors**
- Thermal stress from mirror mounts/housing
  - Due to CTE mismatch, or from temperature variations/differences
- Gravity sag in ground operations, and gravity release in space

Angular Resolution Budget

- 5.0" - Observatory requirement
  - 4.6" - Mirror assembly on-orbit performance
    - 4.0" - Mirror assembly as built and tested on ground
      - 3.8" - Mirror modules as built on ground
        - 3.6" - Pair of mirrors aligned and bonded in module
          - 2.4" - Individual mirror segments bonded (one reflection)
            - 2.2" - Individual formed mirror segments (one reflection)
              - 1.5" - Individual forming mandrel (one reflection)

Mounting Approach

- ***Mounting Approach pursued at NASA/GSFC: Preservation of the mirror figure***
  - No further adjustment of mirror figure during mounting (c.f. active adjustment of mirror figure)
  - Necessarily assume mirror figure meets requirement
  - Mounting technology can be developed independent of the quality/state of the mirror
- Mounting steps
  1. Temporary Mount: Capture the mirror's figure, distortion-free, onto a strongback
     - for transportation, metrology, alignment
  2. Permanent Mount: Align mirror (translations and rotations only), transfer to permanent housing, dismount from Temp-Mount
- Qualification of procedures
  - FEA of suspended and bonded mirror, optimization
  - Characterization of forces and local displacements in Temp-Mount and Permanent Mount
  - Testing
    - » Sub-aperture test of focusing
    - » Surface metrology between steps
    - » X-ray tests

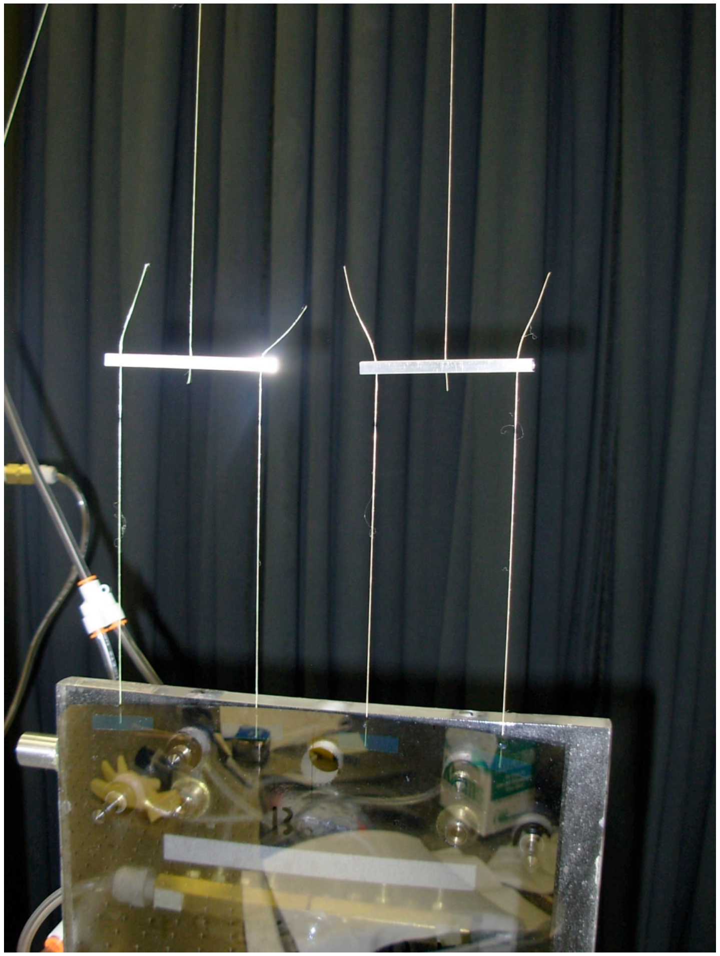
[redacted]

Temporary Mount:

To capture the figure of a mirror, without distortion

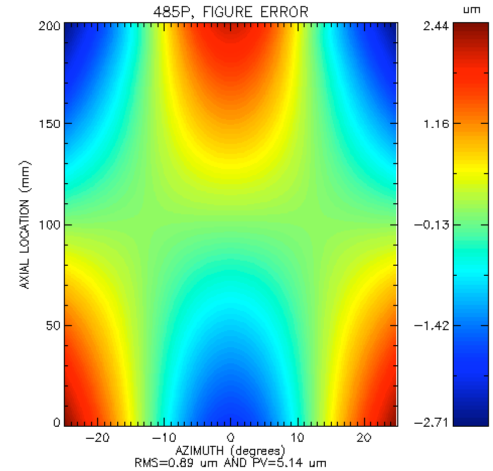
4-string suspension

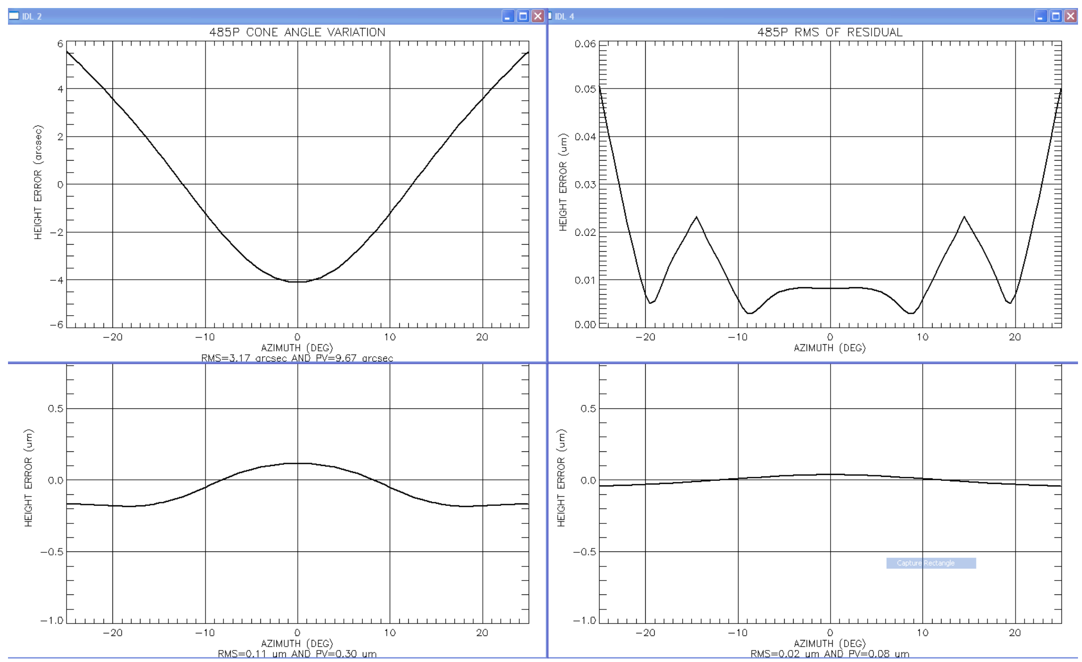
- 4-string implementation
  - Whiffle-tree type design with 2 additional cross-bars for string-length compensation
  - Automatic adjustment for tensions in strings
- FEM shows 4-string suspension meets requirement:
  - HPD < 1”, Radius variation < 0.1 μm, Sag < 0.01 μm
- From finite-element model, 2-string suspension is found to contain a cone-angle error, even when the mirror is hung vertically.
  - This error affects the optimal focal lengths of individual mirrors.
  - This error is also nulled from standard surface metrology (small change in null lens angle)
  - Errors from primary and secondary mirrors cancel each other



Remarks on 2-string suspension

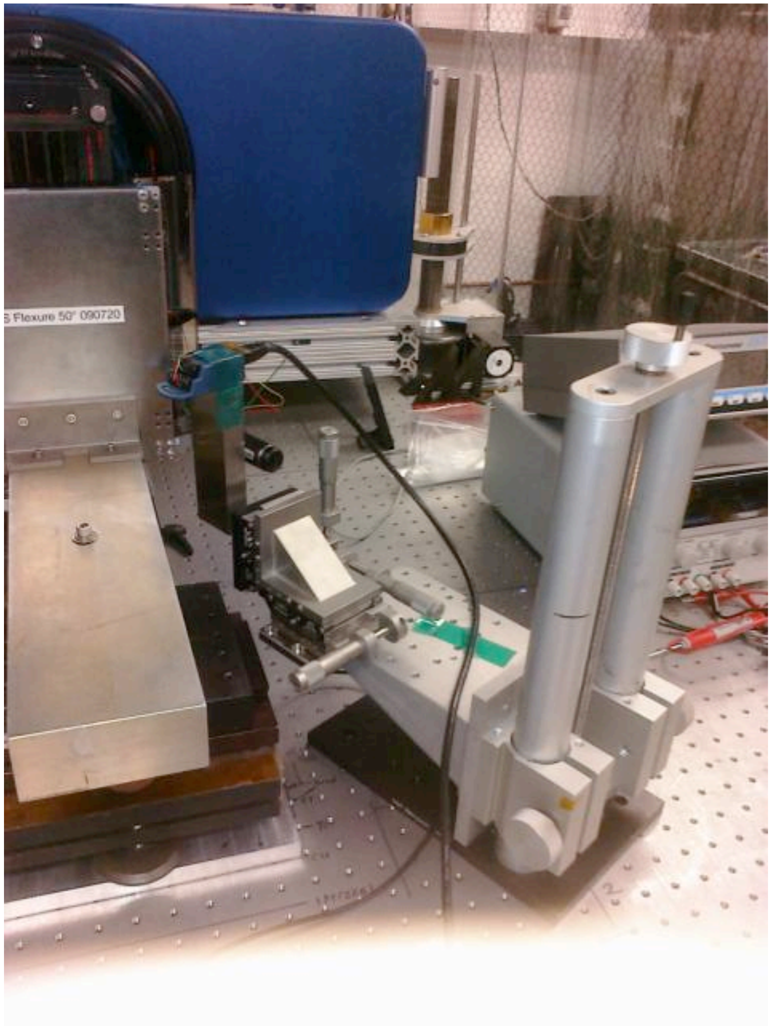
- **Model indicated a cone angle error even when mirror is vertical**
- **FEM:**
  - **Separation of 2-string is chosen so that the mirror is vertical (central meridian)**
  - **FEM shows even in this case there is a cone angle variation**
  - **Model HPD = 12”**
- **Models show independence of**
  - **Primary or Secondary mirror, or cone angle**
  - **Similar result even from a cylindrical mirror**



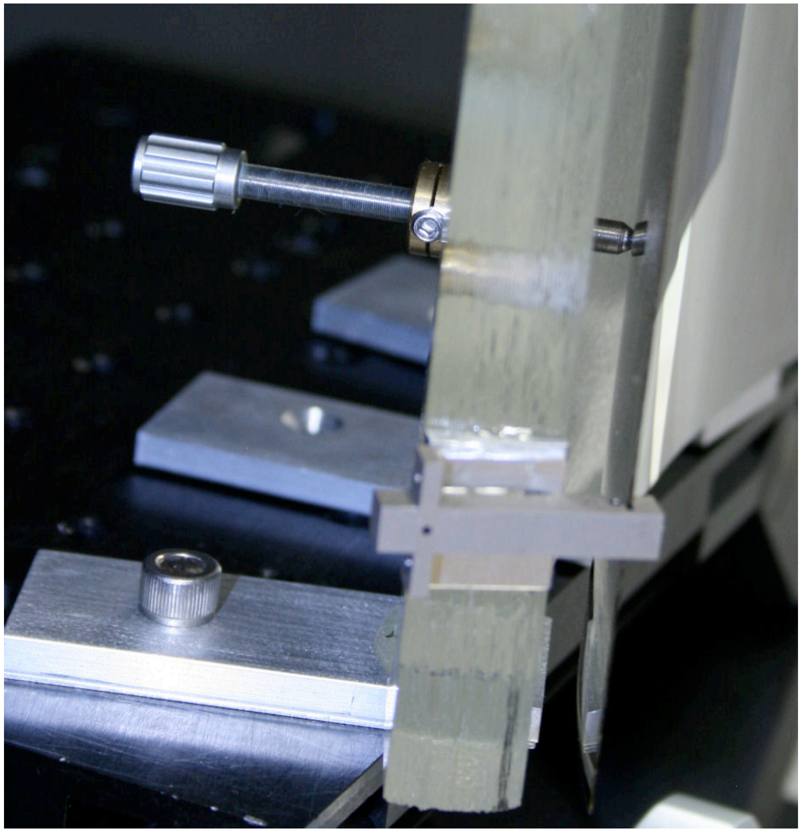


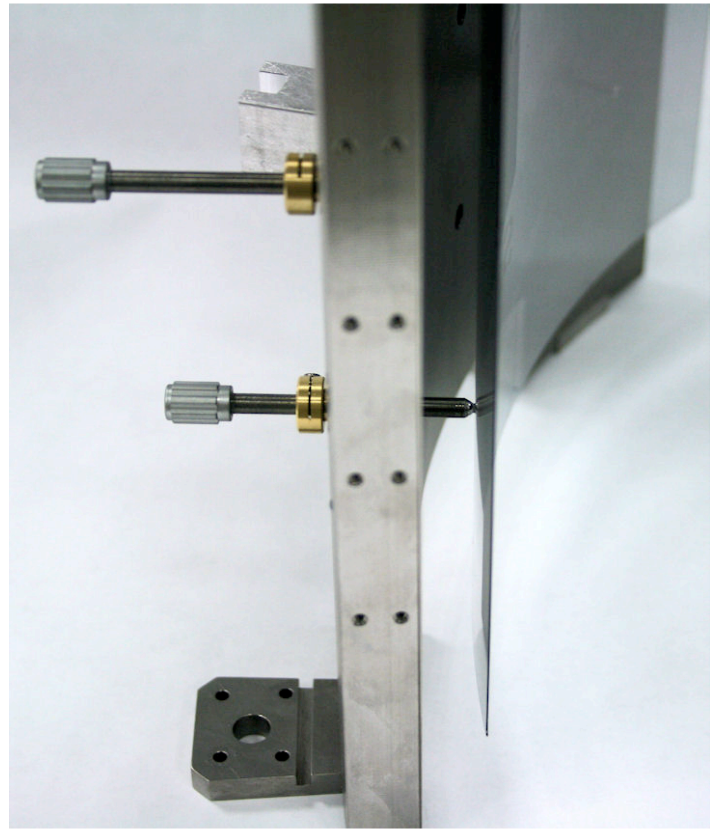
Temporary bond

- To bond the hung mirror onto a strongback
- Only small forces are allowed in the process in order not to distort the (axial) figure of the mirror.
  - Finite element model and experiments show forces required < 1 mN (depending on bonding configurations)
  - To avoid CTE-mismatch, strongback is made of the same glass
- Implementations and refinement of a distortion-free bonding:
  - > **Direct bonding of with epoxy onto tips of adjustment pins**
  - > **Bonding onto pins in low friction air-bearings**
  - > **Bond under controlled conditions: zero-force, zero displacement**



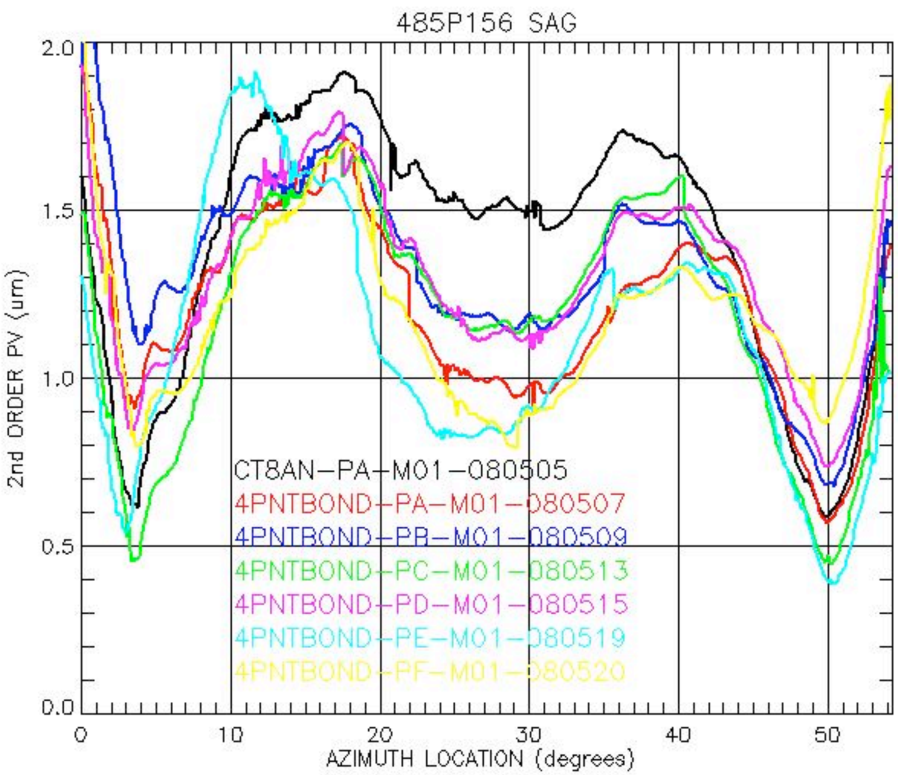
Temporary Mount with Simple Direct Bonding





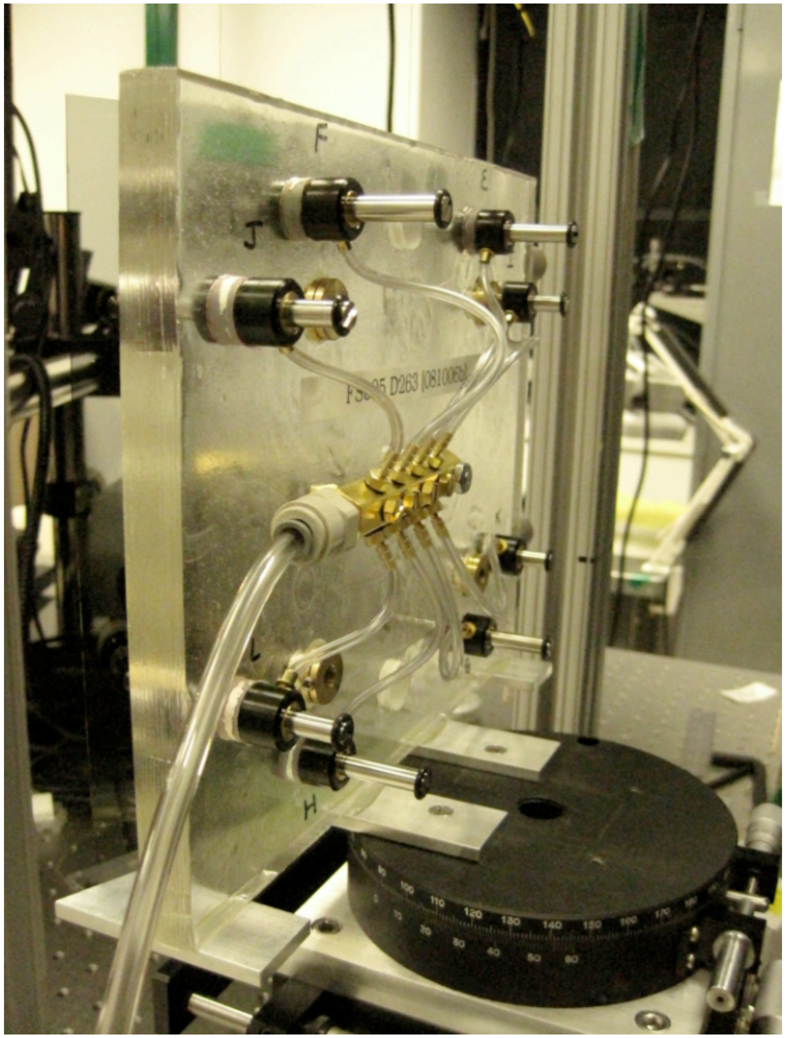
- **With Glass (exact CTE) or Ti-15Mo alloy (close, but not exact CTE) strongback**
- **4-pin or 8-pin**

Temporary Mount: Direct Bonding at 4 points



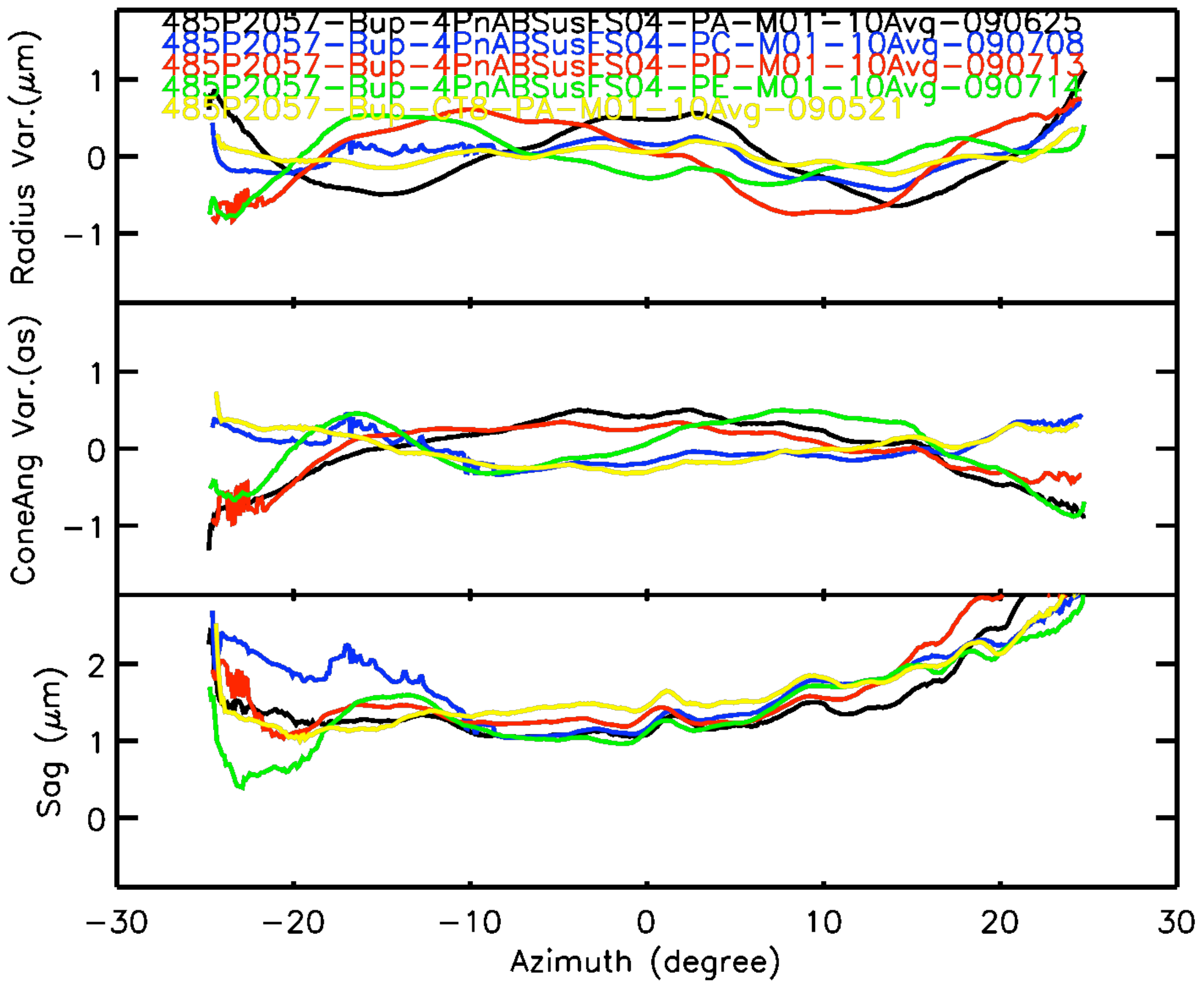
- Direct bonding at 4 points with epoxy Hysol 9313
- Process highly repeatable
- Low distortion when compared to "free-standing" mirror. Some variation in tilt angles
- Further control of size and location of the epoxy beads is limited:
  - epoxy injection with an electronic fluid dispenser can produces bead as small as ~< 1 mg each
  - But fractional variation is large
- Experiments show variations due to
  - Instant action of injection
  - Fluid actions (surface tension, etc.)
  - Longer term variation due to curing

Temporary Mount: low friction floating pins



- Floating pin replacing “epoxy insertion” onto fixed pins
  - The mirror is now attached to freely floating pins before the pins are fixed
  - This technique removes the uncertainty arising from the volume of the epoxy
- Near frictionless air bearings ($\mu \approx 0.002$)
- Pins in air bearings are modified to stabilize at specified longitudinal position
  - To achieve very soft spring action ($k \approx 20\ \mu$N/mm) of pins on air
  - Forces and displacement are measured in controlled experiments

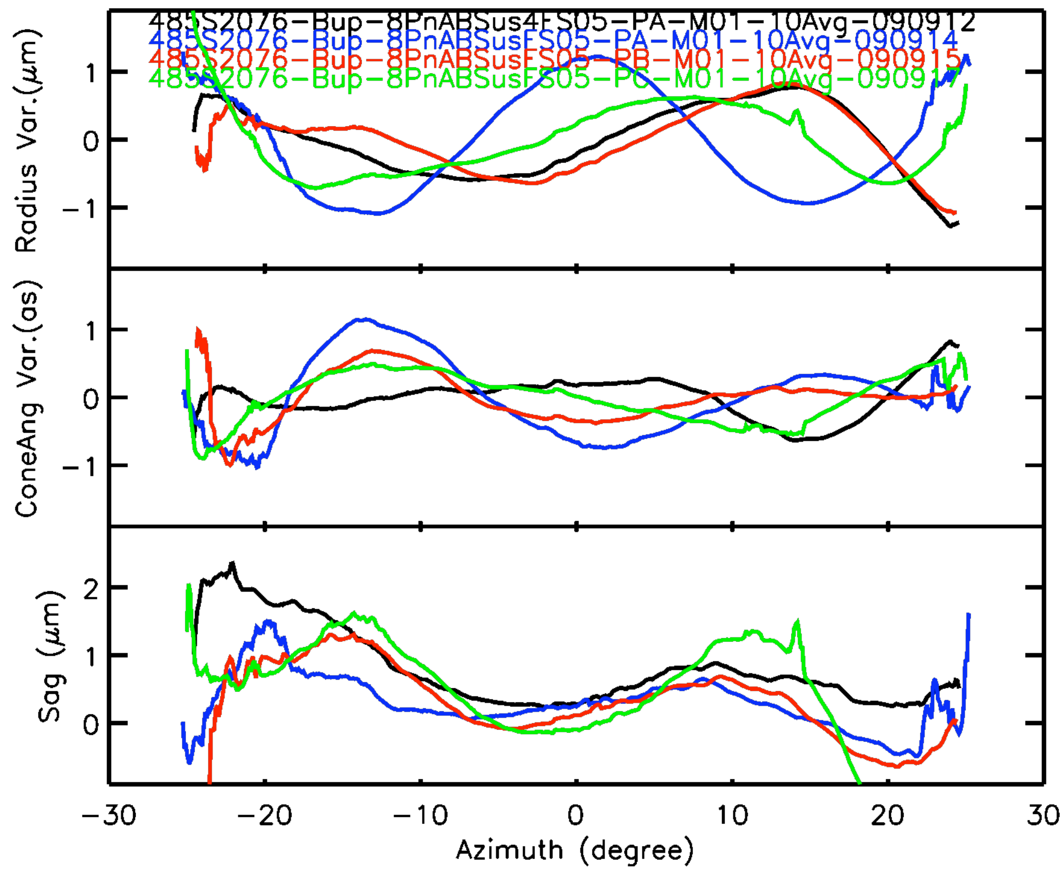
Temporary Mount: floating pins on air-bearings: 4 pins



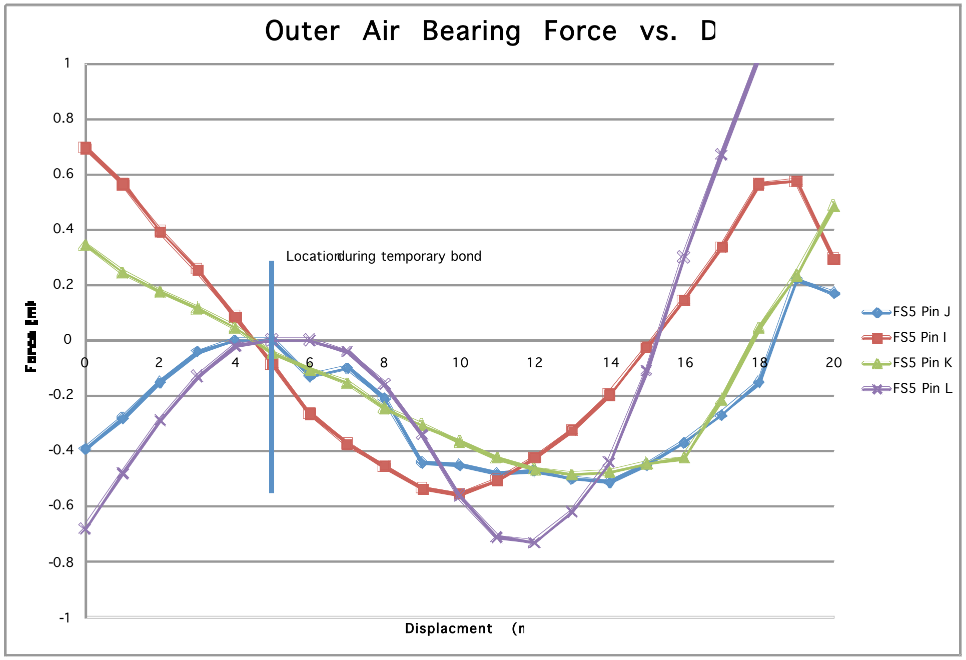
- Mirror bonded at 4 pins at mirror's back
- Surface measurement show good repeatability not just in axial sag, but also in azimuthal tilt
- Further improvement in precision of setting pin equilibrium will further improve bonding

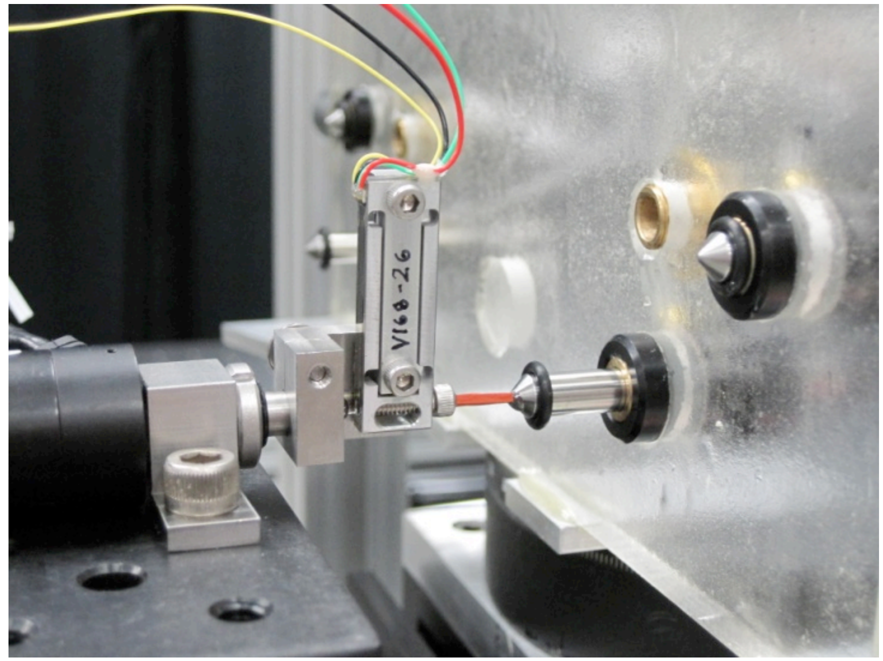
Temporary Bond on Pins on Air bearings: 8 pins

- **8-pin bond allows:**
  - Stronger holding of mirror for subsequent mirror transfer
  - Larger mirror to be tilted without distortion in subsequent integration
- **8-pin bonding result:**
  - Excellent repeatability
  - 8-pin bonding has reached the effectiveness of the 4-pin bonding
  - Need to improve mirror stability during epoxy curing



Temporary-bond onto Pins on Frictionless Air-bearings

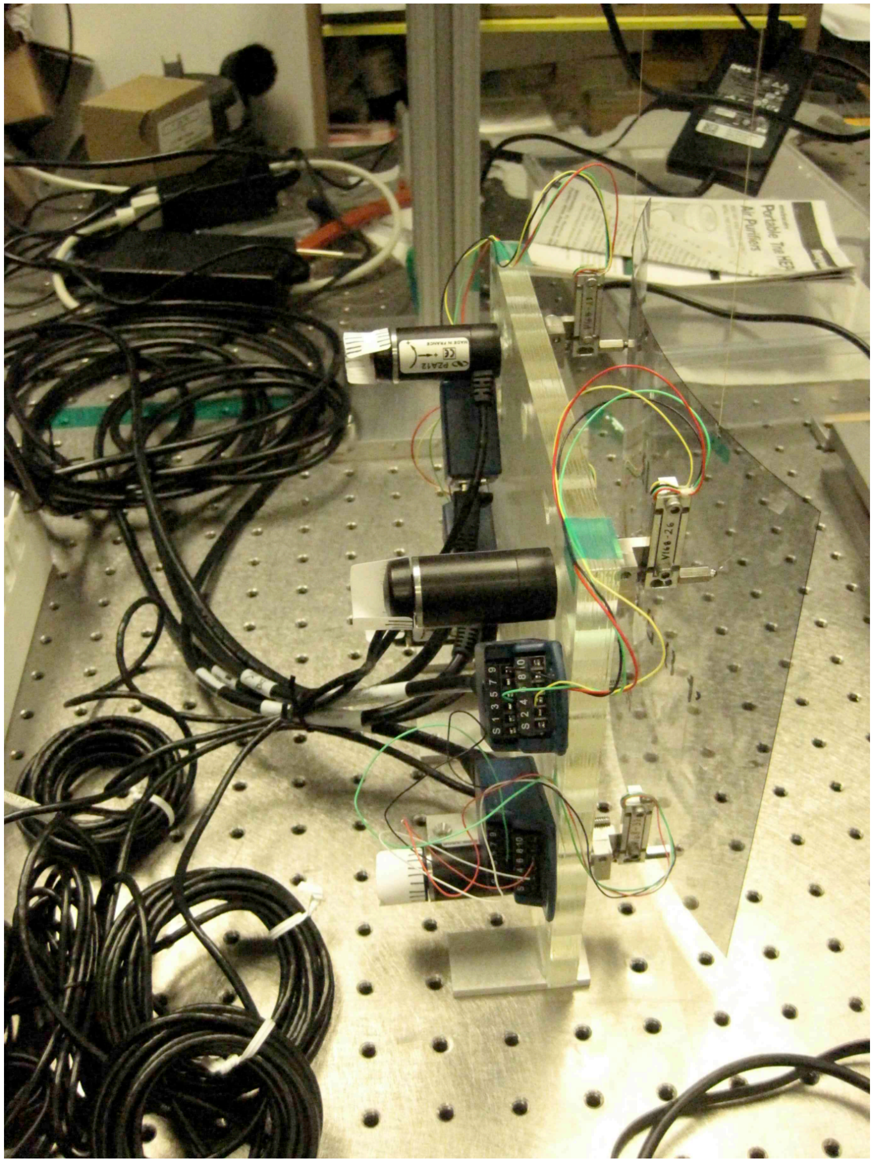




- Direct measurement of pins' restoring force with micro-force gauge
- Can also be estimated from pins' oscillations

Stress-free mounting (in development)

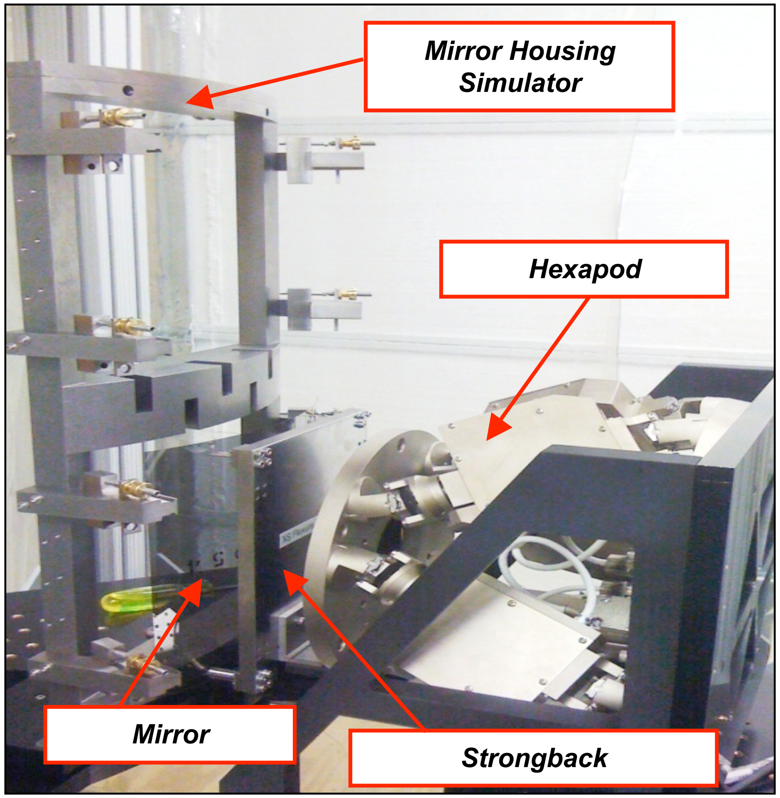
- **‘Smart-pins’ platform**
  - Stress-free condition from local real-time force monitoring (resolution ~ 10 μN)
  - Actuated with integrated nano-actuators
  - Complemented with real-time local displacement monitoring (resolution < 0.05 μm)
- **Equivalent Displacement-free platform**
  - Displacement-free condition from displacement close-loop with actuator
- **Allows constant monitoring of displacement and force at specific positions, at different mounting stages**
  - Portable platform
  - Allow identification of major phase of distortion (e.g. temporary mount vs. permanent bond vs. dismount from temp-bond)



Alignment & Permanent Bonding:

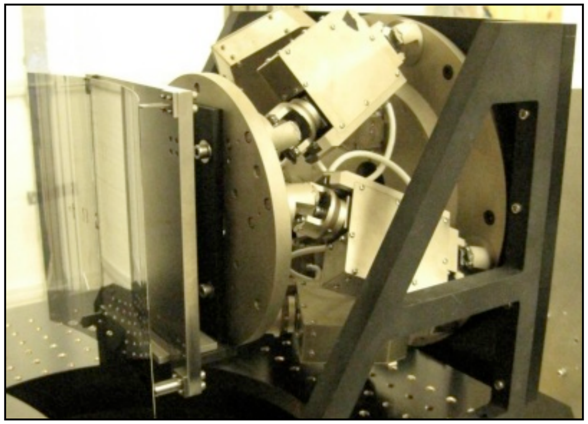
To transfer the mirror onto the mirror housing

Alignment Set-up



- Vertical Alignment Facility (VAF)
  - Temporary-bonded mirror aligned by hexapods in optical beam
  - Mirror is transferred to Housing Simulator

- Enclosure
  - –Reduces mirror instability from air current
  - –Improves thermal control to about +/- 0.25° C

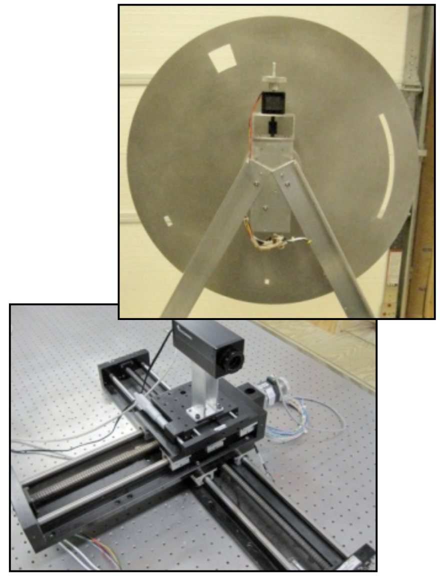


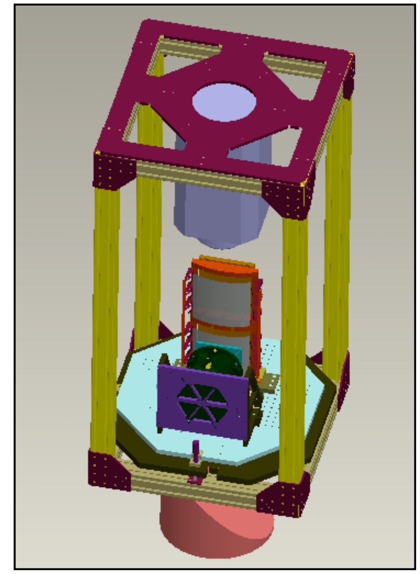
- Precision hexapod (6 DOF) for alignment
  - –Repeatable alignment without backlash
  - –Displays absolute mirror position

Hartmann Sub-aperture Test & Permanent Bonding set up

Automated detector stages and Hartmann mask

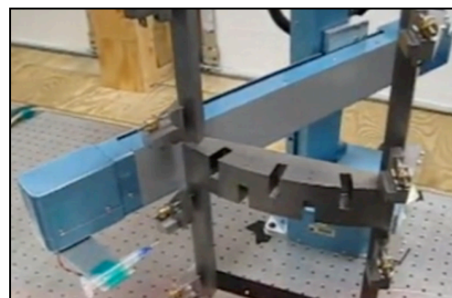
- Automated rotation of the mask & focal distance adjustment between tests
- Ability to perform multiple tests for image optimization

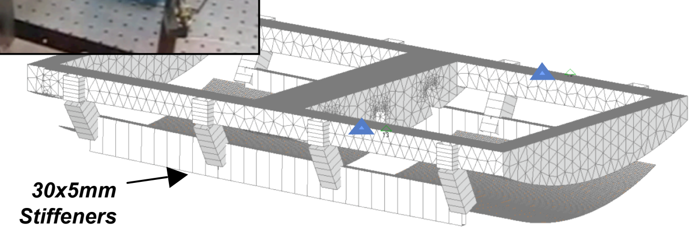




Bonding onto Housing Simulator

- Simulator with stiffening bars for horizontal x-ray testing
- 4 DOF robot for epoxy injection
- Robot precision 0.15 mm
- Ability to implement nano-probe zero-displacement bonding (in progress)

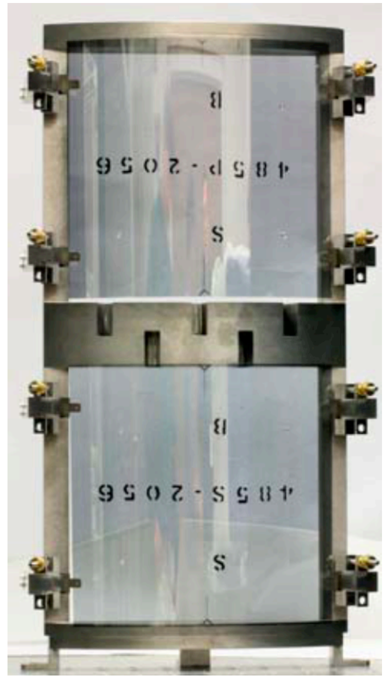


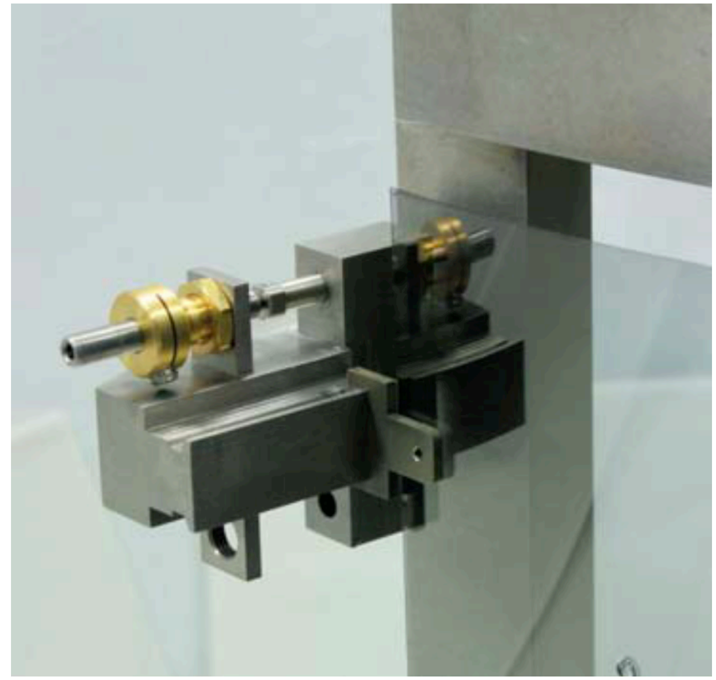


Linear Stage and Hartmann Mask

Permanent Mount onto Mirror Housing Simulator

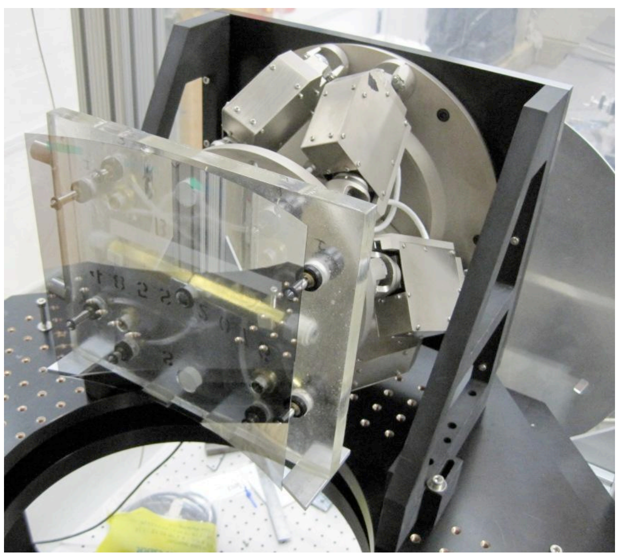
- Ti-15Mo frame
  - As a platform to develop permanent bonding and transfer process
  - Two stages, can accommodate multiple pairs of mirrors
  - 200 mm long, 50° mirror
- Ti mounting tabs
  - Tab mechanism for capturing mirrors
- Alignment of mirror
  - Alignment of mirror on strongback with hexapod
  - In-situ focus measurement with parallel optical beam
- Dismount from temporary bond has been tested successfully



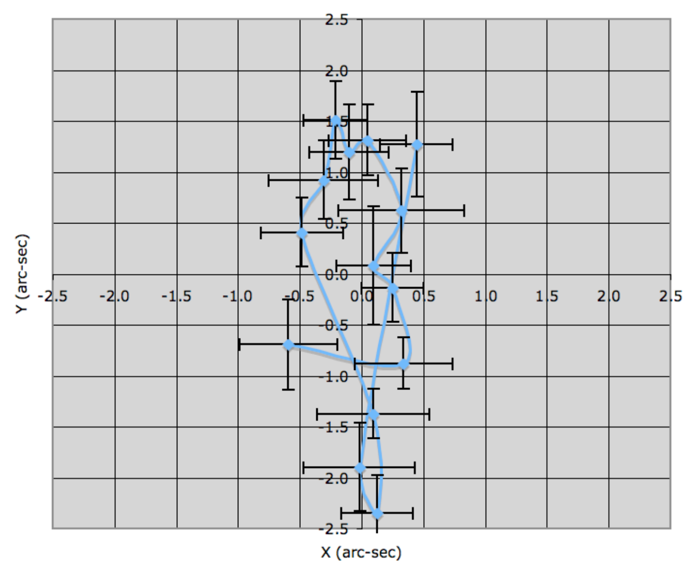


Alignment

- Single mirror repeatable to 0.17" (rms) for overall RMSD; repeatable 0.6" (rms) for each centroid
- For a 4-string, temporary mounted mirror at 4-pin linear bearing *and* 8-pin air bearings: 2" to 3".
- Hartmann focus at nominal or near nominal (a few mm) and optimal focal distances.

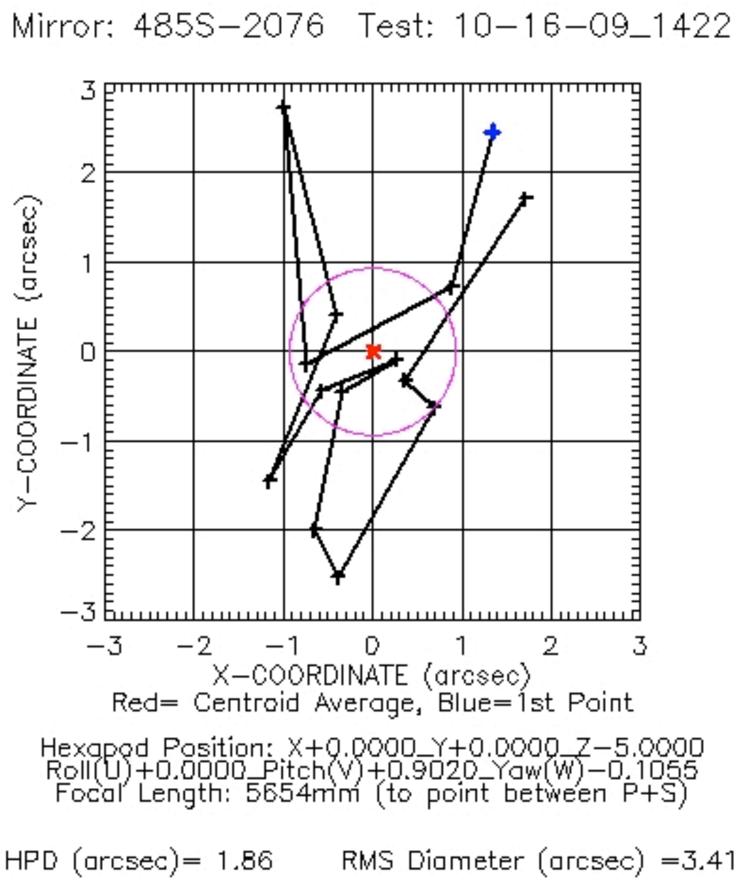


Alignment of 8-pin Air Bearing Mounted Mirror



Hartmann Test Repeatability < 0.2" (10 tests)

Hartmann Sub-aperture Test:

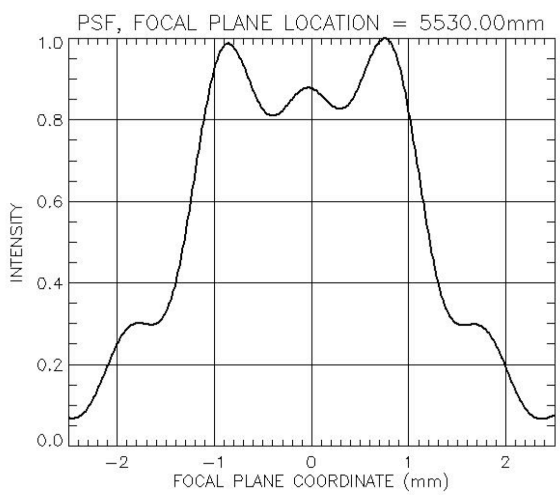


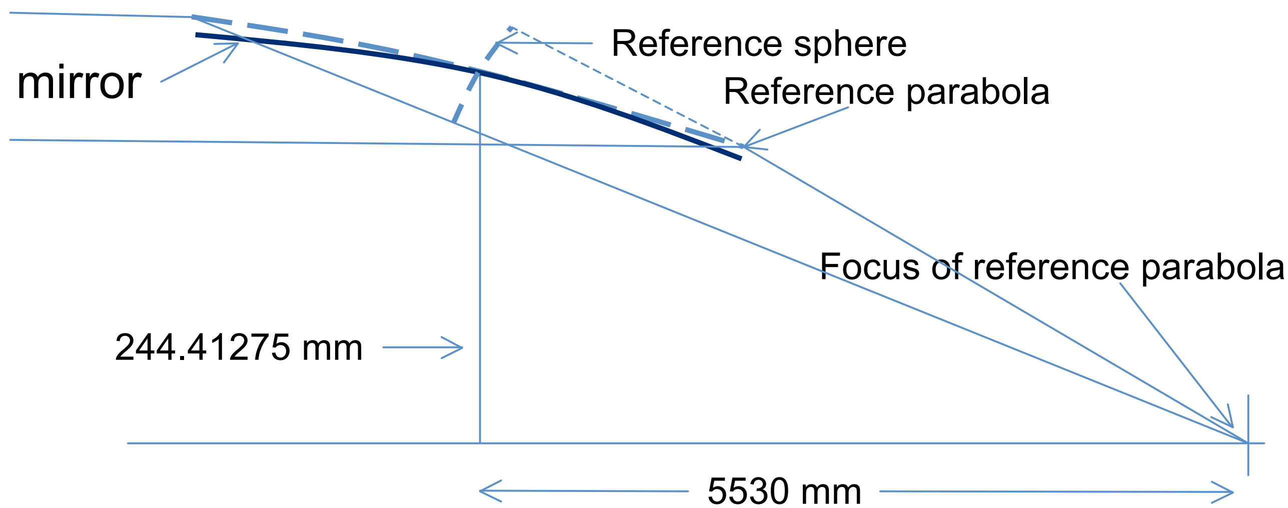
Pictures taken by CCD camera during Hartmann Test (5 of 18)

Low-order Surface Retrieval from Sub-aperture Optical Test --- Glazing Incidence Metrology

Low-order surface retrieval from Sub-aperture optical test

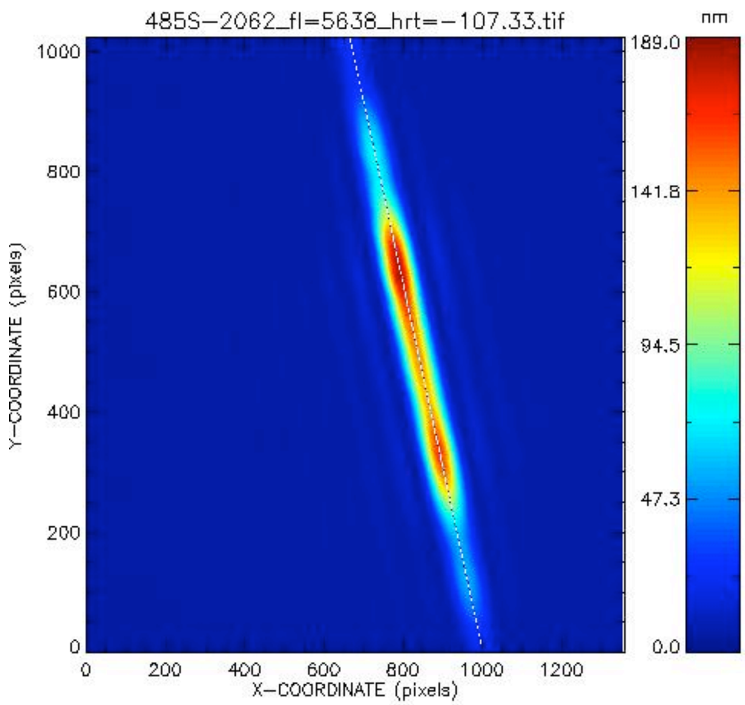
- **Diffracted 'slit' image can be model to provide information on the axial profile of the mirror**
- **Single mirror is successfully modeled**
- **Analysis:**
  - **Single mirror alone does not form perfect geometric image in collimated beam**
  - **Introduce reference parabola: reference parabola is complimentary of reference sphere. Reference parabola intersects secondary at the midpoint of the mirror and focus at the secondary best focus (5530 mm from the center of the mirror)**
- **Diffraction profile of a perfect mirror (with currently tested mirror dimension, f = 5530mm) is modeled (at λ = 633 nm)**

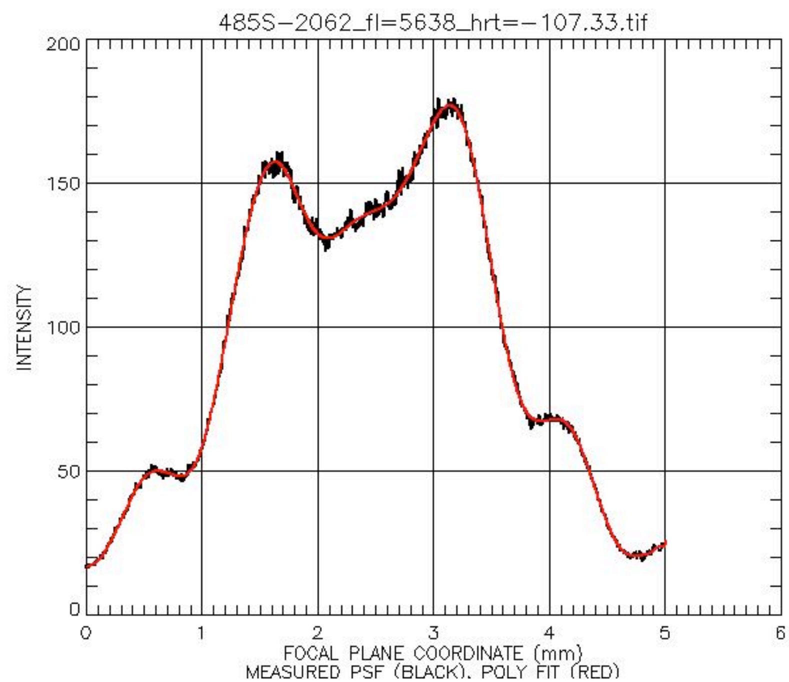




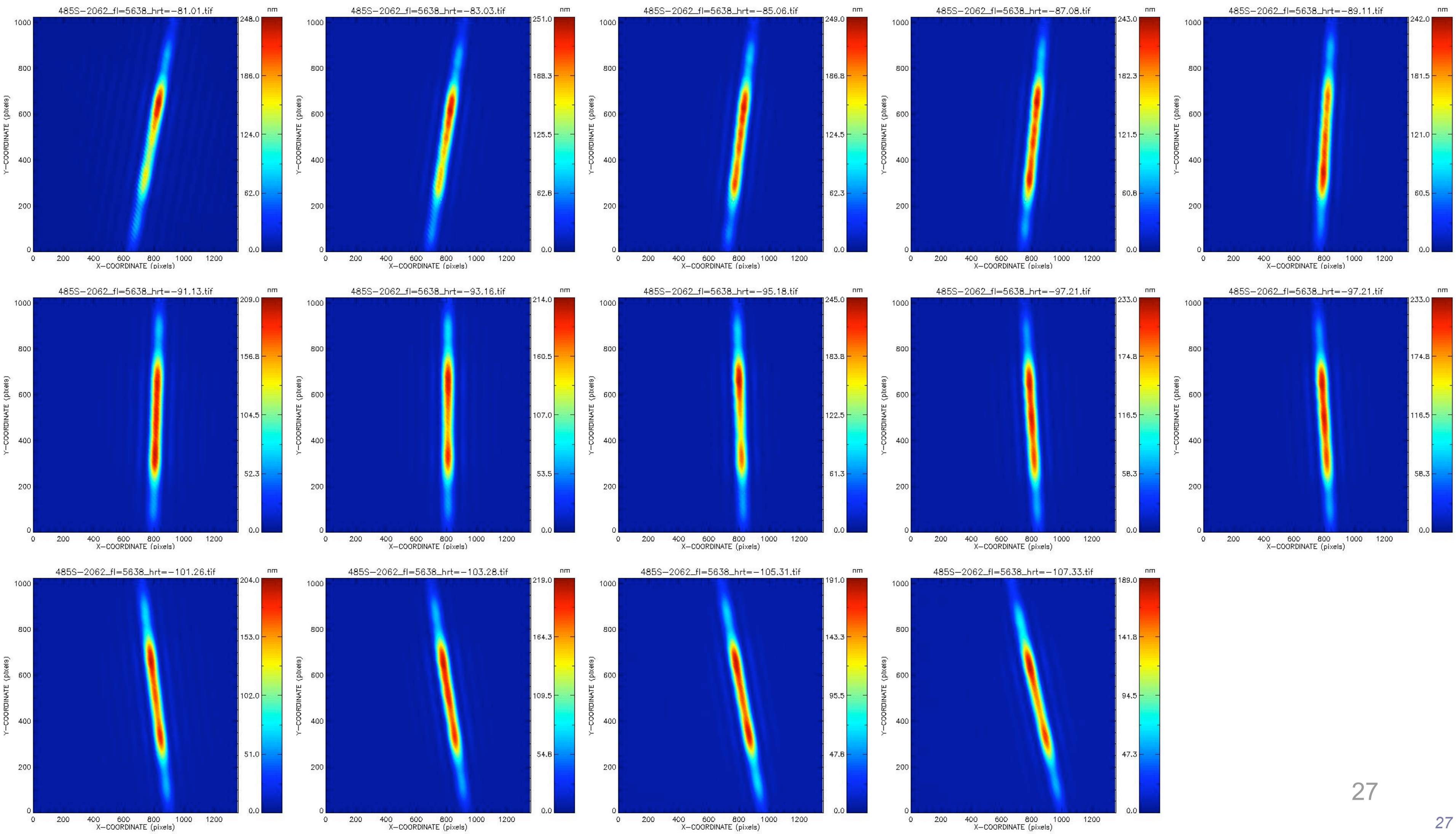
Modeled PSF

- Obtain tilt from single slit image (2-degree aperture currently)
- Extract PSF and fit





Repeat for all sectors



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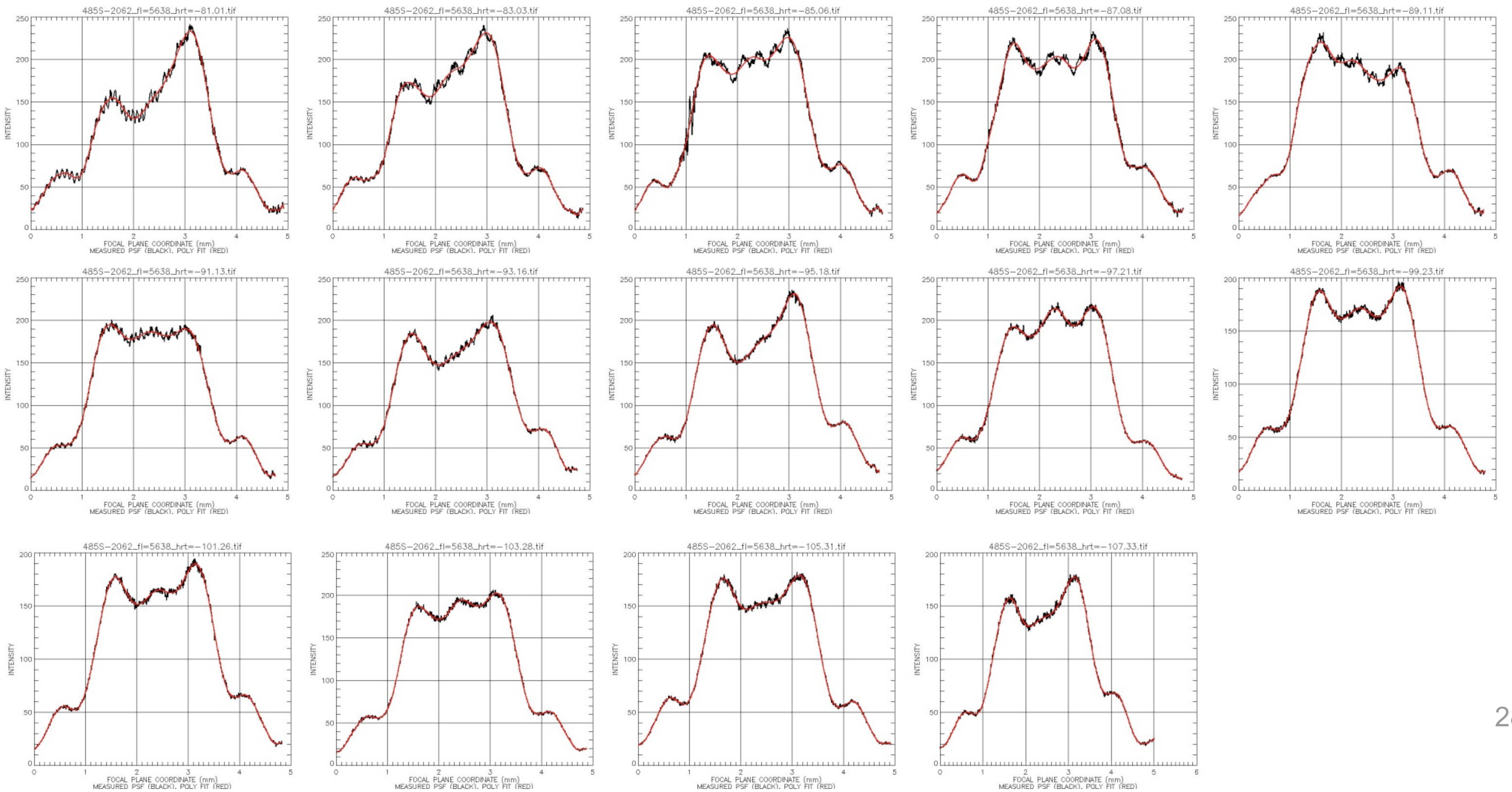
Extracted radial intensity profiles



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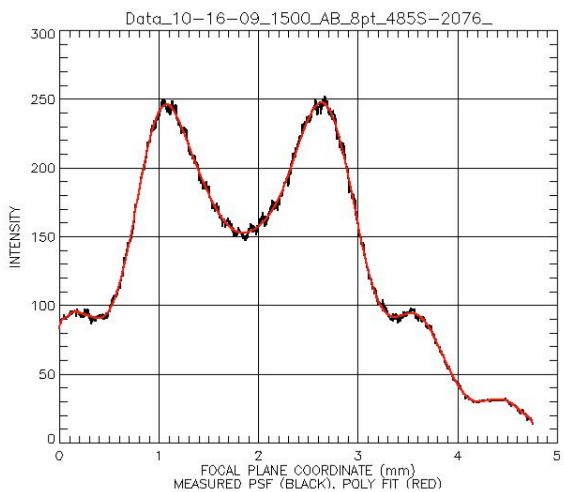
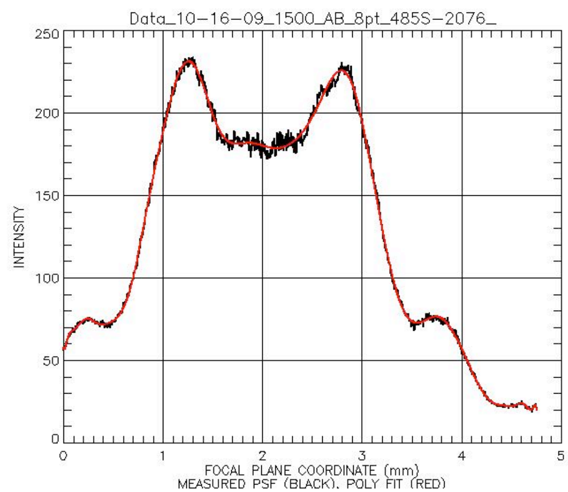
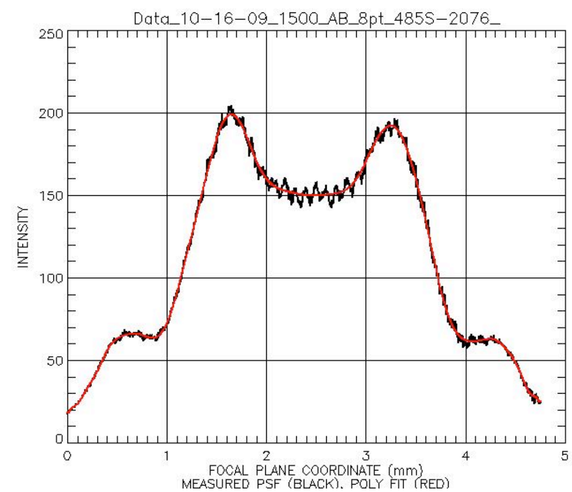
Also for Out-of-focus PSF

- **Diffraction image is different at different image distance**
  - **Defocused PSF is equivalent to PSF from an additional 2nd order sag of the wavefront**
- **Example below:**
  - **+/- 150 mm from nominal focus**
  - **In focus in the middle**
  - **PSF is wider at farther distance, with decreased central minimum**

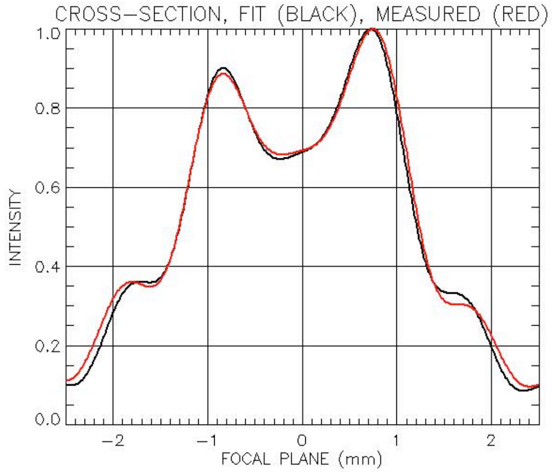


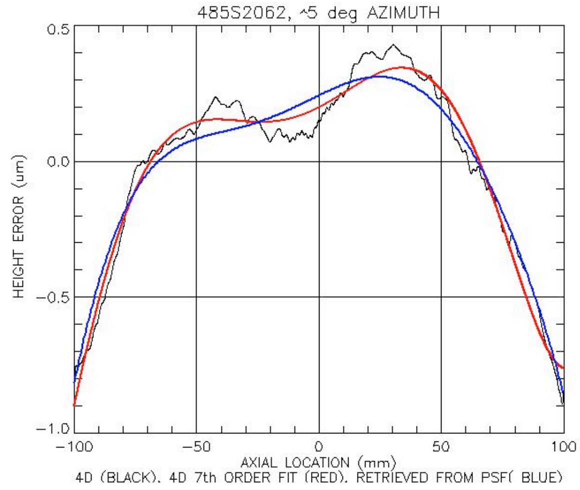


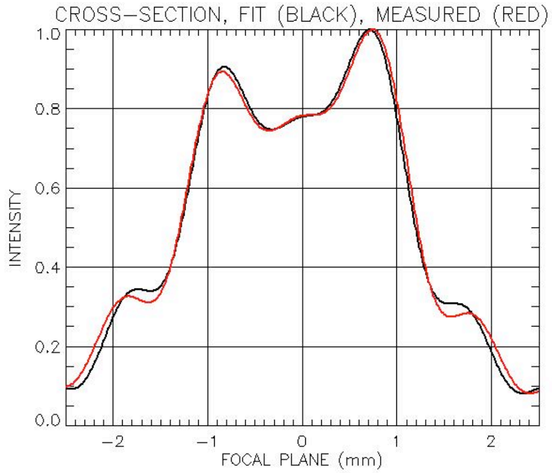


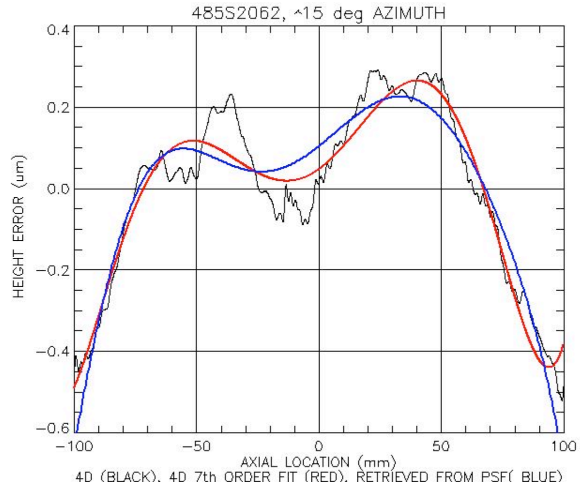
Retrieved PSF and Low-order Axial Profile

- Fitted PSF
  - Wave front sensing code fits the central section quite well.
- Low order Axial profile
  - 7th order poly fit to the data (red)
  - Profile retrieved (7th order Legendre polynomial used)f rom the PSF (blue).
  - Lowest order errors are recovered well
  - Axial profile is retrieved ~ ±0.1 µm









Summary

- Requirement to mount a mirror segment with sub-arc-second distortion
- Break process down to 2 intermediate steps: 1. Temporary-Mount; 2. Align and Transfer (Permanent Mount)
- Successfully develop a 4-string suspension suspension to meet initial requirement
  - Verified by surface metrology, correlated with finite element models
- Develop a low-force temporary bonding mechanism with pins on air-bearings
  - Supported by force measurements and surface metrology
  - Being refined with real-time force control and displacement monitoring
- Set up a Vertical Alignment Facility for alignment and sub-aperture testing
  - Hartmann measurement precision 0.2”
  - Mirror Sub-aperture centers ~ 2”
- Transfer of mirror in progress
  - Dismount of mirror from temporary-bond is demonstrated