Spatial Calibration and Flight Validation*

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ALI Technology Transfer Forum

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50 years
MIT LINCOLN LAB

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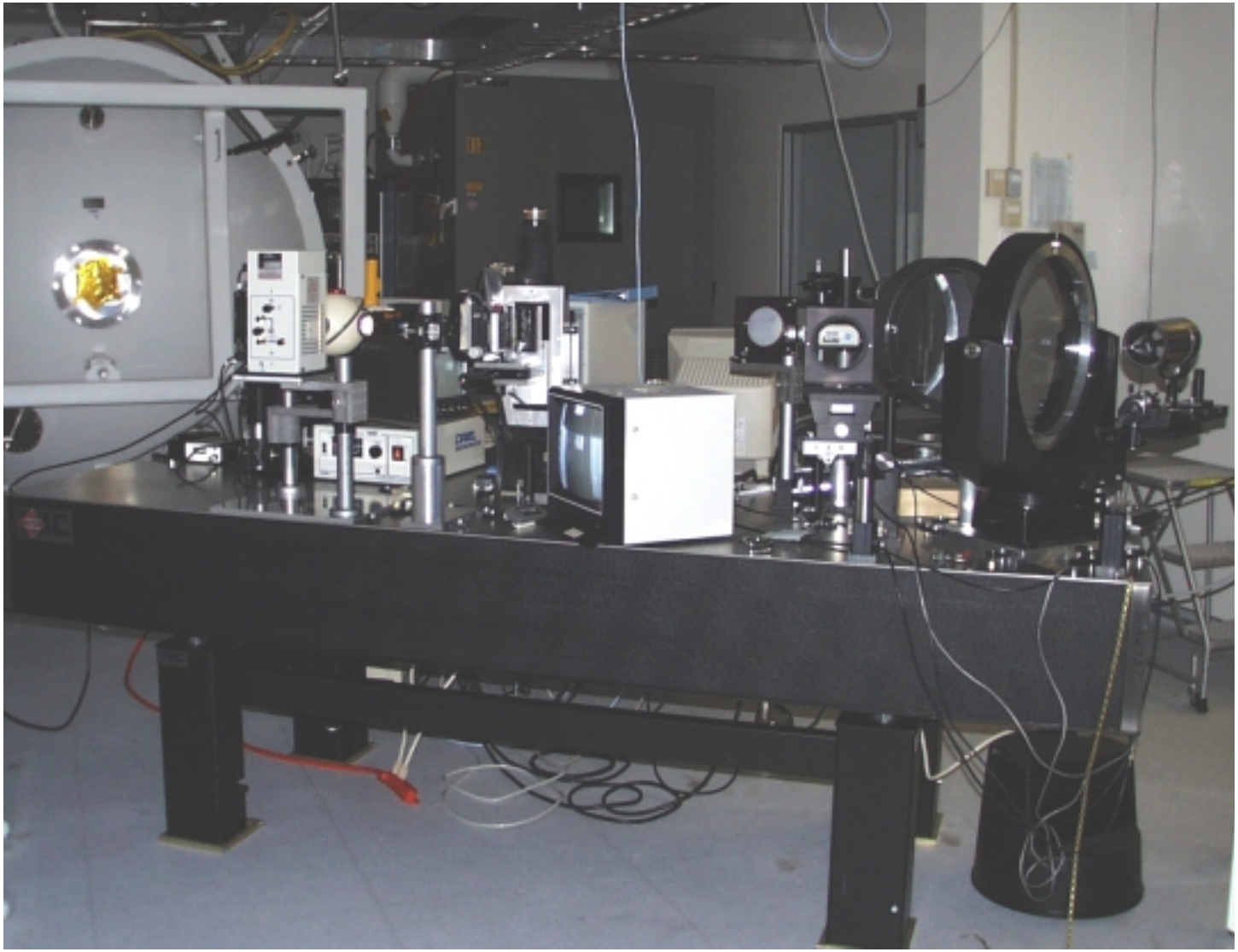
Outline of Talk

- Spatial calibration ground support equipment
- Focal plane integration
  - Initial focus setting
  - End-to-end imaging test
- Laboratory spatial calibrations
  - Modulation Transfer Function (MTF) measurement
  - Line-of-sight (LOS) measurement
- On-orbit performance assessment
  - MTF
  - LOS
- Summary

Spatial Calibration GSE

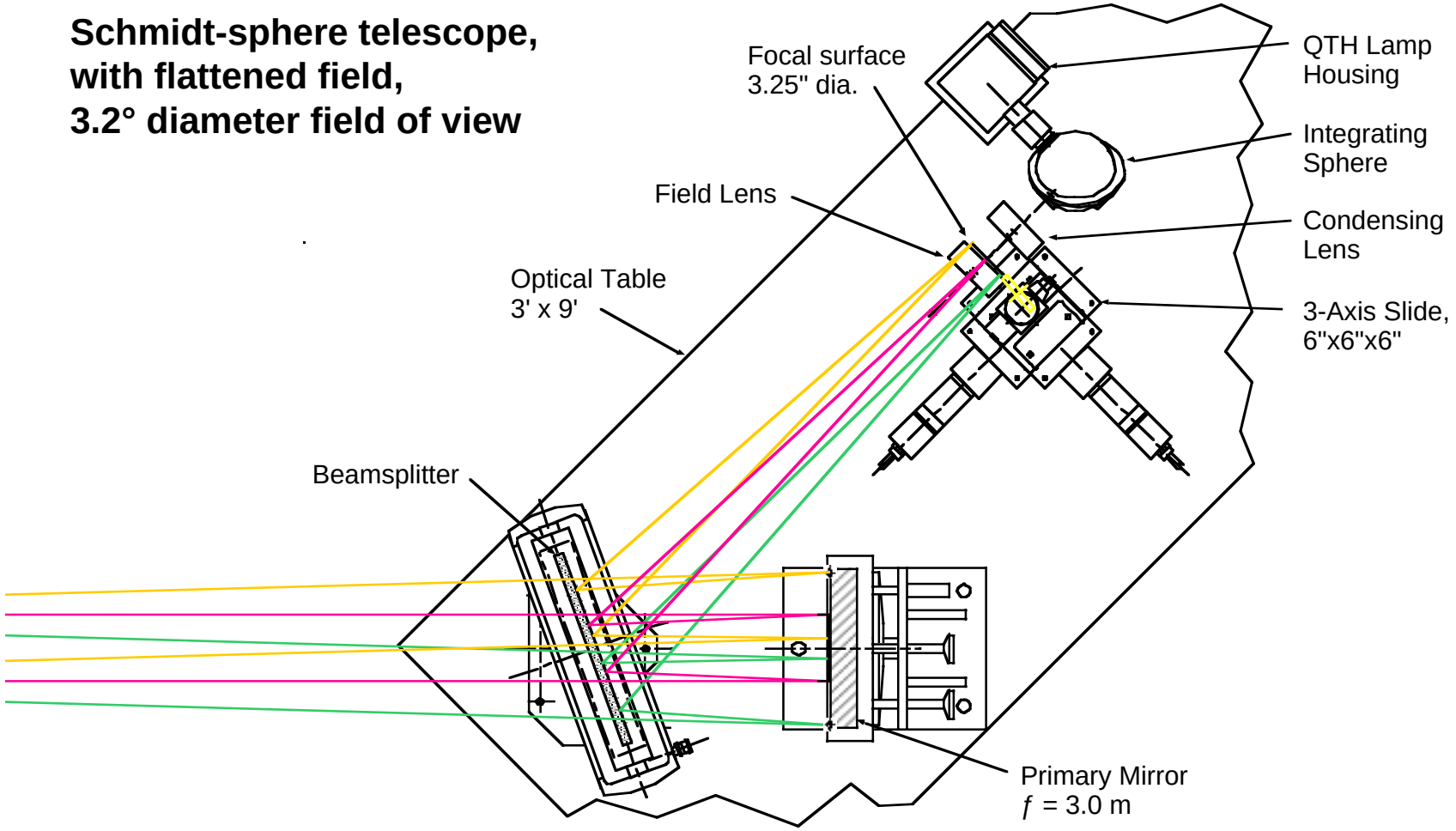
- Imaging Collimator
- Control and data acquisition system
  - ALI Calibration Control Node (ACCN)
    - Windows NT platform
    - LabVIEW control software
  - Sun/Storage Concepts data acquisition workstation (EGSE1)
  - Silicon Graphics R10000 unix workstation to process and store data (Performance Assessment Machine)
    - Large amount of RAM, RAID disk array, DLT archive
    - IDL and ENVI software for processing
- Positioning and support systems
  - Flotron fixture, under class 1,000 hood
  - Azimuth positioner (± 1 arc sec), inside vacuum chamber
- Thermal vacuum system

Imaging Collimator

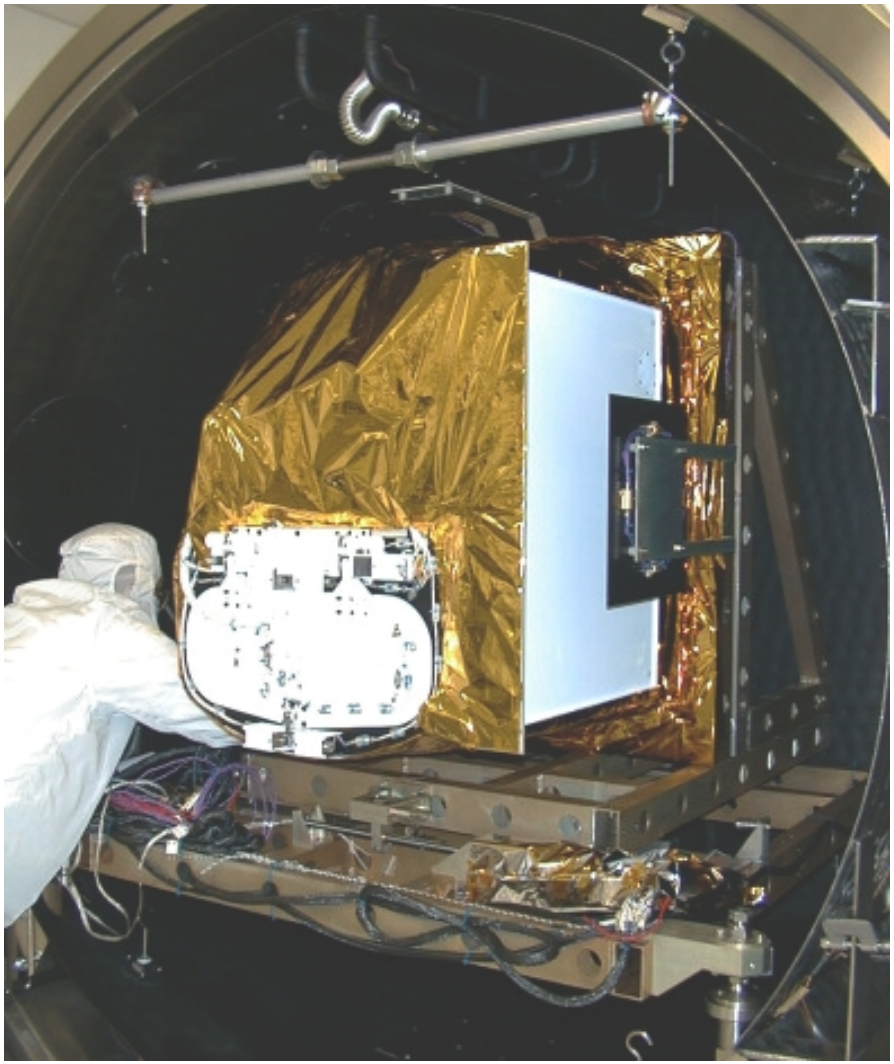


Imaging Collimator Layout

Schmidt-sphere telescope,
with flattened field,
3.2° diameter field of view



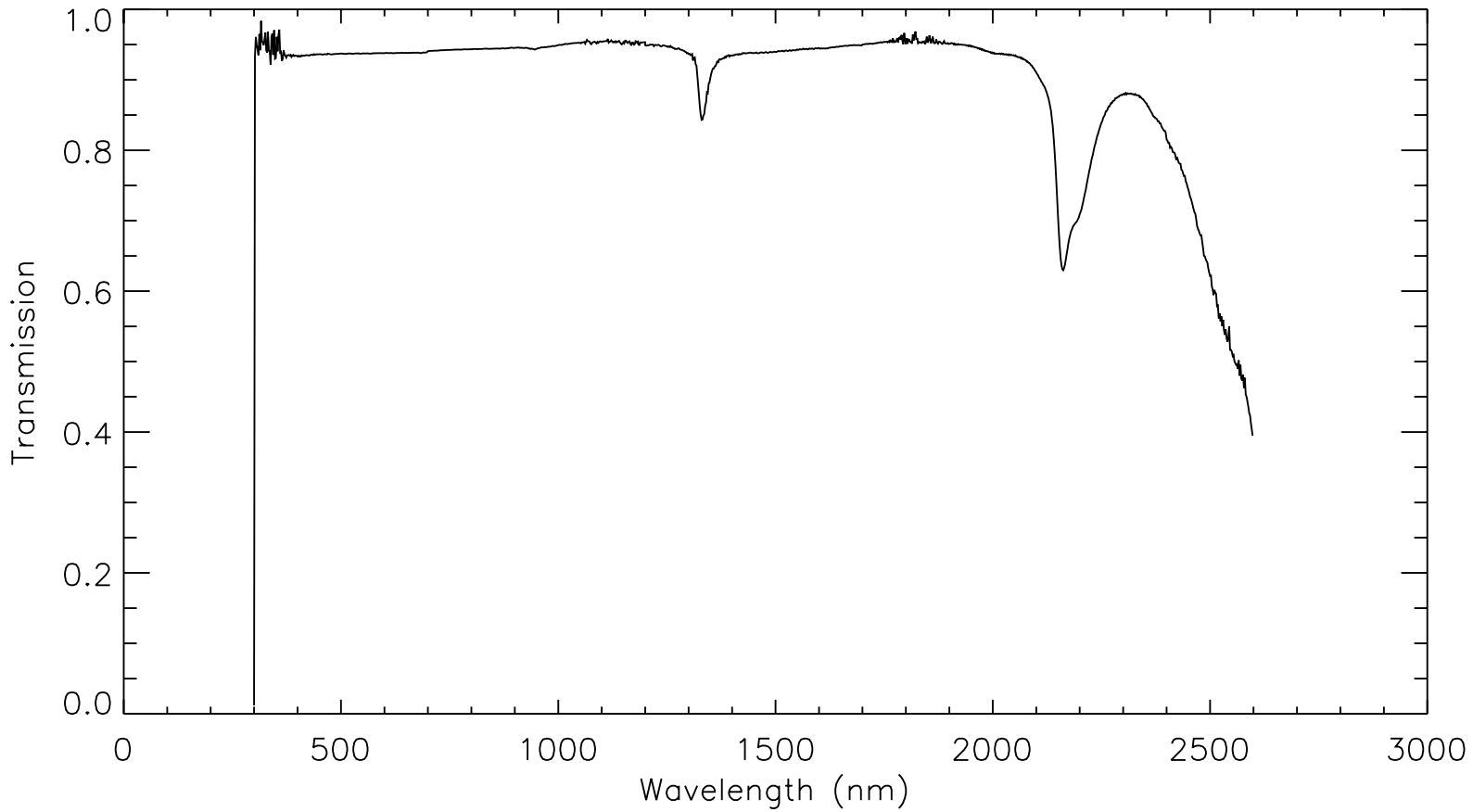
Installation of ALI in Vacuum Chamber



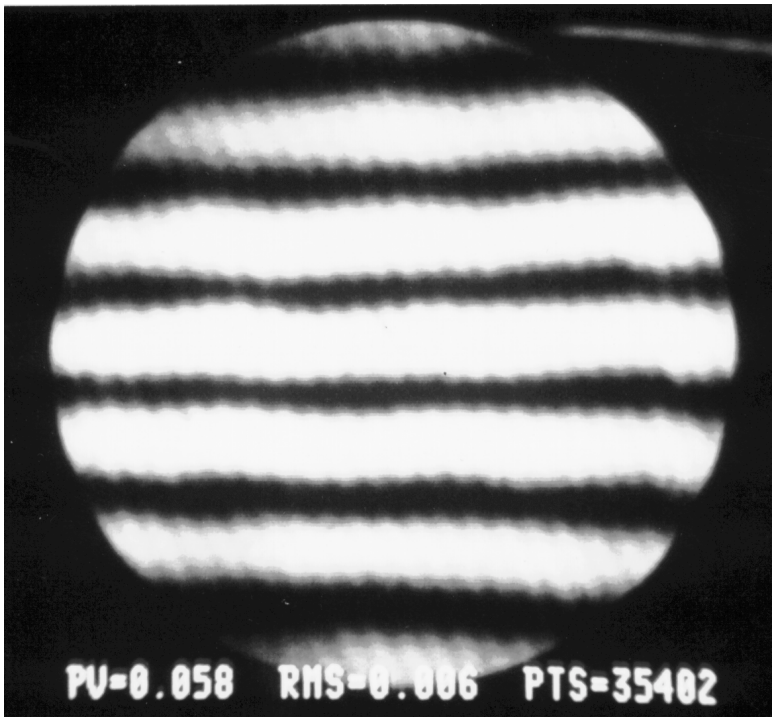
Vacuum Chamber Window Optics

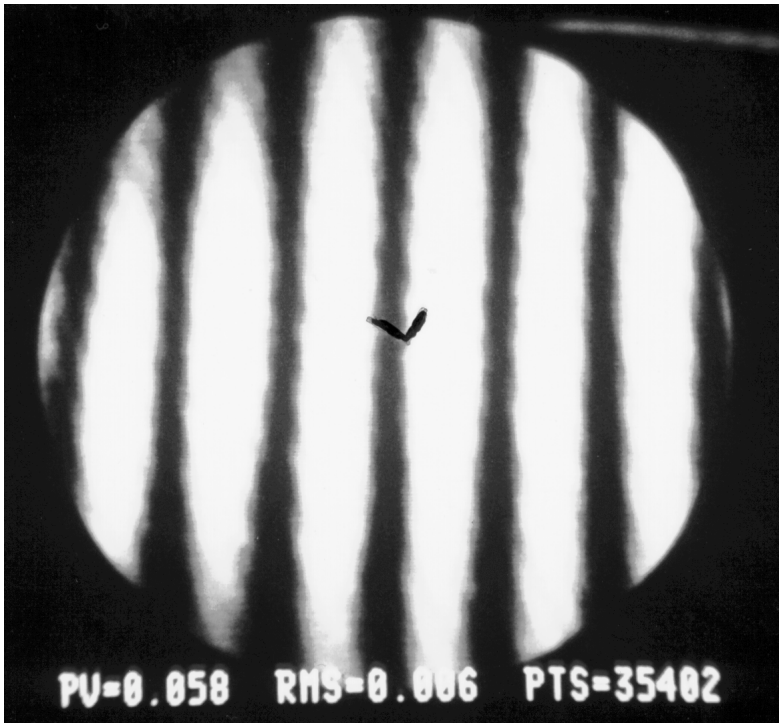
- Spectral Transmission
- Optical Figure
- Optical power induced by temperature gradients
- Measurement and compensation of optical power

Spectral Transmission of the Window



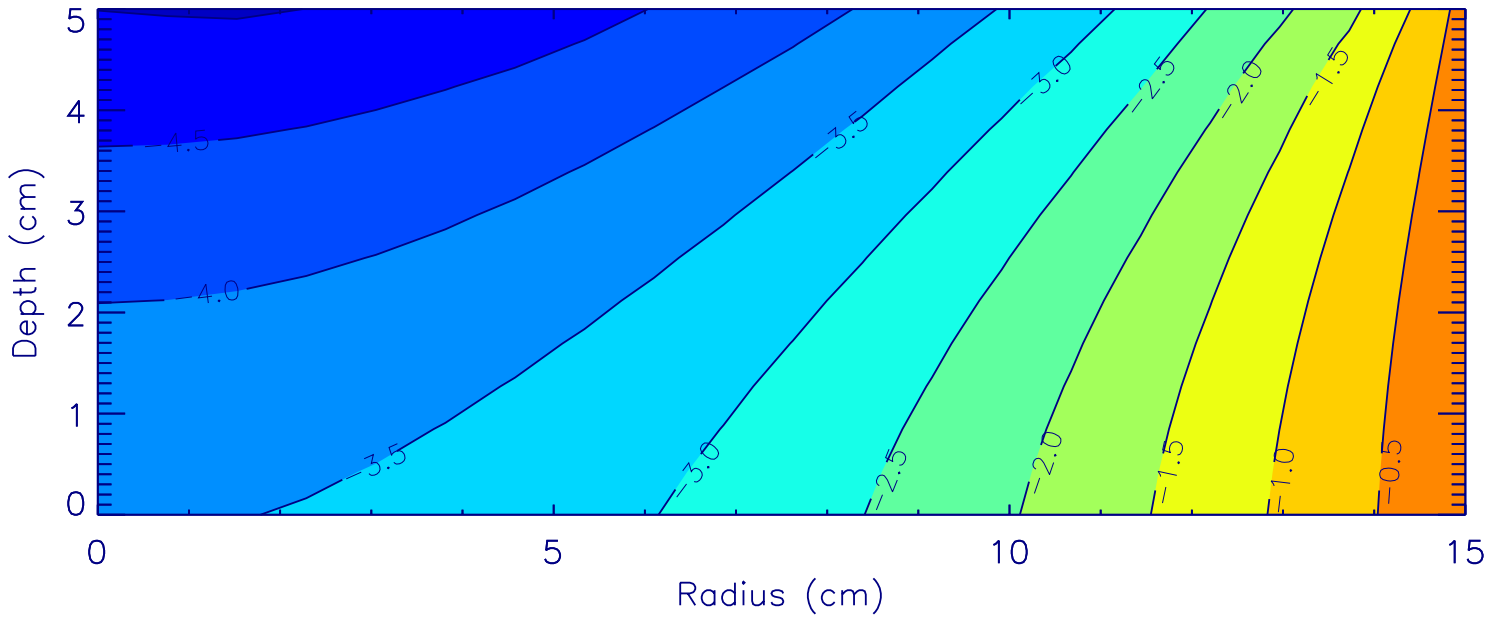
Optical Figure of the Window





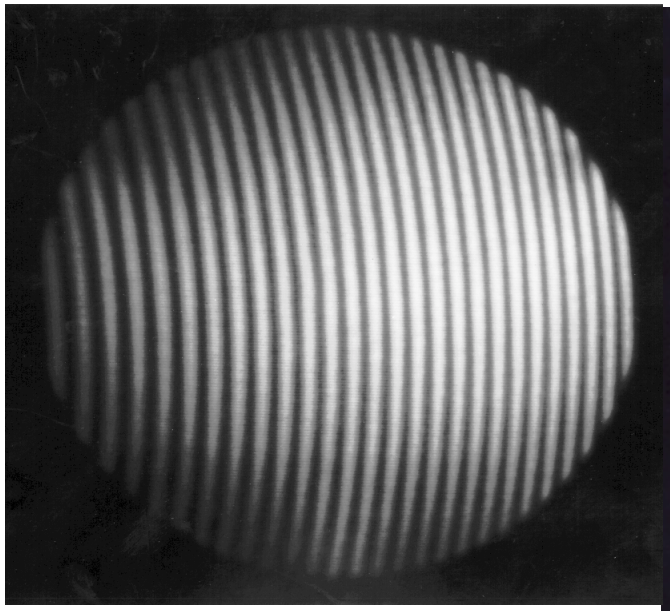
Transmitted wavefront error = 0.05 ~ 0.08 waves peak-to-valley
= 0.005 ~ 0.012 waves rms (@ 633 nm)

Window Temperature Distribution, Cold Chamber



Optical Measurement of Window

Zygo Displays, Cold Window



Fringe monitor

Control display

Compensation of Power with the Collimator

- If the window power ($1/f_w$) is known, the test target in the collimator can be offset from the infinity focus by an amount Δz to compensate for the power of the window.

$$\Delta z = \frac{f_c^2}{l - f_c - f_w} \approx -\frac{f_c^2}{f_w}$$

  - f_c = focal length of the collimator
  - l = separation of window and collimator primary mirror

- The collimator/window system is thus correctly collimated.

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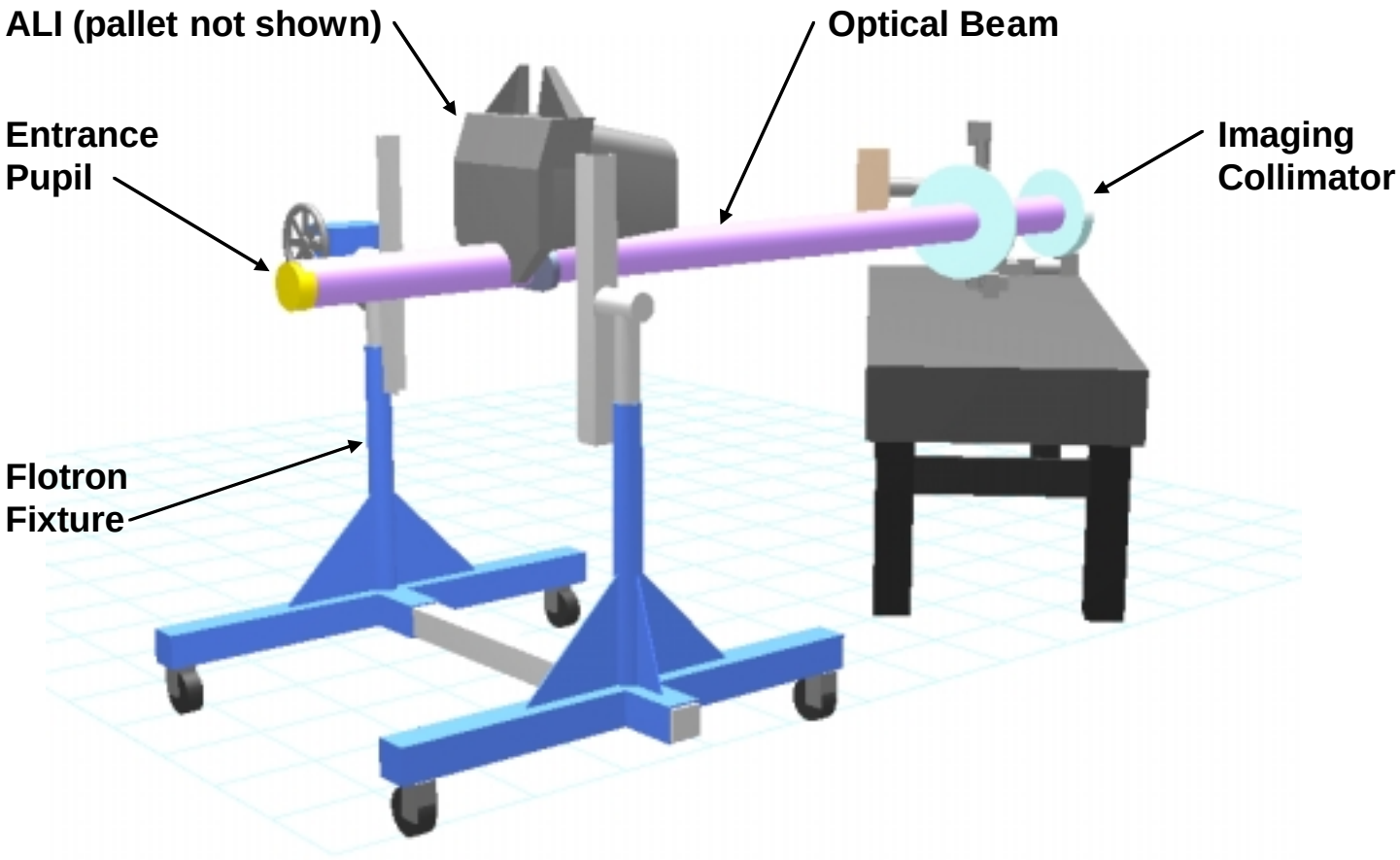
Focal Plane Integration Setup



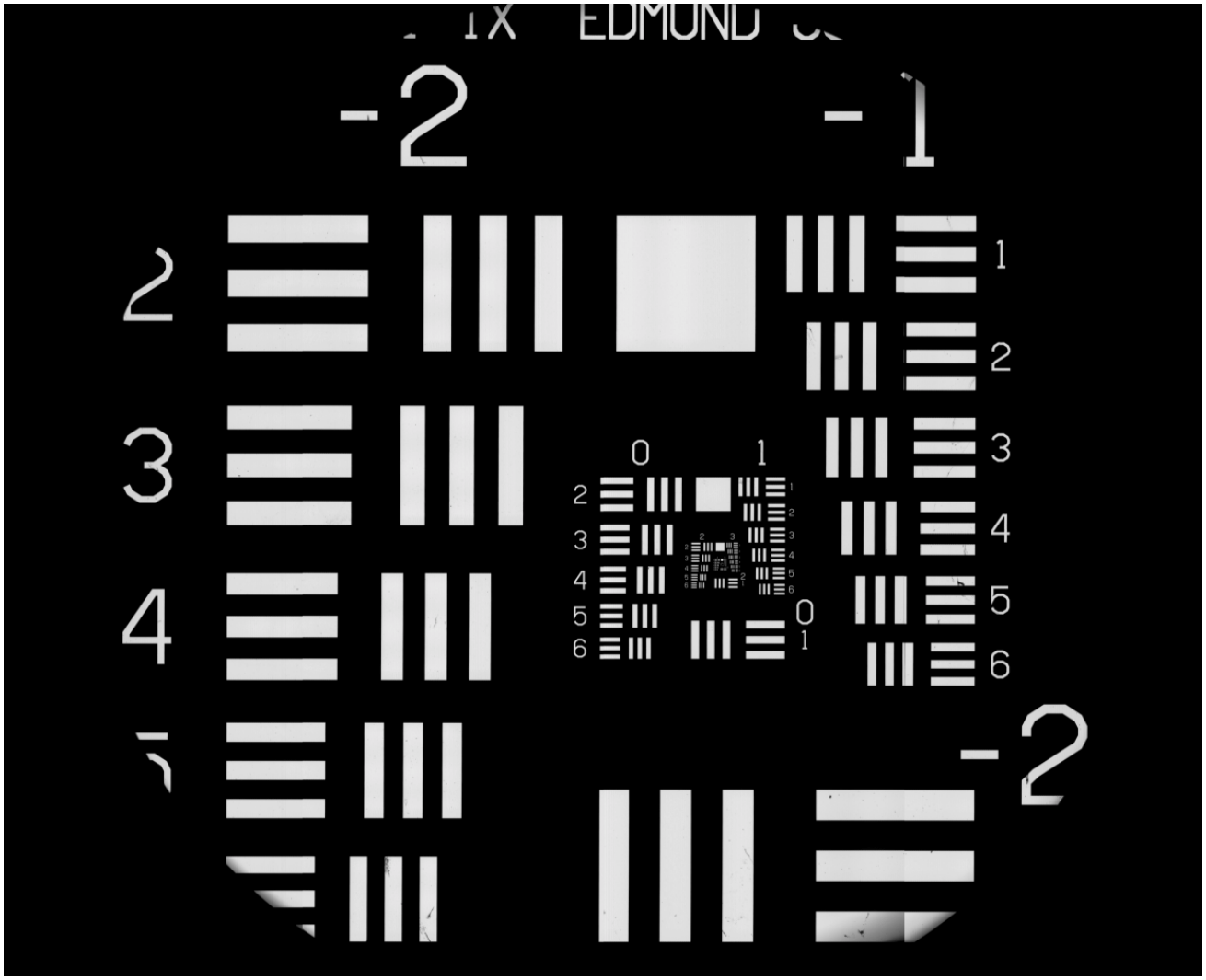
Focus Measurement and Adjustment

- Measure edge-spread function (ESF) and compute a figure-of-merit, such as peak edge slope
- Shift focus position of knife edge in collimator, and repeat ESF measurement
- Plot figures-of-merit *vs*. focus shift from true collimation, Δz
- Fit to find Δz_{opt} for best focus
- Modify focal plane shim according to

$$\Delta z_{shim} = \left(\frac{f_{ALI}}{f_{coll}} \right)^2 \Delta z_{opt}$$

- Repeat process until focus error is insignificant

End-to-End Imaging Test



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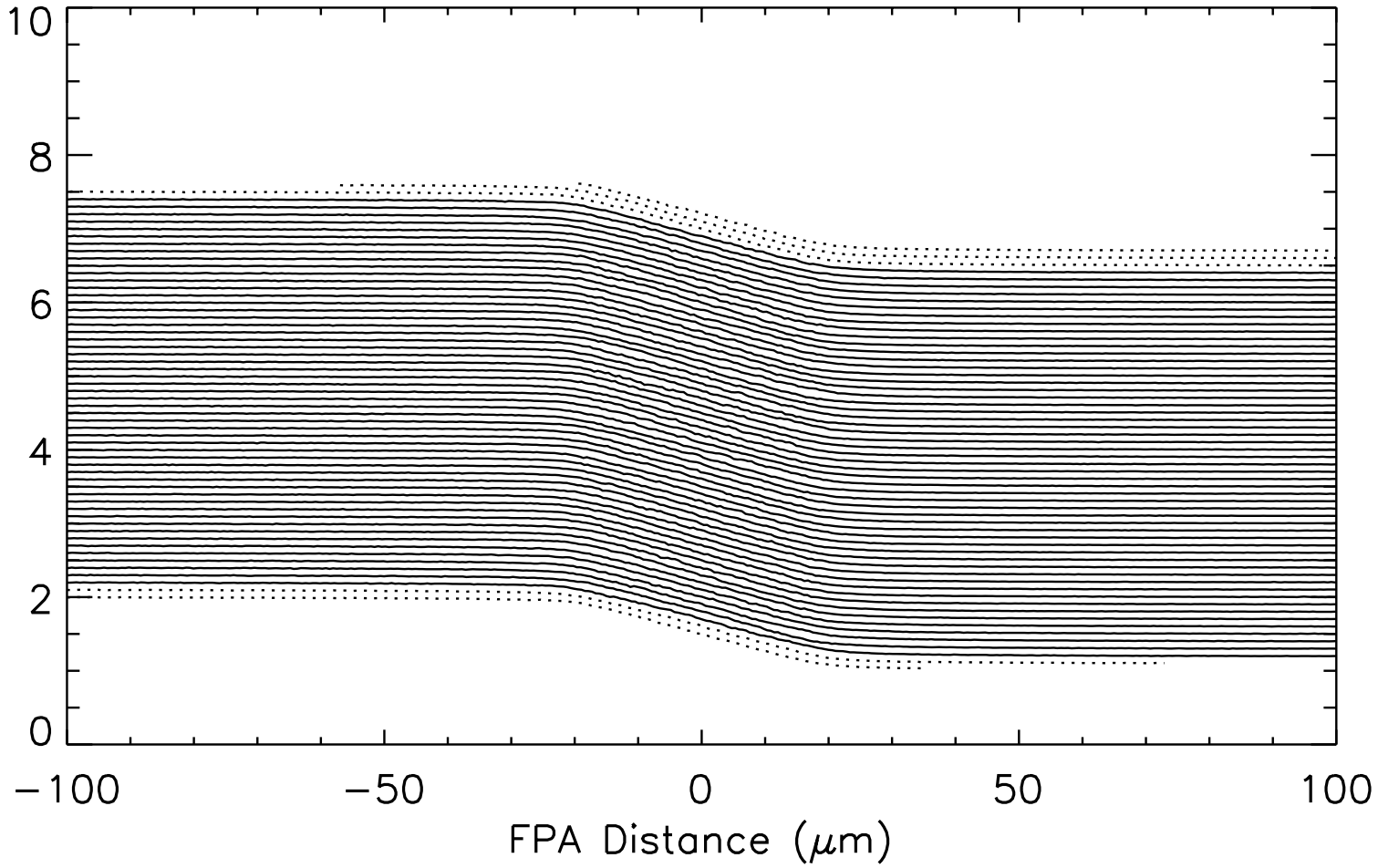
MTF Measurement Procedure

- Scan knife edge slowly across pixel to obtain edge-spread function (ESF)
  - 127 µm/s at FPA, 226 frames/s, 40 µm pixels
  - 22.6 samples/pixel
- Differentiate ESF to obtain line-spread function (LSF)
  - Shift pixel ESF's to a common origin before averaging
  - Make use of diffraction cutoff frequency to smooth data
- Fourier transform LSF to obtain modulation transfer function (MTF)
  - Imaginary component of MTF represents asymmetry of LSF
  - Measured MTF is a one-dimensional slice through the two-dimensional MTF
  - Horizontal and vertical knife edge scans were performed

Edge-Spread Functions, Band 4

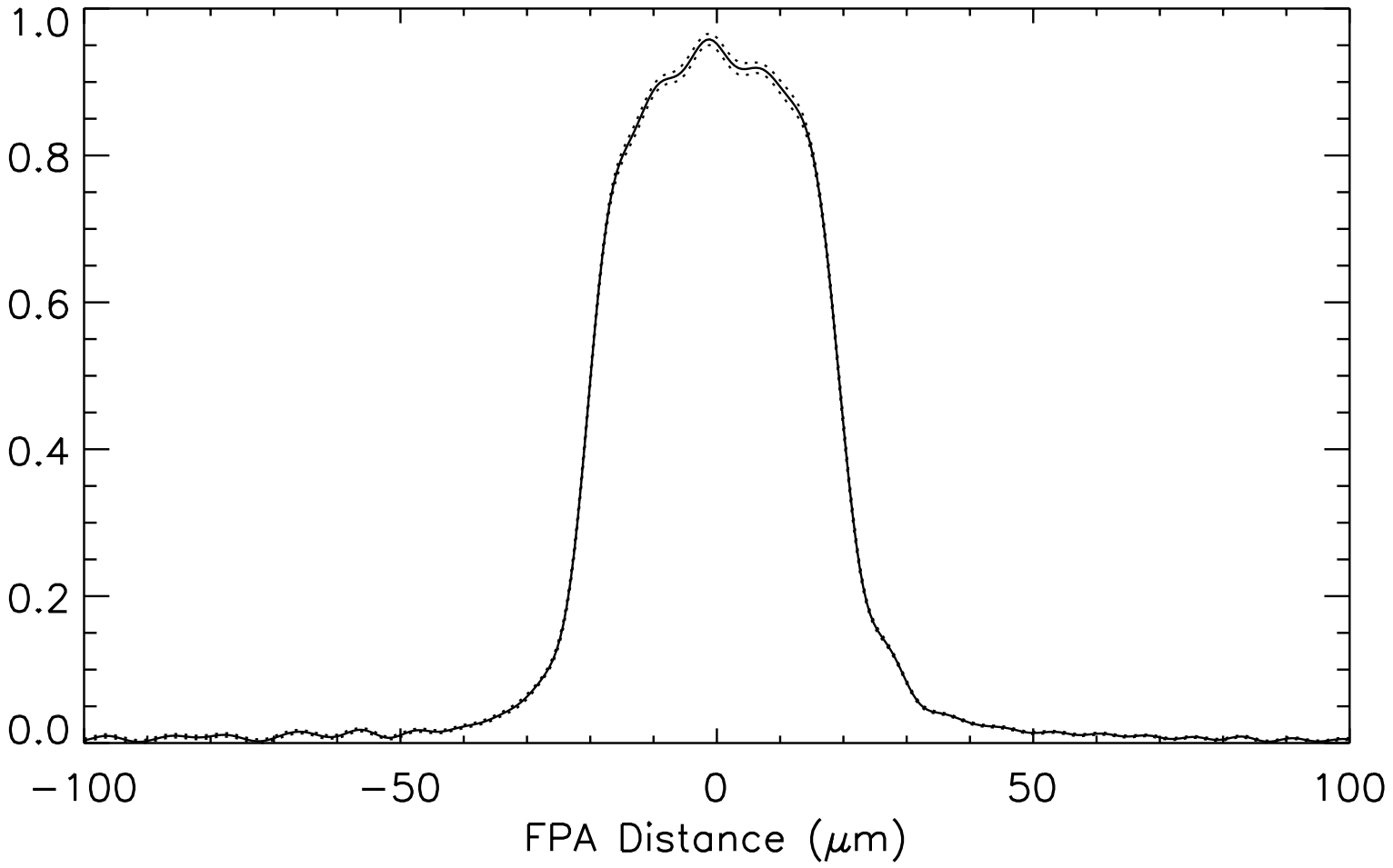
Cross-track scan



ESF's have been normalized and co-aligned

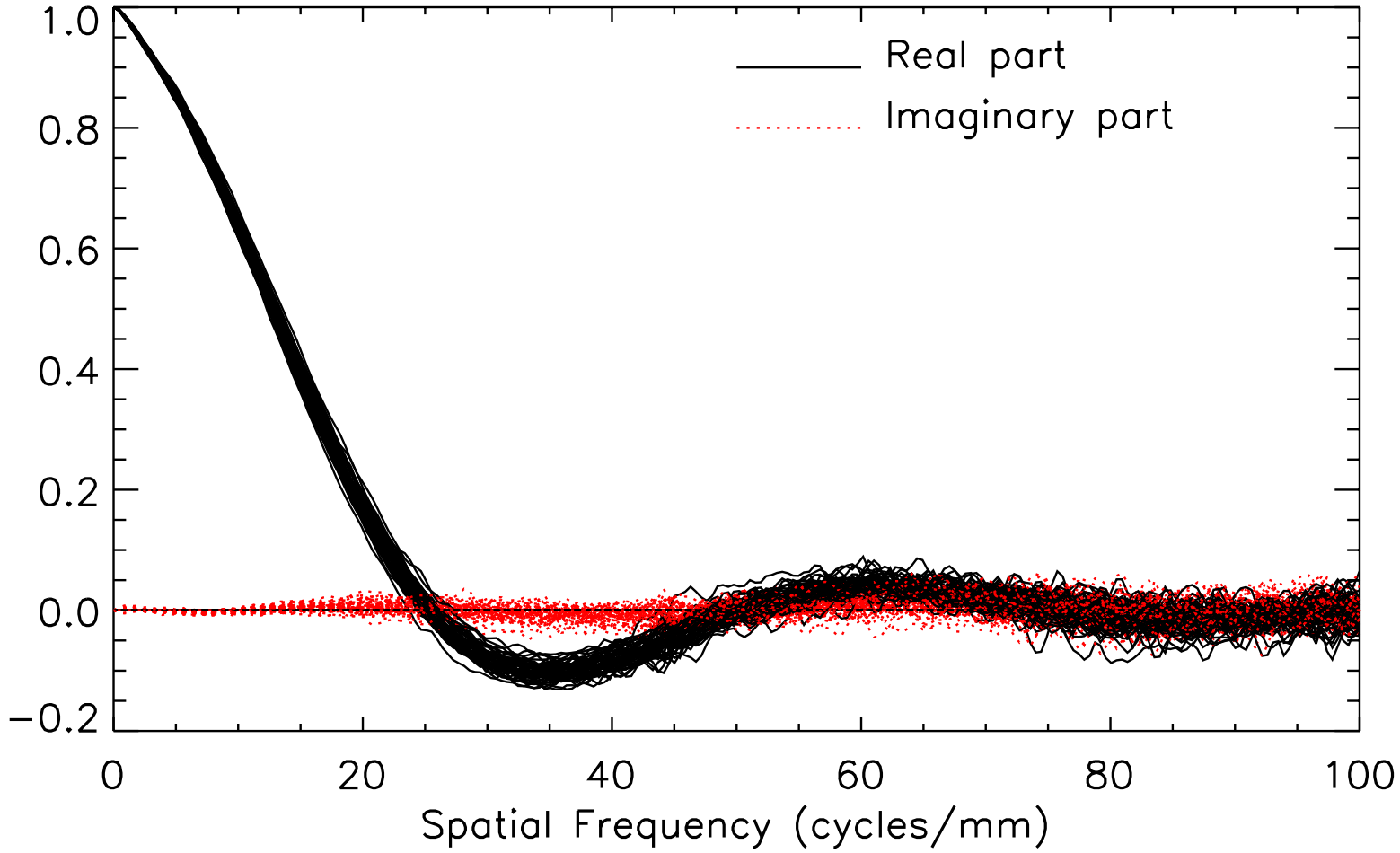
Average Line-Spread Function

Band 4, cross-track



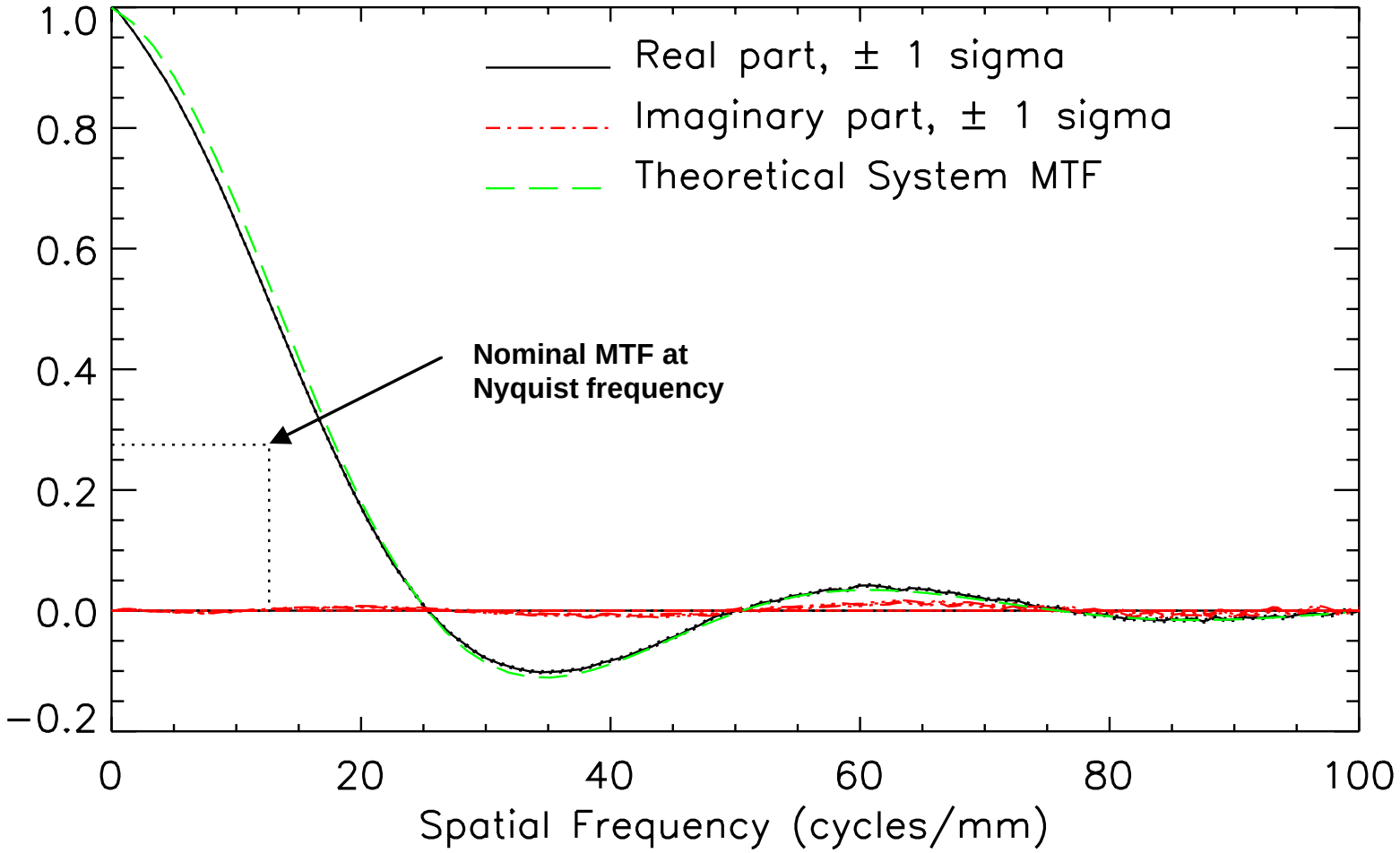
Pixel Modulation Transfer Functions

Band 4, cross-track



Mean Modulation Transfer Function

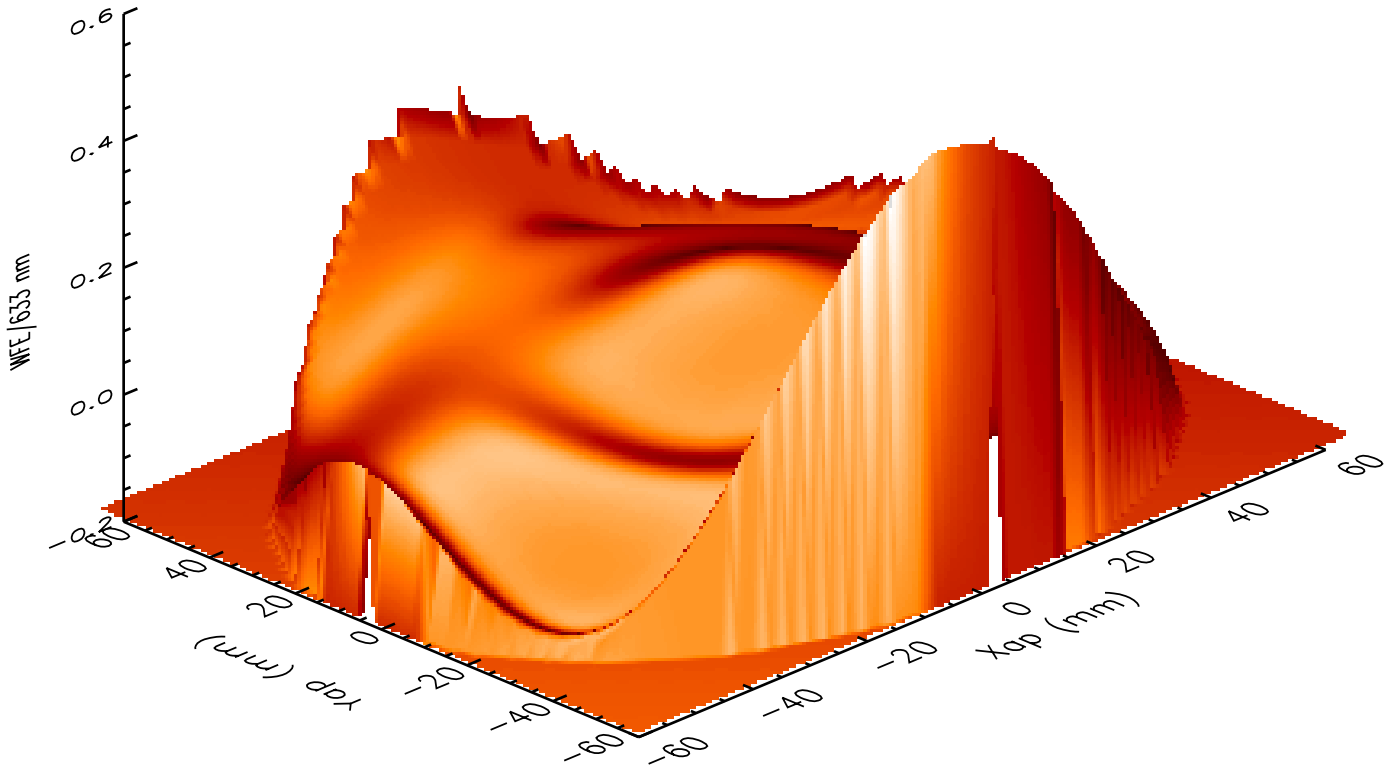
Band 4, cross-track



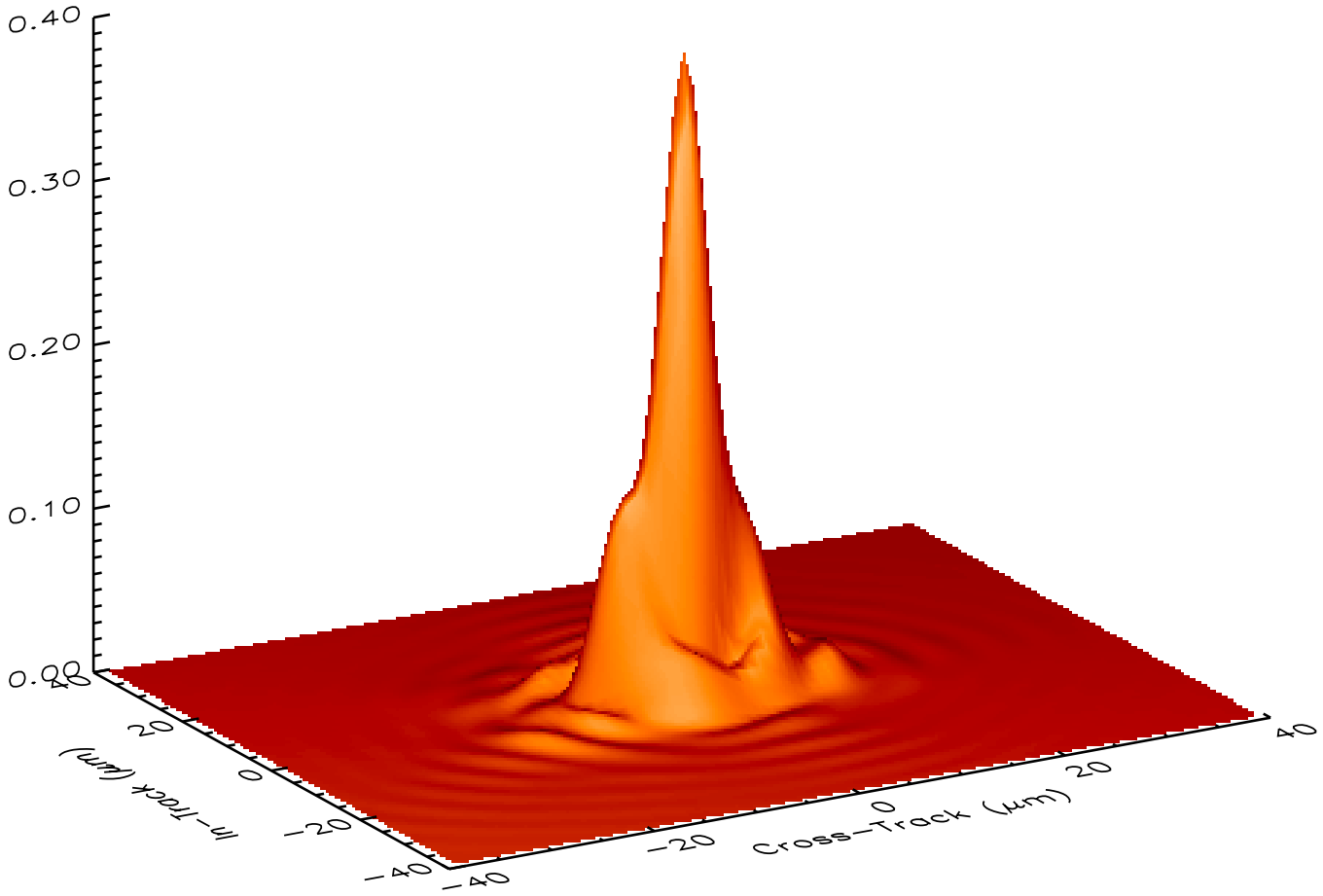
MTF Computation from Wavefront Error

- ALI wavefront error (WFE) measured by SSG with a LUPI, at 11 positions around focal plane
- WFE transmitted as a set of Zernike polynomial coefficients
- WFE expanded from 34 coefficients, with adjustable focus term
- Optical point-spread function (PSF) computed from WFE expansion, via Fourier Transform
- Optical MTF computed from PSF, via Fourier Transform
- Pixel MTF x optical MTF = static system MTF

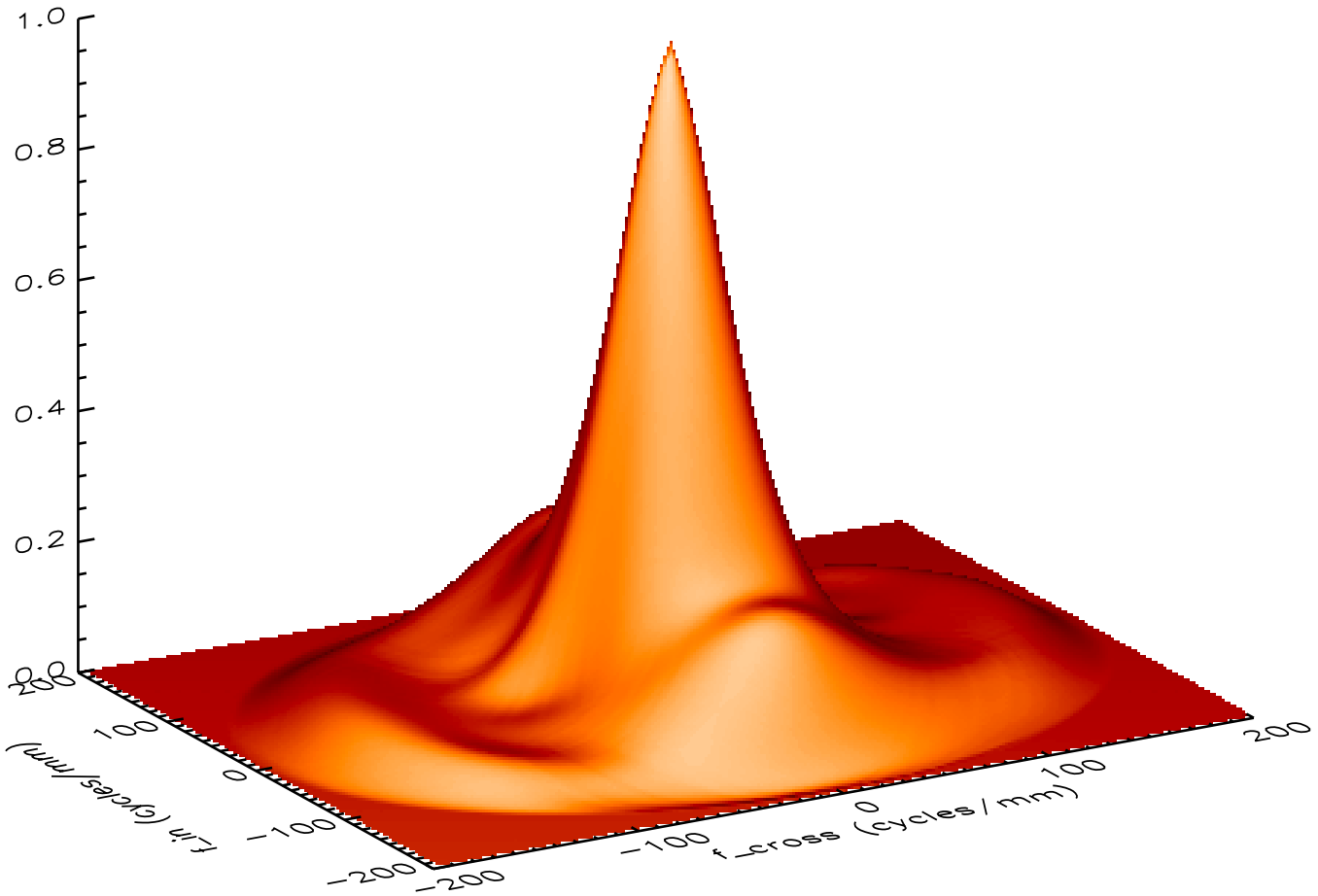
Wavefront Error



Point-Spread Function, with Focus Error

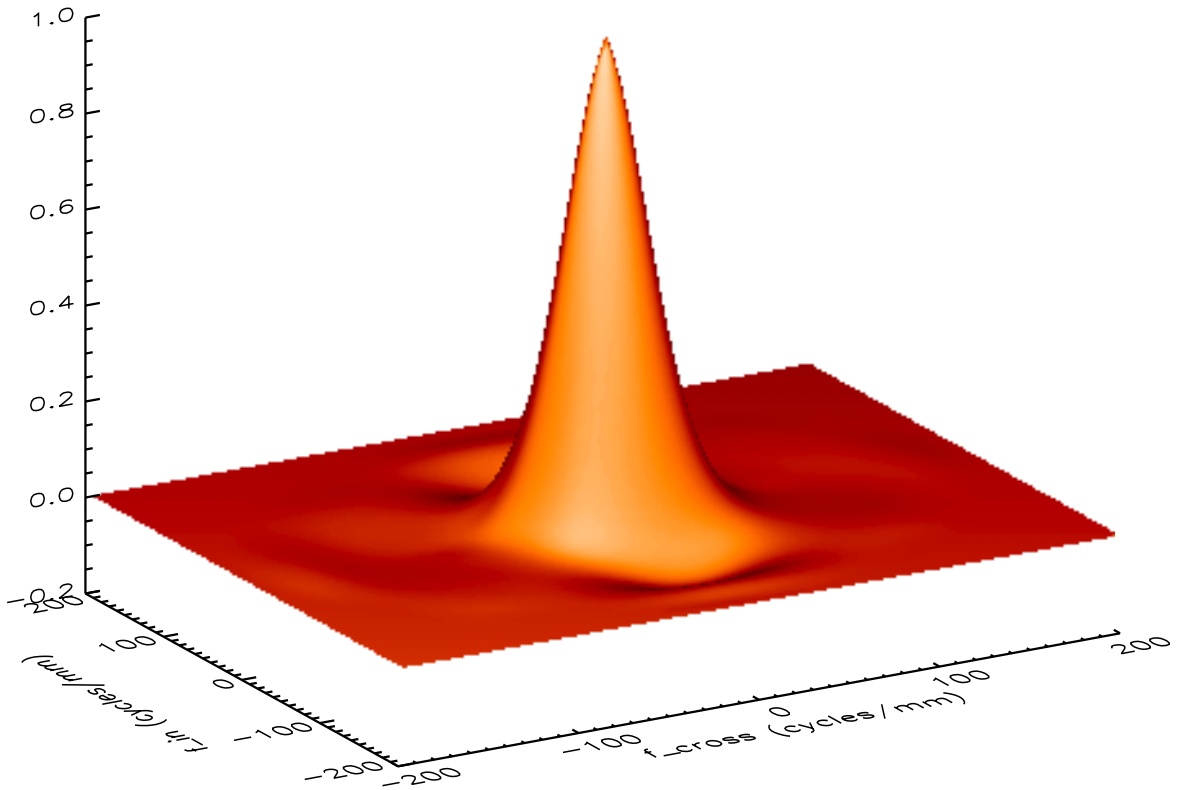


Optical Transfer Function

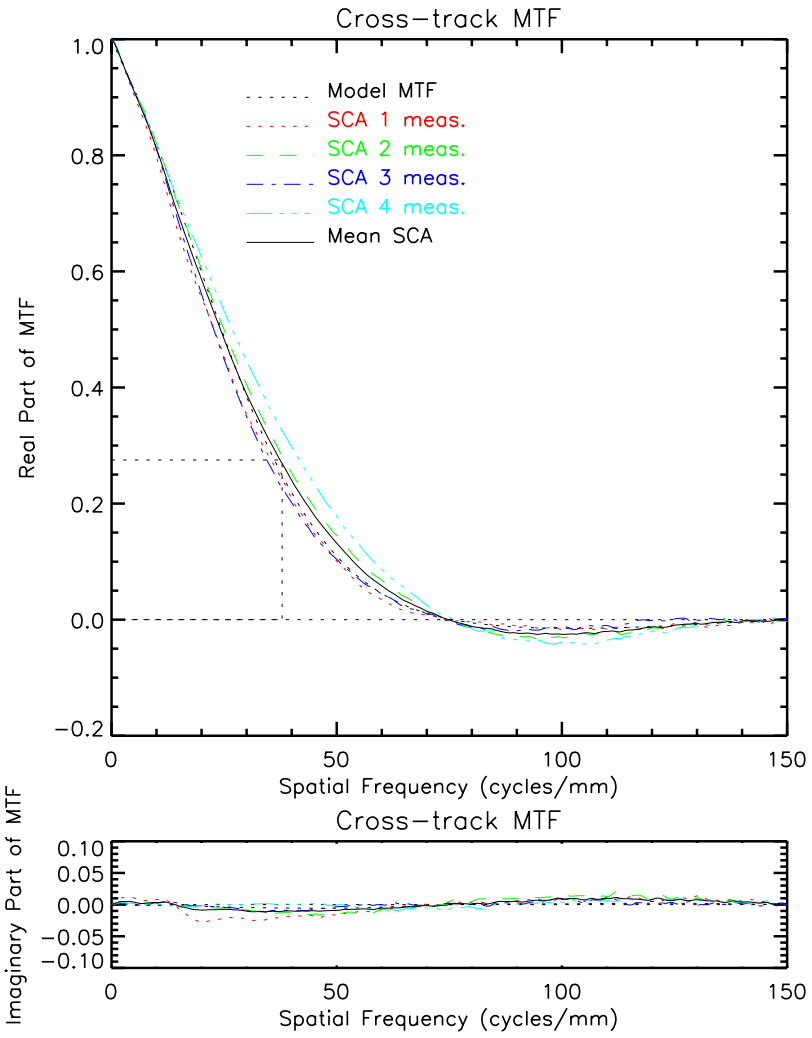


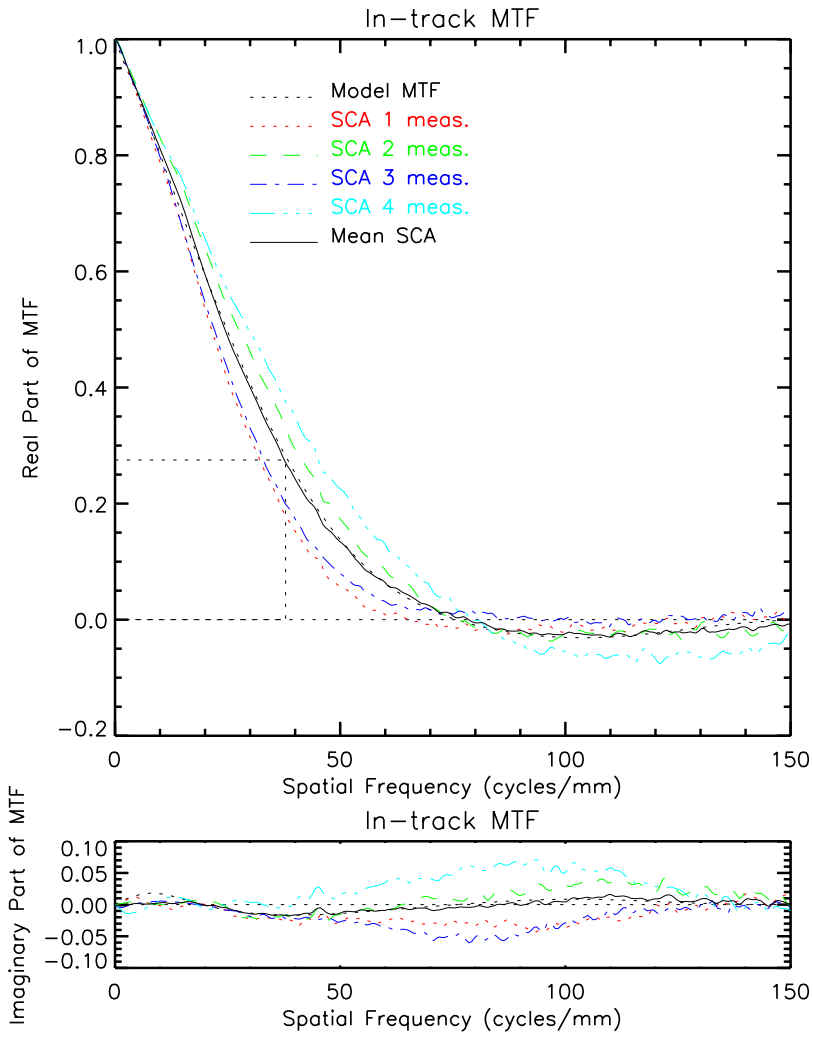
(real part shown)

System MTF, Pan Band



Pan MTF, Measured & Modeled



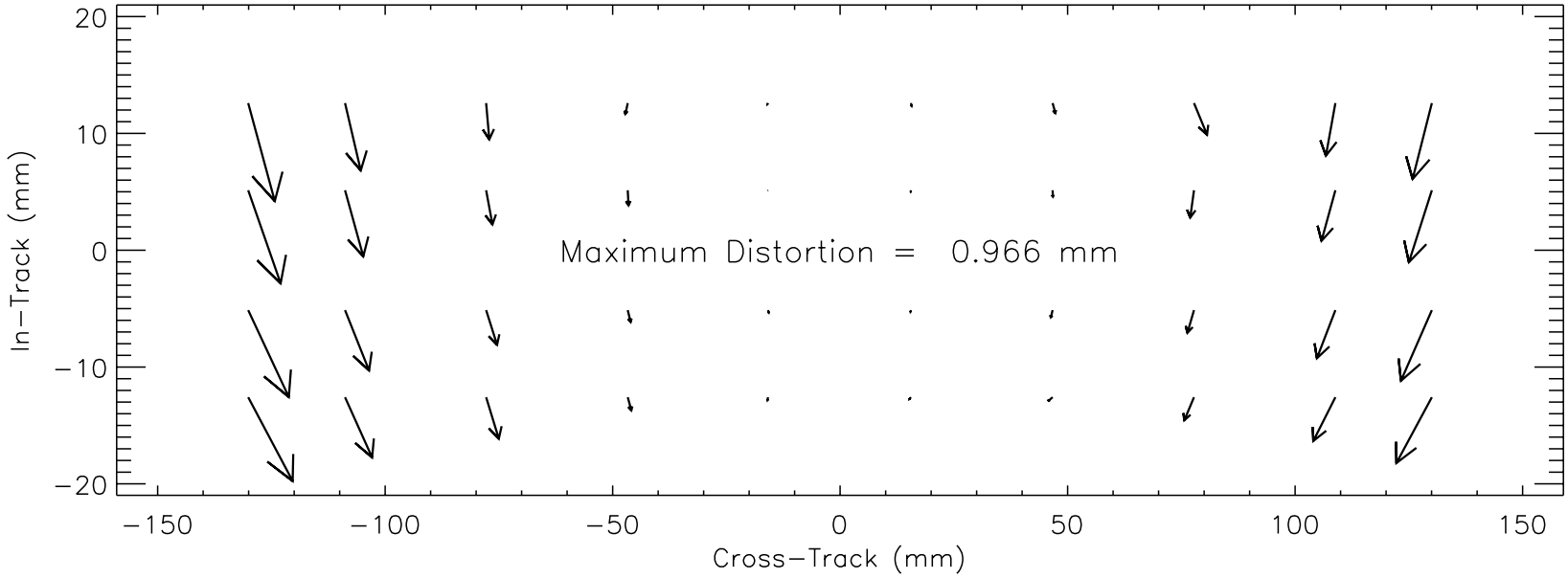


Laboratory LOS Calibrations

- Relative lines-of-sight fitted to static images of Ronchi ruling
  - LOS calibration file constructed from optical distortion and SCA position parameters
- Parameters:
  - Layout of Sensor Chip Assemblies (SCA's) — FIXED
  - SCA positions (24)
  - Optical distortion cubic polynomial coefficients (32)
  - Effective focal length
- LOS calibration file
  - Computed from design and fitted parameters
  - Effective focal length, in mm
  - Apparent position of every detector on focal plane, in mm
- Angles between telescope axes and ALI reference cube estimated from theodolite sightings

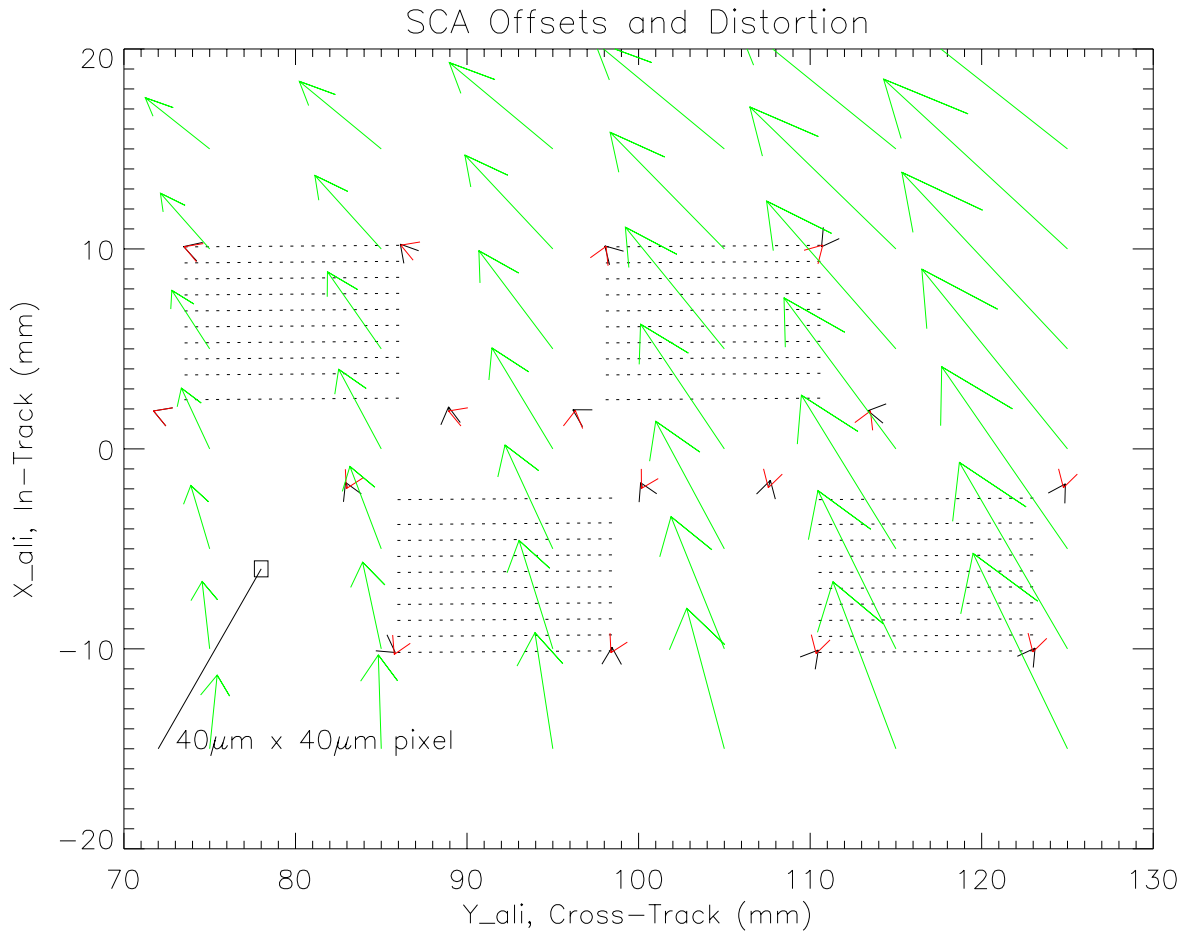
Measured Optical Distortion

Full 15° x 1.6° field of view:



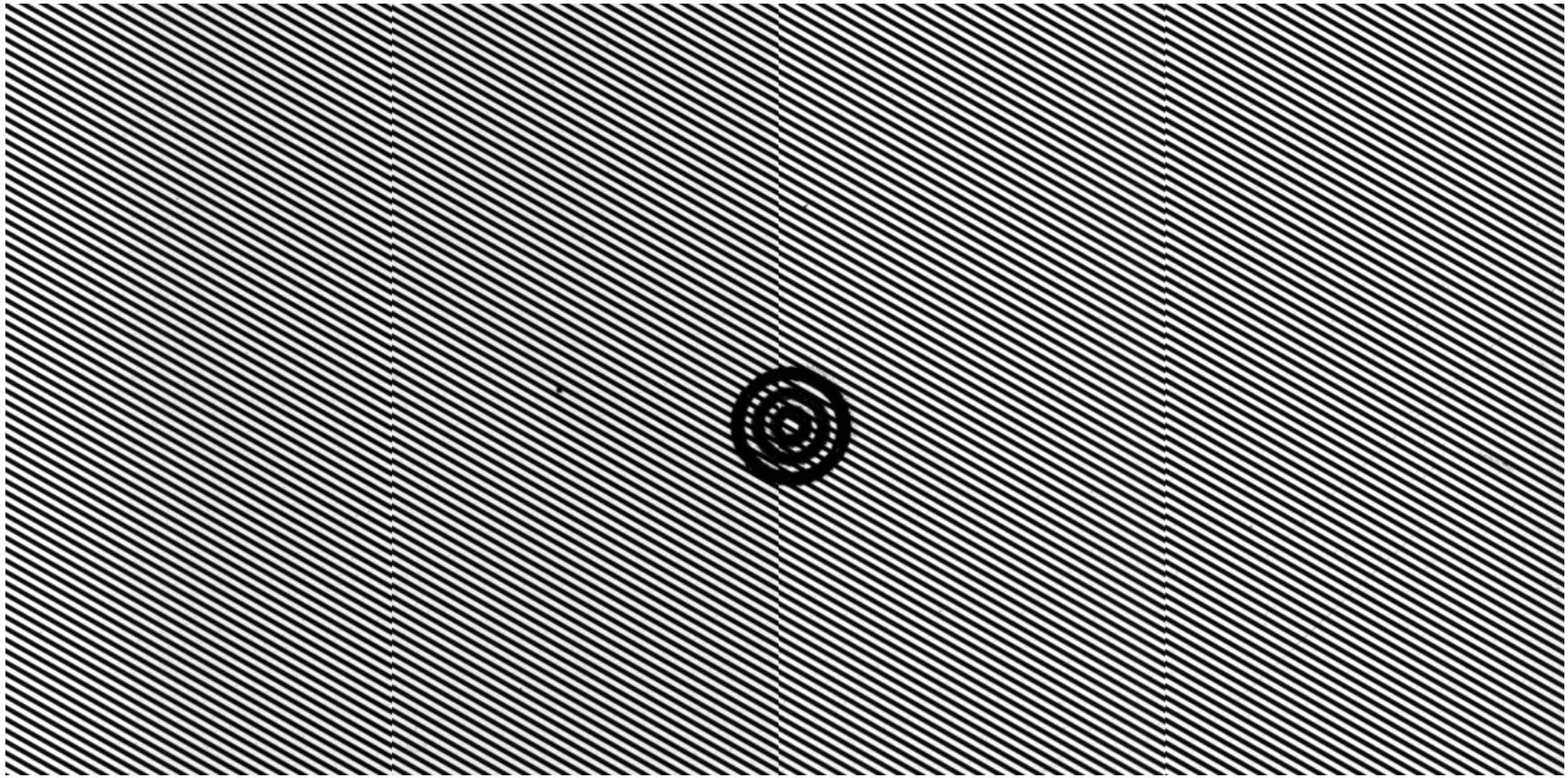
Cubic polynomial fit: rms residual = 8.6 μm

Distortion and Detector Position Errors



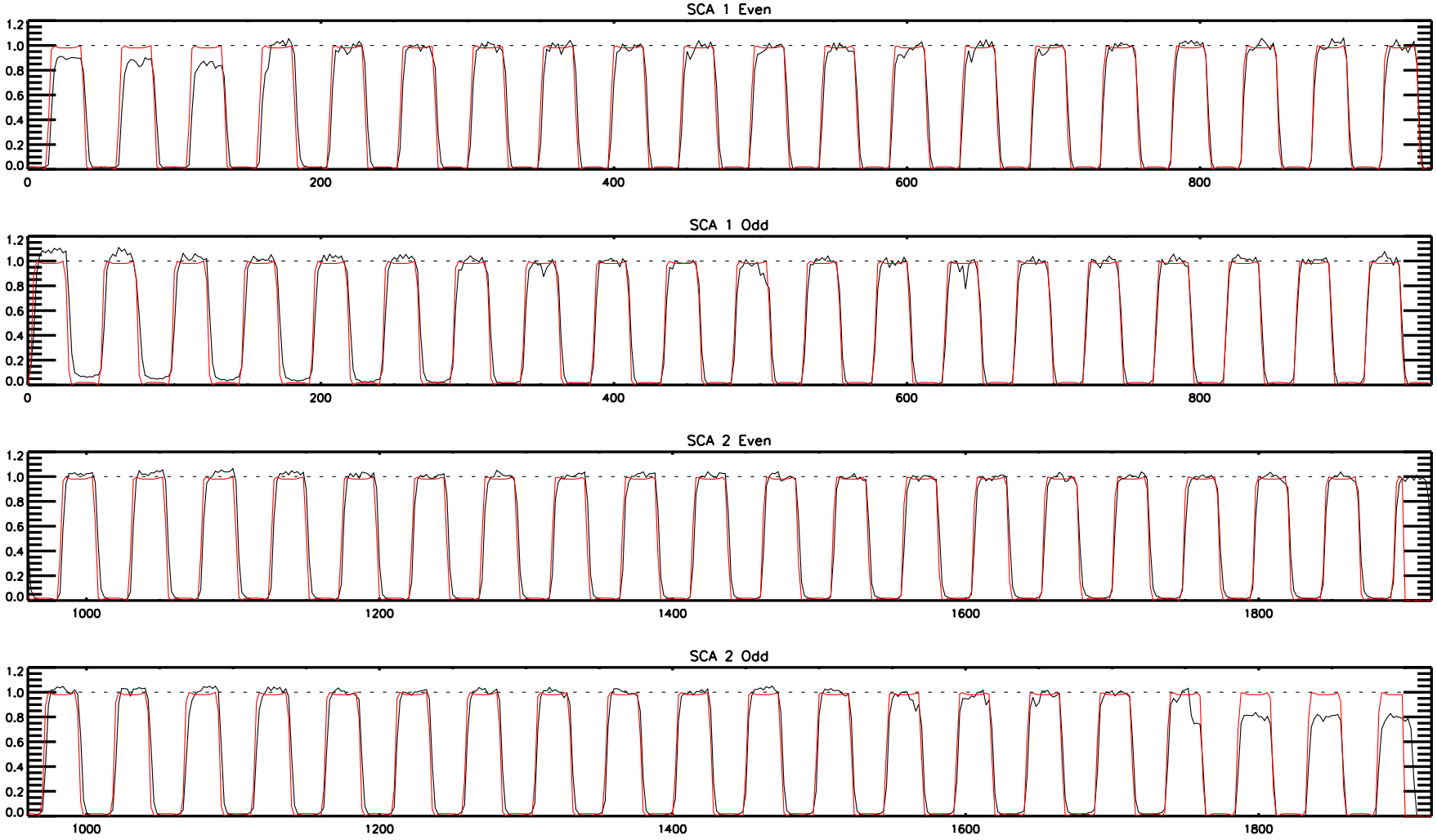
Scanned Image of Ronchi Ruling

Ruling frequency = 2.0 cycles/mm



Bullseye marks axis of collimator

Measured & Modeled Ronchi Image



Theodolite Measurement Setup

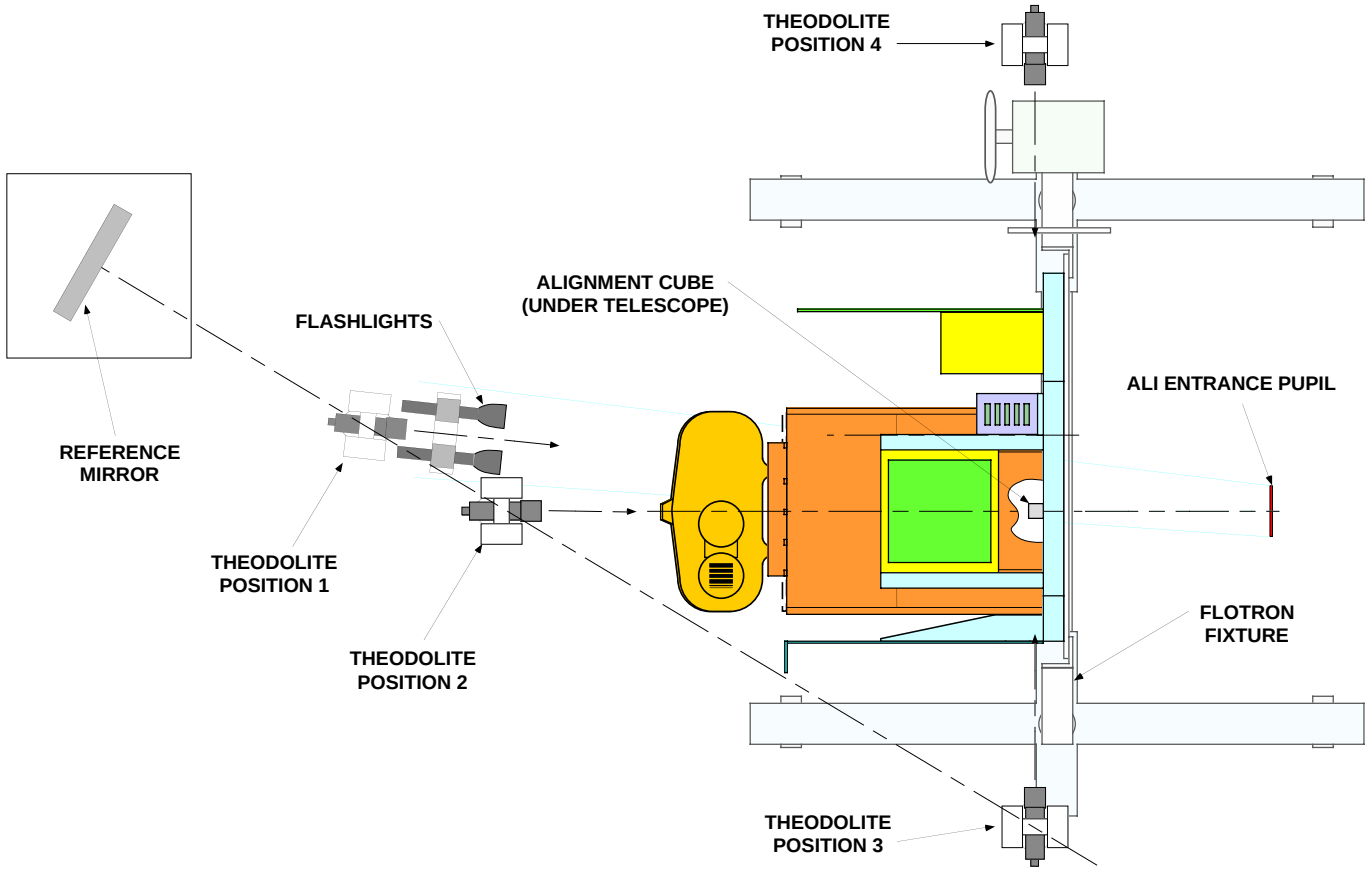


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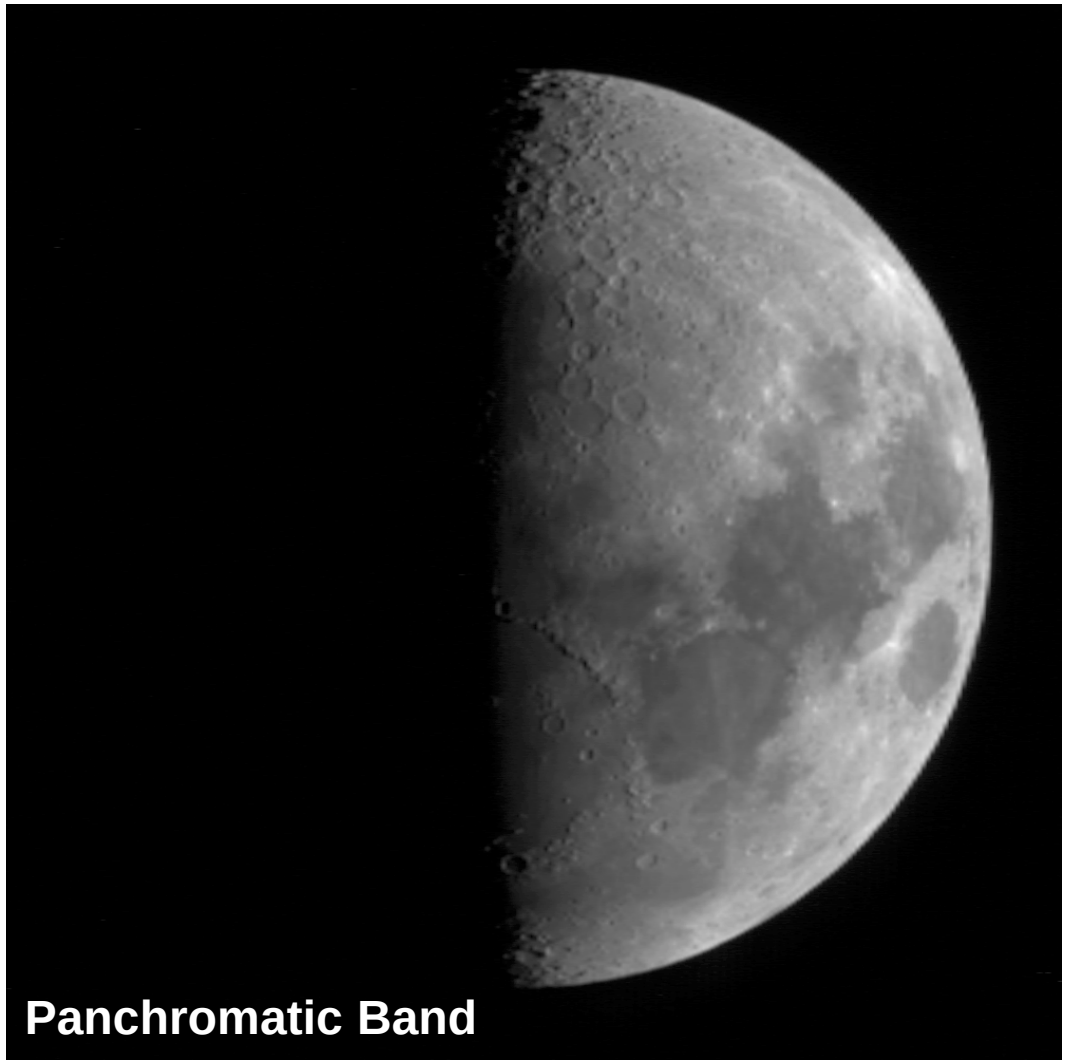
Image Reconstruction

- Read Level 1R HDF files (one per SCA)
- Restore original sample timing (odd/even pixel alignment)
- Assume image moves across focal plane at constant velocity
- Read LOS calibration file
- Estimate image speed and yaw from overlapping Pan pixels
- Resample detector readings in the in-track (X) direction
- Resample in the cross-track (Y) direction
- Resampled image is *system* corrected, not ground referenced
- Write Level 1G HDF files (one per SCA)
- Write JPEG files of full 3-color images

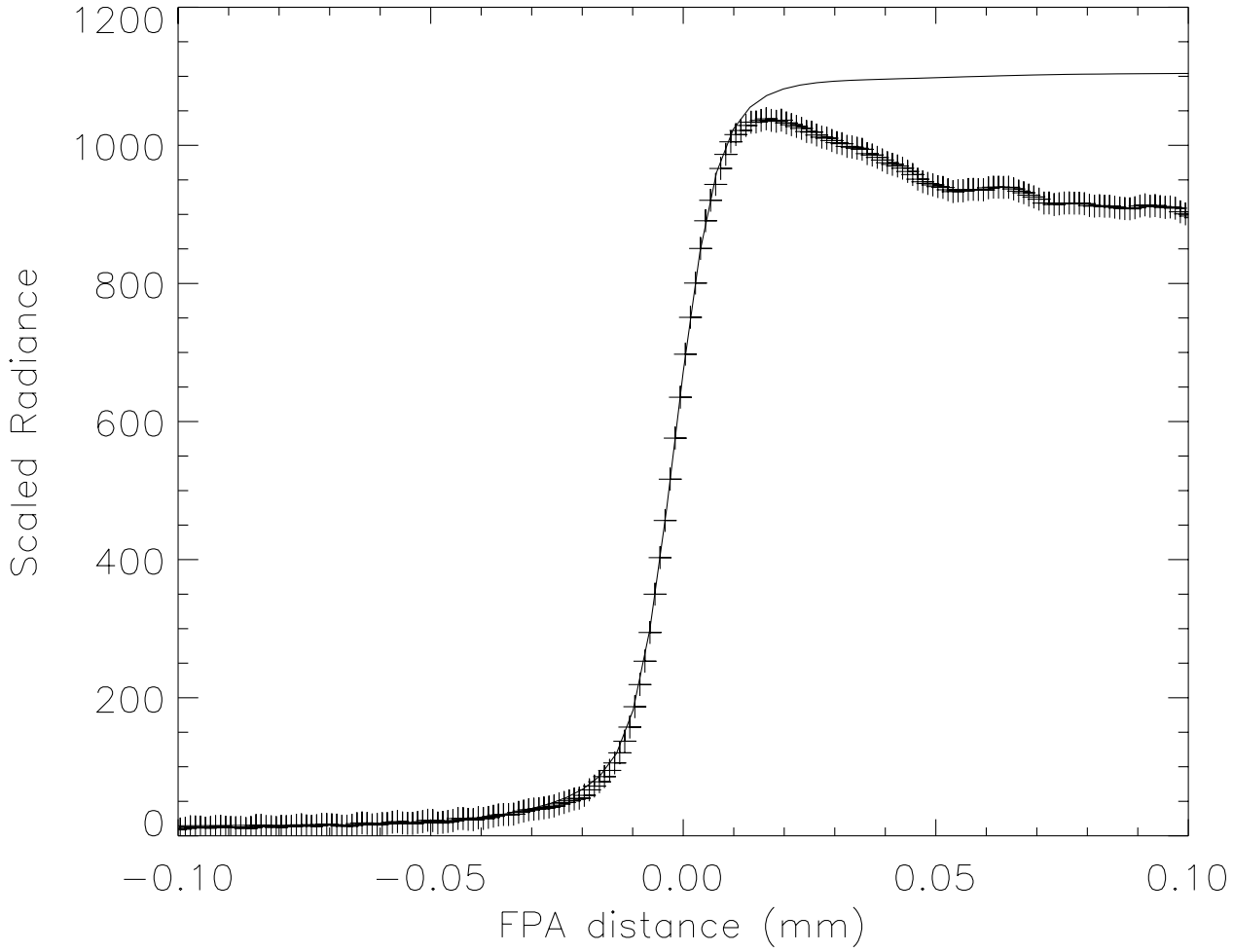
Oahu, HI

Lunar Calibration Scan



Lunar Limb Profile

Panchromatic Band



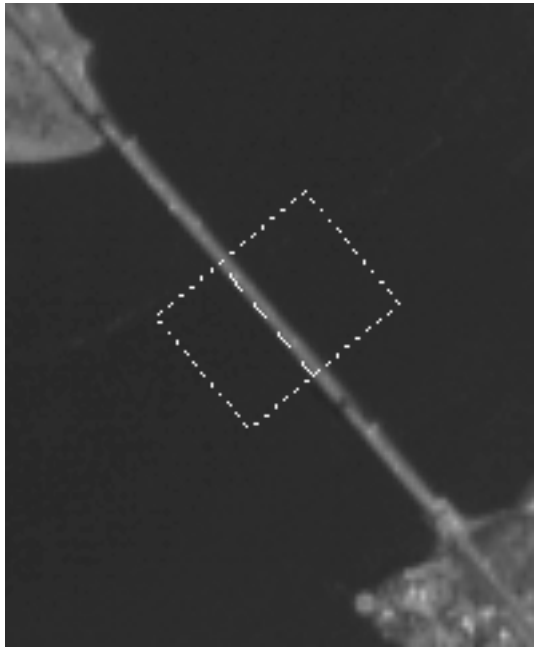
New York City, March 20, 2001

Bands
3, 2, 1

Bronx Whitestone Bridge

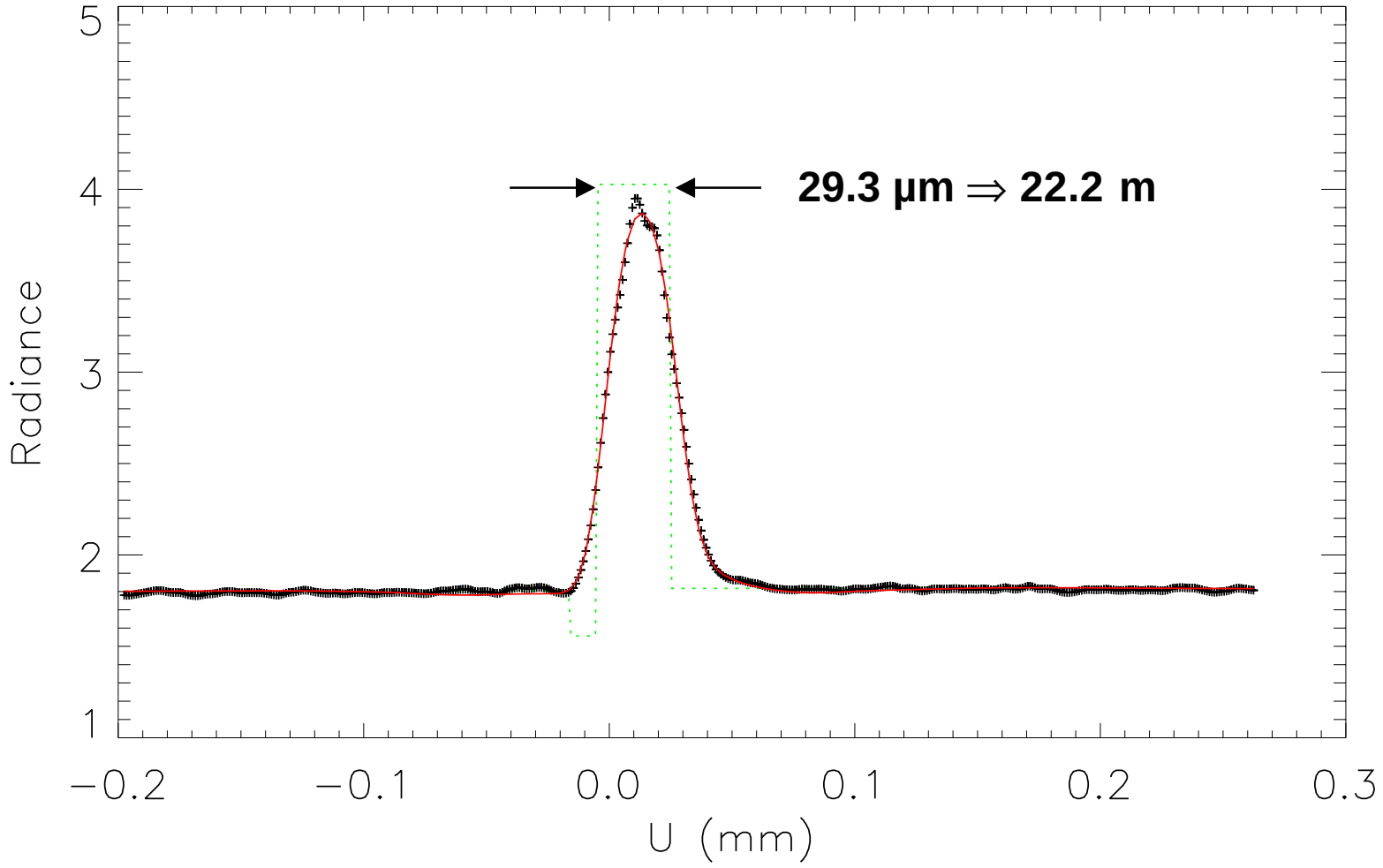
1998 photograph

Width = 23.5 m



ALI Pan image

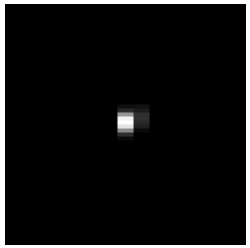
Bronx Whitestone Pan Profile Fit



Vega Image, SCA 4 PSF Fit

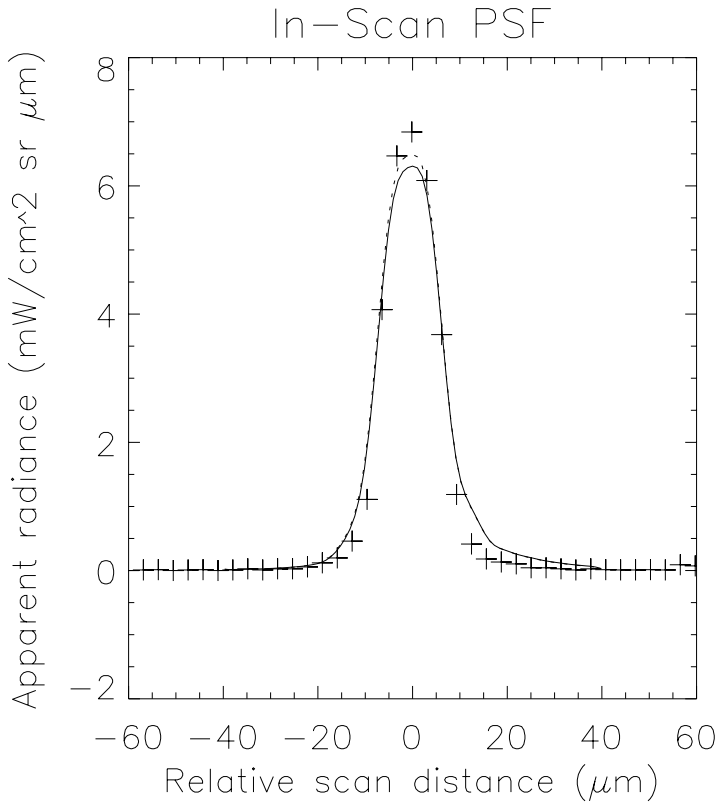
True Values:

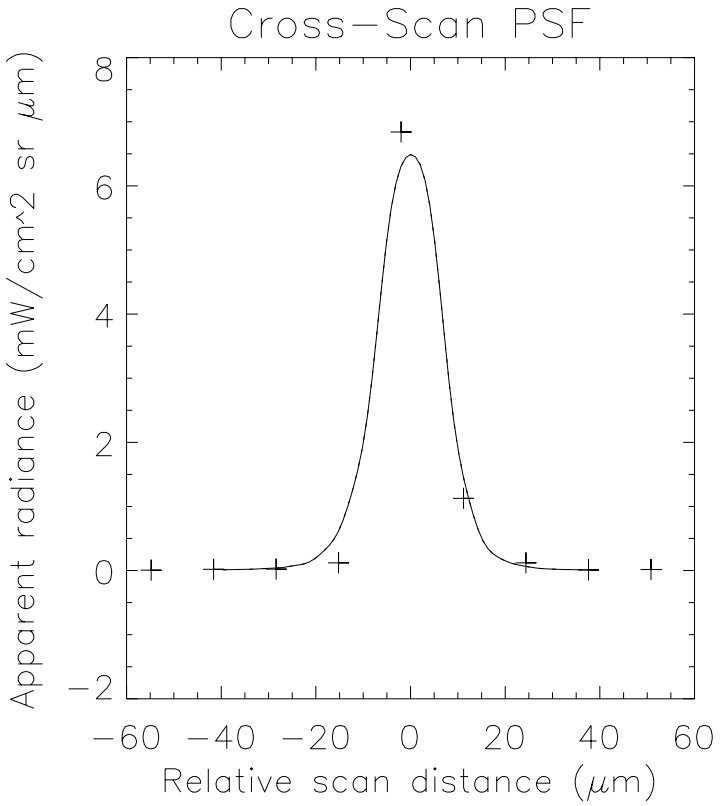
R.A. =	279.234735 deg
Dec. =	38.783692 deg
V magnitude =	0.03 (A0Va)



Fitted Values & Formal Errors:

R.A. = 279.089265 ± 0.0000003 deg
Dec. = 38.460552 ± 0.0000001 deg
Peak Rad. = 6.4937 ± 0.0013 mW/(cm^2 sr μm)





Summary

- Equipment and procedures were developed to perform laboratory system spatial calibrations of the ALI
  - Modulation Transfer Function
  - Detector Lines-of-Sight
- ALI spatial calibration files represent parameters fitted to both subsystem and full system measurements
- On-orbit spatial performance appears to validate the system design
  - MTF is at least as good as estimated before flight
  - No LOS errors are apparent from inspection of images
  - On-orbit spatial performance is in process of refinement
    - Focus parameters
    - Sub-pixel LOS errors