Evaluation of a CCD-based high resolution autocollimator for use as a slope sensor

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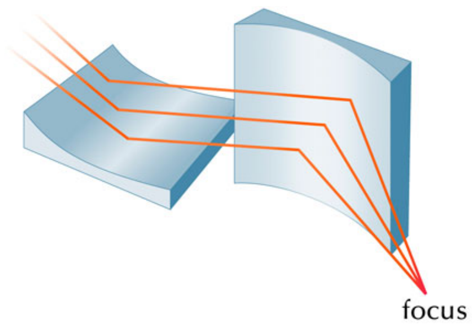
Introduction

- The Advanced Photon Source (APS) at Argonne National Lab generates high energy **x-rays** for experiments in a variety of fields.
- One of the ways to focus x-rays to diffraction limit is by using Kirkpatrick-Baez mirrors



- A high degree of smoothness is required to preserve source properties.
- Surface irregularities exceeding 0.2 rms micro radian slope error will cause the focused beam profile to broaden and decrease its peak intensity
- Project:
  Evaluation of a compact CCD-based high resolution autocollimator with a small probe beam for potential use as a slope sensor

Basic Principle of Autocollimators

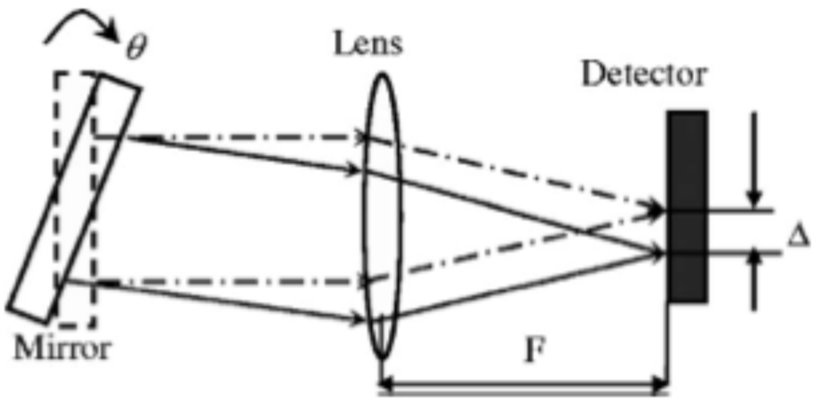
- Uses a collimated beam reflected off a plane surface to measure small angles
- Reflected beam is focused on detector, and deviation is measured
- Fundamental relation between deviation and angle

$$\Delta = F \tan 2\theta$$

- Using small angle approximation, this becomes

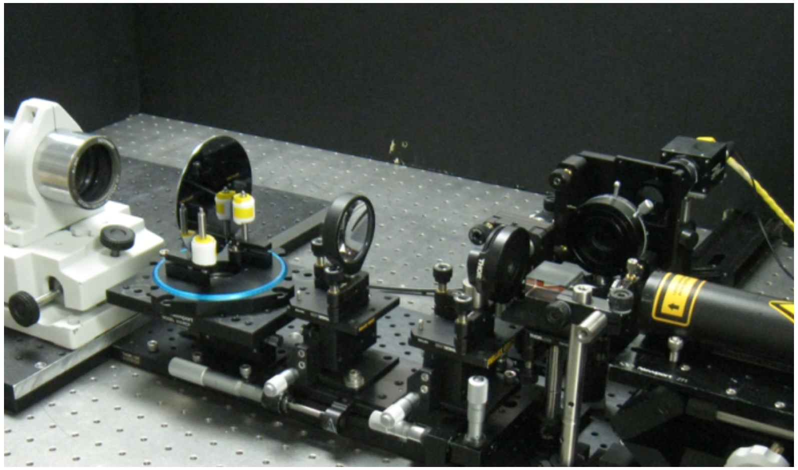
$$\theta = \frac{\Delta}{2F}$$

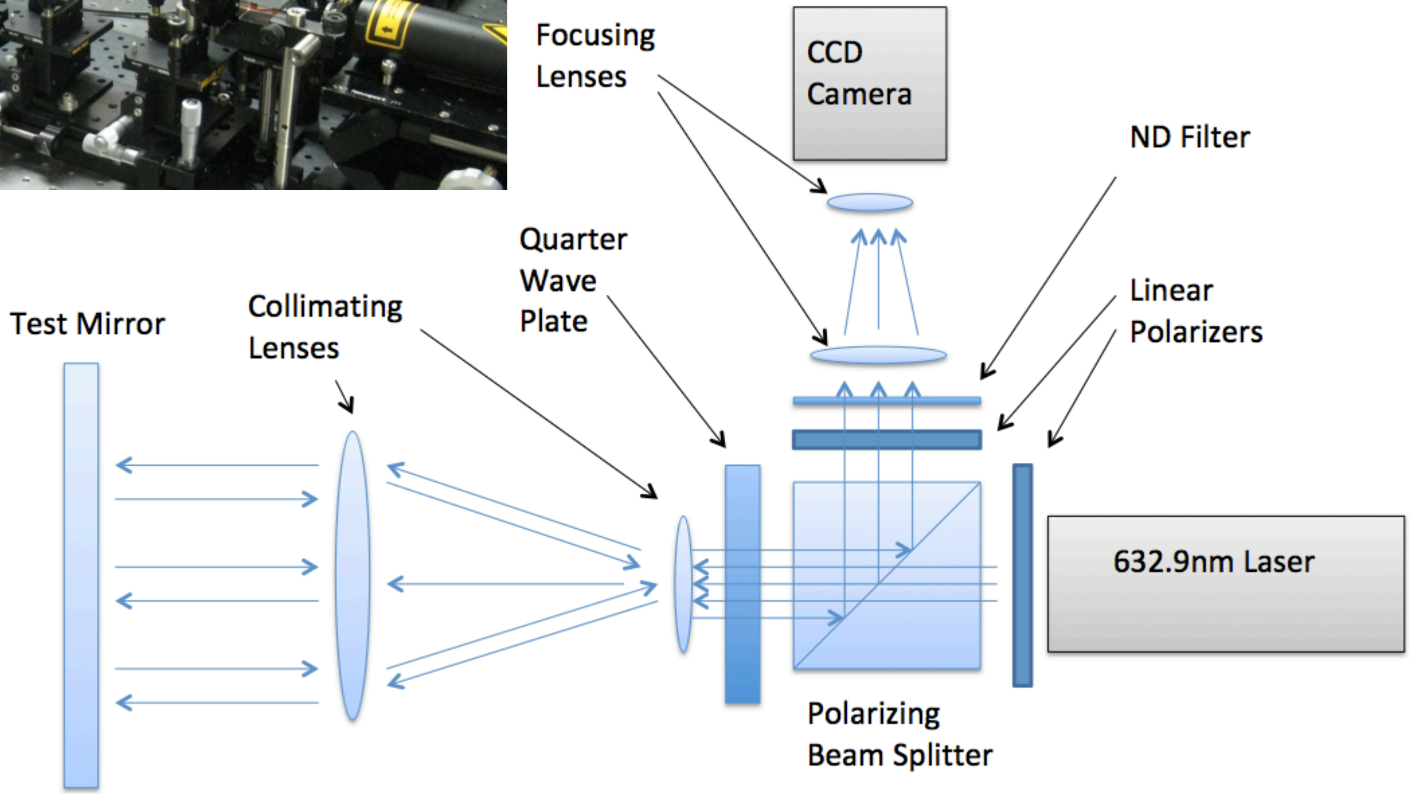
- High resolution achieved using
  - long focal length of lens
  - High spatial resolution of detector



[Kuang, Cuifang, En Hong, and Qibo Feng.]

Our Setup





Focusing Lenses
CCD Camera
ND Filter
Quarter Wave Plate
Linear Polarizers
Test Mirror
Collimating Lenses
632.9nm Laser
Polarizing Beam Splitter

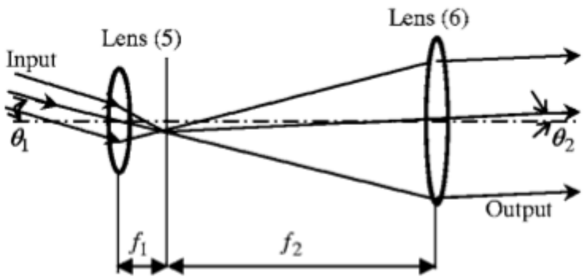
Combination lenses

Collimating lenses

- The angular change in the beam path after the collimation is given by

$$\theta_2 = \frac{f_1}{f_2}\theta_1$$

- For a small in change in the angle of the mirror (θ_2), θ_1 will be amplified by a factor of 10, as f_2 = 100mm and f_1=10mm
- Collimating lenses increases the angular resolution by a factor of 10
- Collimation was tested using a bilateral image shearing interferometer (633nm ParaLine Collimation Tester)

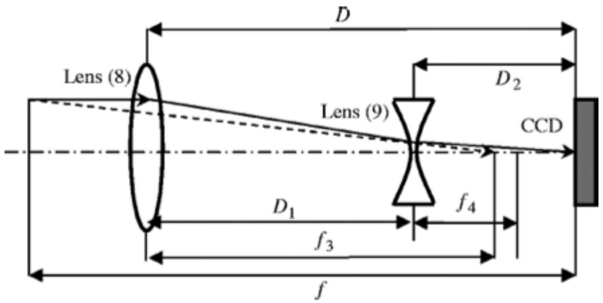


Focusing lenses

- Combination lenses in front of CCD increase angular resolution while decreasing installation space.
- By changing the distance between the lenses (D1), and the distance from the CCD (D2) using the following equations, we can increase equivalent focal length (f) while decreasing total size (D)

$$D_2 = f_4(f_3 - D_1)/(D_1 - f_3 + f_4)$$

$$f = f_3 f_4/(D_1 - f_3 + f_4)$$
$$D = D_1 + D_2$$



[Kuang, Cuifang, En Hong, and Qibo Feng.]

Data Processing

- Data was acquired from Prosilica GC2450 CCD using manufacturer software
  - 100 frames (2448 x 2050 8bit gray scale TIFF images) averaged in MATLAB for each point
- Centroid detection using Fourier method
  - A real profile can f(x) can be represented as a Fourier series

$$f(x) = \sum_{k=-N}^{N} C_k e^{2\pi ikx/N} \qquad C_k = a_k + ib_k$$

  - If the function is symmetric about the origin x=0, imaginary components of C vanish
  - Measure of asymmetry of function centered at Δx is given by

$$A(\Delta x) = \sum_{k>0}^{N} (IM[C_k e^{-2\pi ik\Delta x/N}])^2$$

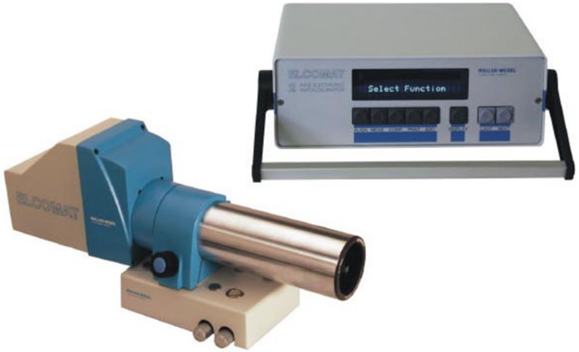
  - If we assume symmetry of profile and limit to fundamental frequency k=1

$$IM[C_1 e^{-2\pi i\Delta x/N}] = a_1 \sin(2\pi\Delta x/N) - b_1 \cos(2\pi\Delta x/N) = 0$$

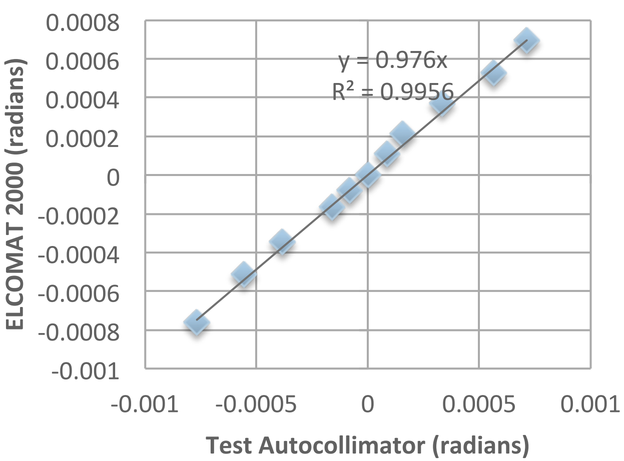
$$\Delta x = \frac{N}{2\pi}\left(arctan\left(\frac{b_1}{a_1}\right) + \Phi\right)$$

- 1px on camera corresponds to 3.45µm, using the equations described gives us 1.725µrad/pixel. This gives the system a total theoretical precision of **about 40.1 nano radian**

Testing and Results

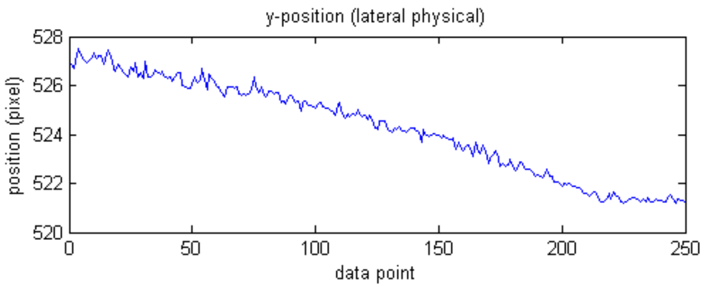


- Double sided Silicon mirror
  - Surface roughness about 7Å, diameter of about 100mm
  - Mirror mounted on compact Pizeo-Electric rotation stage
    - Controlled by computer software provided by manufacturer
    - Step size of 0.01° (~174.5μrad)
- Commercial autocollimator (ELCOMAT 2000) aligned on the opposite side
  - Provides measuring in the visible range (660nm)
    - Range of 0.01 radians (35 arc minutes)
    - Precision of up to 0.5 micro radians (0.1 arc seconds)
  - LabView routine to retrieve 4KB (~500 data points) of angular position in both x-axis and y-axis deviation using RS232 Serial connection
  - C++ code to parse data from ELCOMAT 2000
- Position from both autocollimators tested against each other.



Application to the alignment of the new Long Trace Profiler laser

- Use centroid detection system to align the laser
- Constant centroid position over entire length will show alignment



Before Alignment		After Alignment	
Δx	5.688px (0.0367mm)	Δx	1.555px (0.0100mm)
Δy	6.316px (0.0407mm)	Δy	y 2.037px (0.0131mm)
θx	36.687 micro radian	θx	10.027 micro radian
θy	40.740 micro radian	θy	13.141 micro radian