In Situ Focal Plane Metrology

Peter Kim
SLAC

LSST Camera Face-Face Meeting
Oct 17-18, 2005
Brookhaven National Lab

Focal Plane Flatness Requirements

Focal Plane Array of 25 Rafts on Integrating Structure
must be flat to 10 microns (Peak-Valley)
At Operating Temperature (-100^0 C) and
$\pm 45^0$ From Vertical

Flatness Measurements at <1 micron Accuracy

Desirable to have More than One In-Situ Measurement

For Review of Metrology Options and Technical Details,
see R. Schindler's talk at June Camera F2F Meeting
(www-group.slac.stanford.edu/kipac/dkg/
Camera_F2F/CameraF2FJun05/)

OUTLINE

- **Design and Construction of Cold Test Box   H Rogers, R Schindler**
- **Metrology with Non-contact Triangulation Sensors (Keyence LK-G)**
  A Rasmussen, P Kim
- **In-Situ FPA Metrology**

  Diffraction Pattern Generators   W Langeveld
  Capacitive Edge Sensing   E Lee
  Optical Straightedge   E Lee, T Thurston
  Frequency Scanning Interferometer   C West, P Kim, R Schindler

From Presentations at Weekly LSST Camera Cold Metrology and Thermal Design Meetings (M Perl, R Schindler)

Cold Test Box

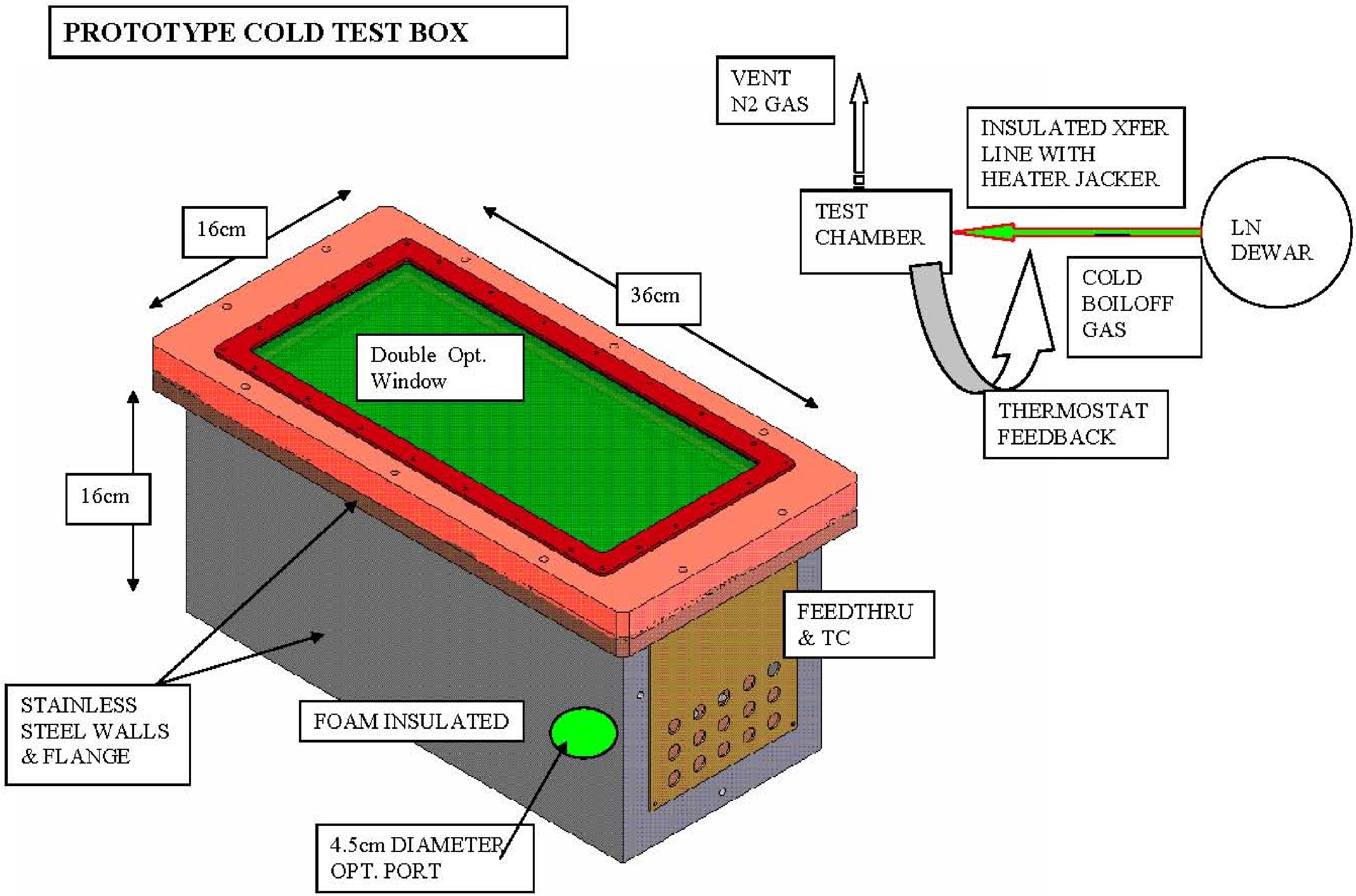
Need a Large Volume Cold Box for

Material Stiffness Studies
Electrical Components Cold Test
Thermal Cycling Test

Use Boiloff N2 Gas,
Temp. down to -120^0 C

Heater Control of N2 Gas with RTD Sensors and Thermostat

Optical Flat Double Pane Window with Dry Gas Flow in between

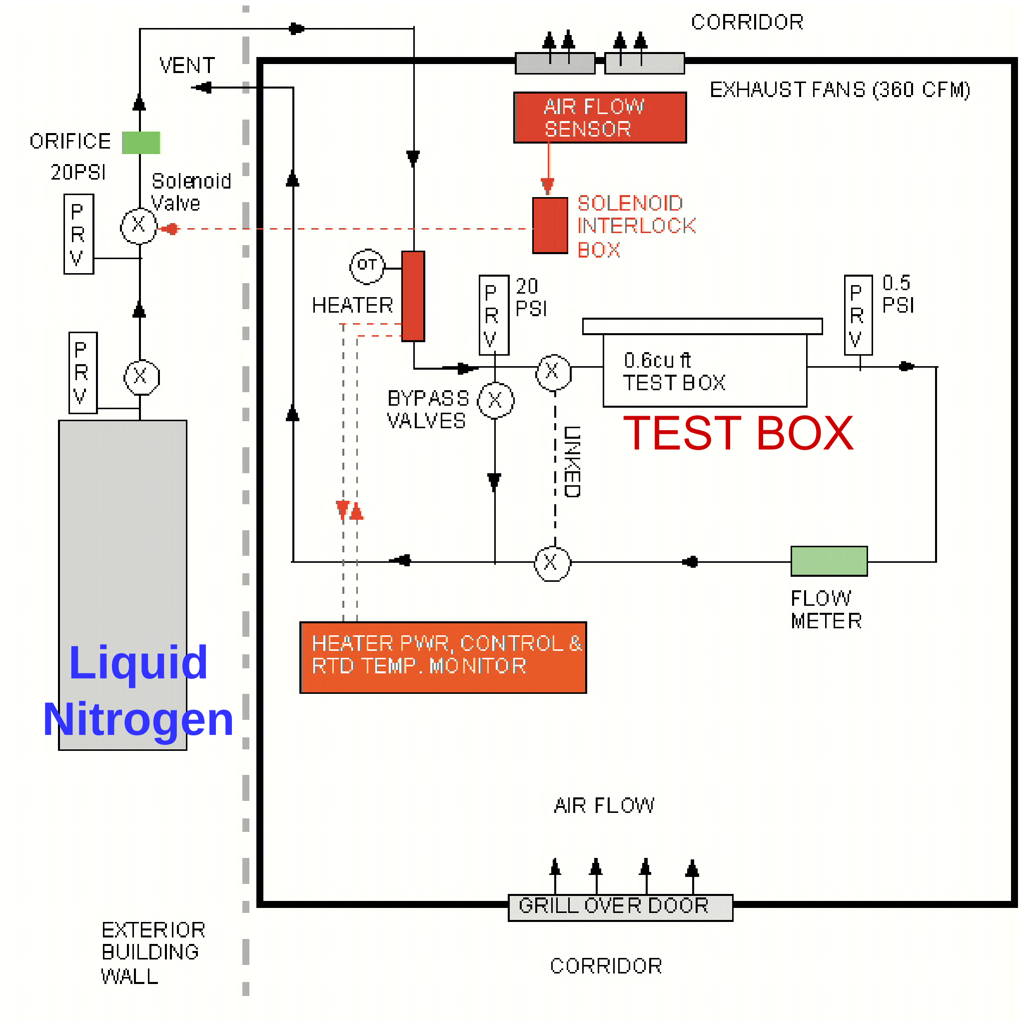

PROTOTYPE COLD TEST BOX
VENT
N2 GAS
INSULATED XFER
LINE WITH
HEATER JACKER
TEST
CHAMBER
LN
DEWAR
COLD
BOILOFF
GAS
THERMOSTAT
FEEDBACK
16cm
36cm
Double Opt.
Window
16cm
FEEDTHRU
& TC
STAINLESS
STEEL WALLS
& FLANGE
FOAM INSULATED
4.5cm DIAMETER
OPT. PORT

Schematics of the Cooling System

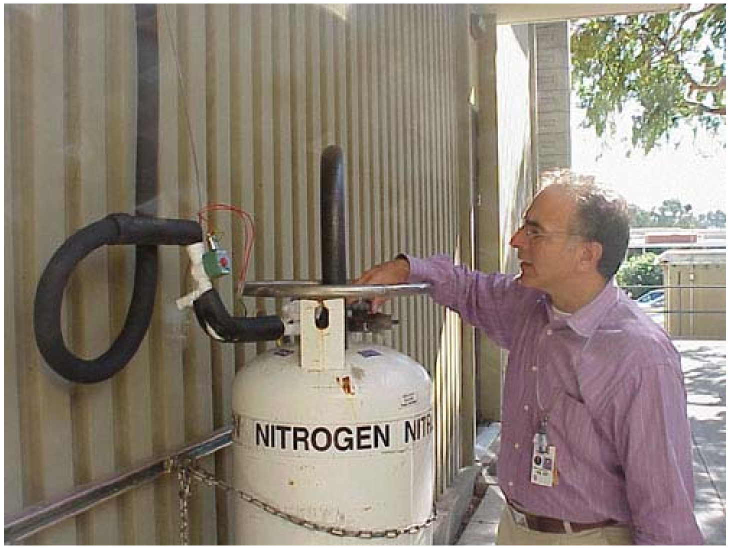
Safety Measures:

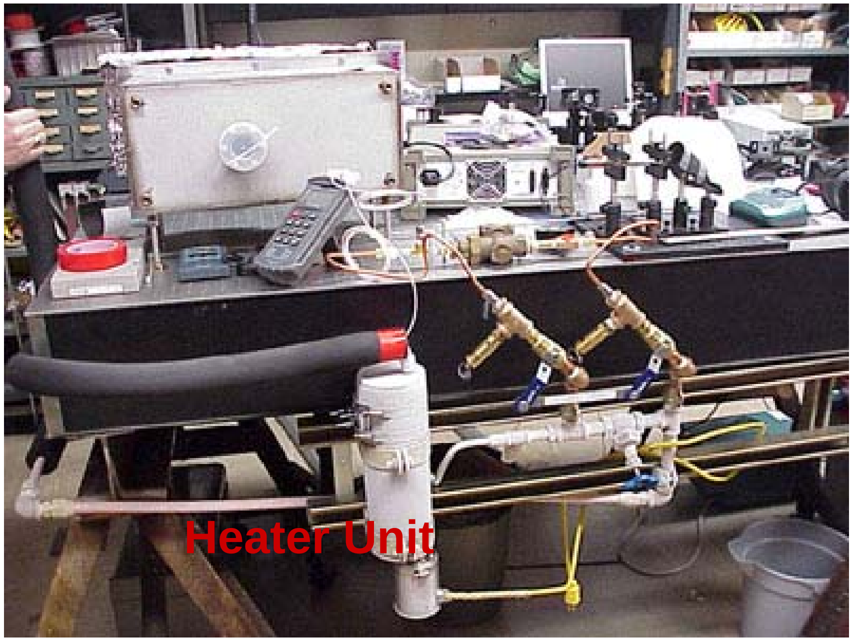
- Liquid Nitrogen outside Building
- Ventilation Fans on both sides of the room
- Solenoid Interlock with Air Flow sensors

SLAC Safety Approval:
Memorandum, JHAM, AHA
Safety Walkthrough



Initial Test of Cooling Lines





Cooling Rate: 4º C / min
T = - 60º C at the end of >10 m line

Safety Features Functioning Well

NEXT: Increase N2 Gas Flow, Insulate the Box/Connections &
Start Thermal Testing of Components

Non-contact Triangulation Sensors

Proven Method

Subaru Suprime-Cam, ESO OmegaCam, etc.

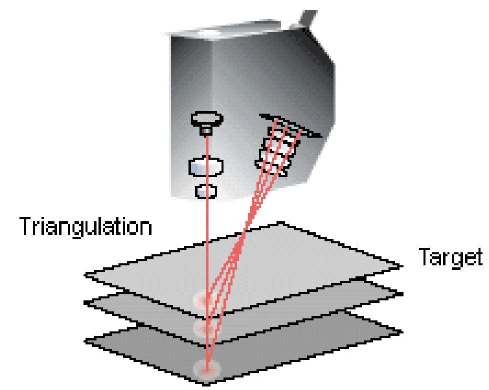
Great Improvements in Sensor Technology

CCD Camera

Higher Resolution over Wide Range of Distances

Measurement Through Glass

–> Cold Surface Measurement



Raft Metrology at BNL: P. Takacs's Talk

Provide Reference Flatness Measurements for In-Situ Devices

Vendor Visit to SLAC (Keyence LK-G System Demo, May, 2005)
Purchased 2 Sensors for FPA R&D (July, 2005)

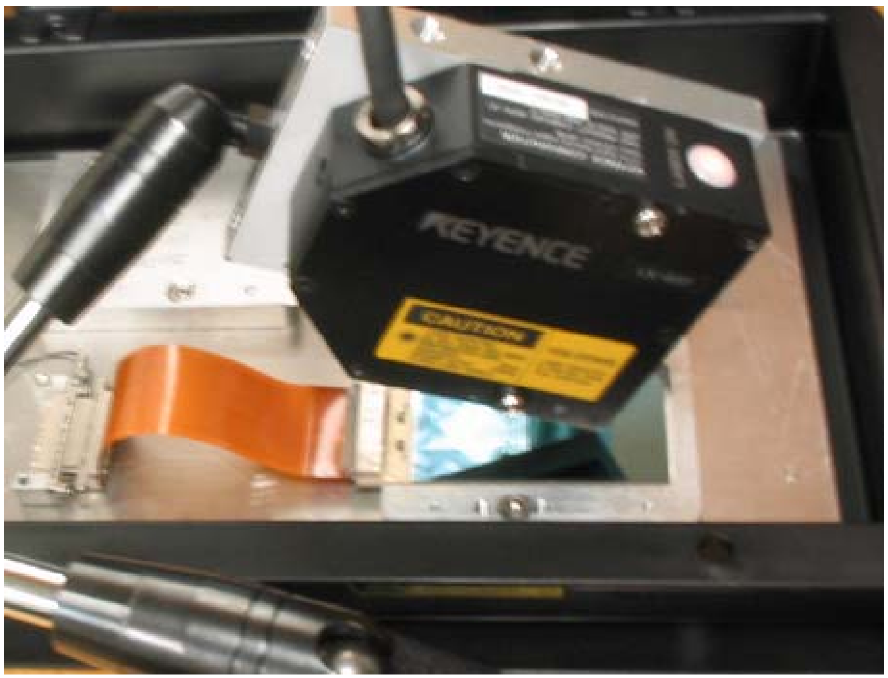
Keyence LK-G Laser/Li-CCD System

Keyence LK-G Non

Sampling Freq. 50 kHz
650 nm Light Source

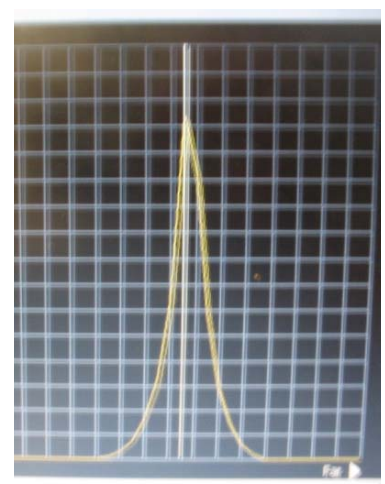
Resolution: 0.01 – 0.5 um
Reference Distance: 10, 30, 150 mm

Works with Diffuse, Transparent, Translucent Targets
Capable of Multi-Layer Measurements
PC Readout Software via USB or RS232



Reflectivity Test with HIRES/Keck CCD Detector (MIT/LL) with AR Coatings from Kirk Gilmore

Received-light Waveform Display on Readout PC
~0.5 μm resol.



Sampl

Acquired 2 Keyence LK-G Sensors

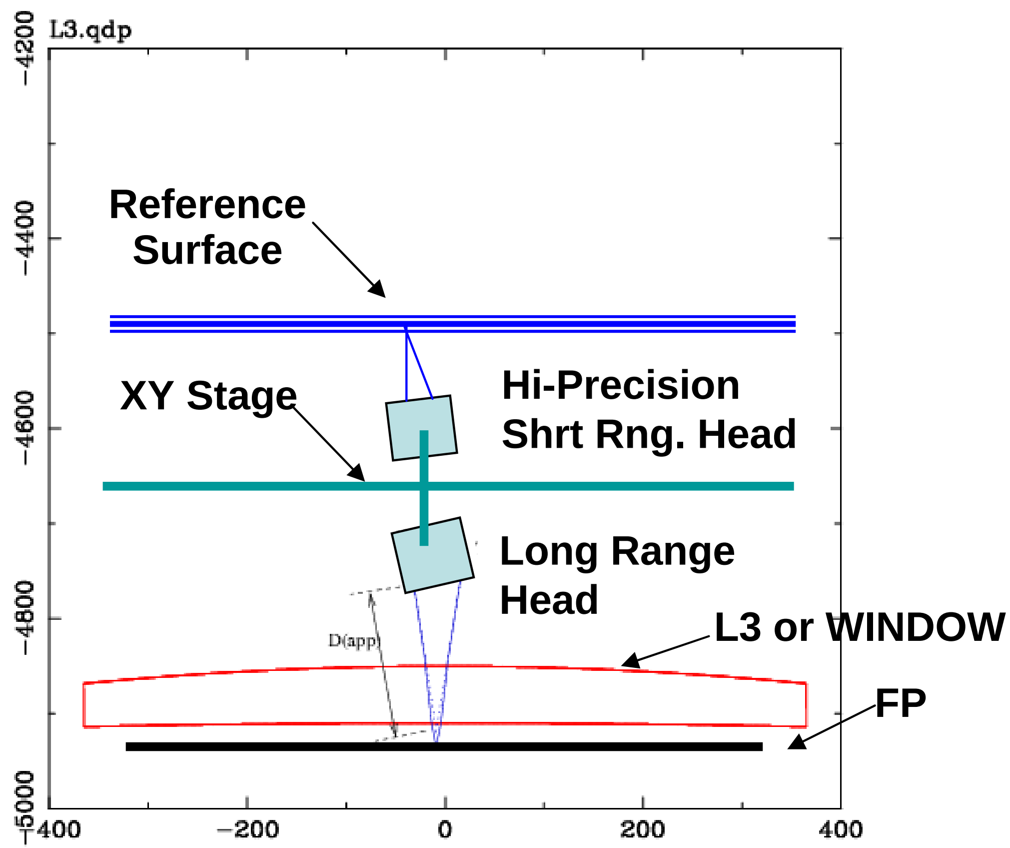
LK-G37 Range: 30 +/- 5 mm
Resol. < 0.1 μm

LK-G157 Range: 150 +/- 50 mm
Resol. = 0.5 μm

USB Connection to Windows PC

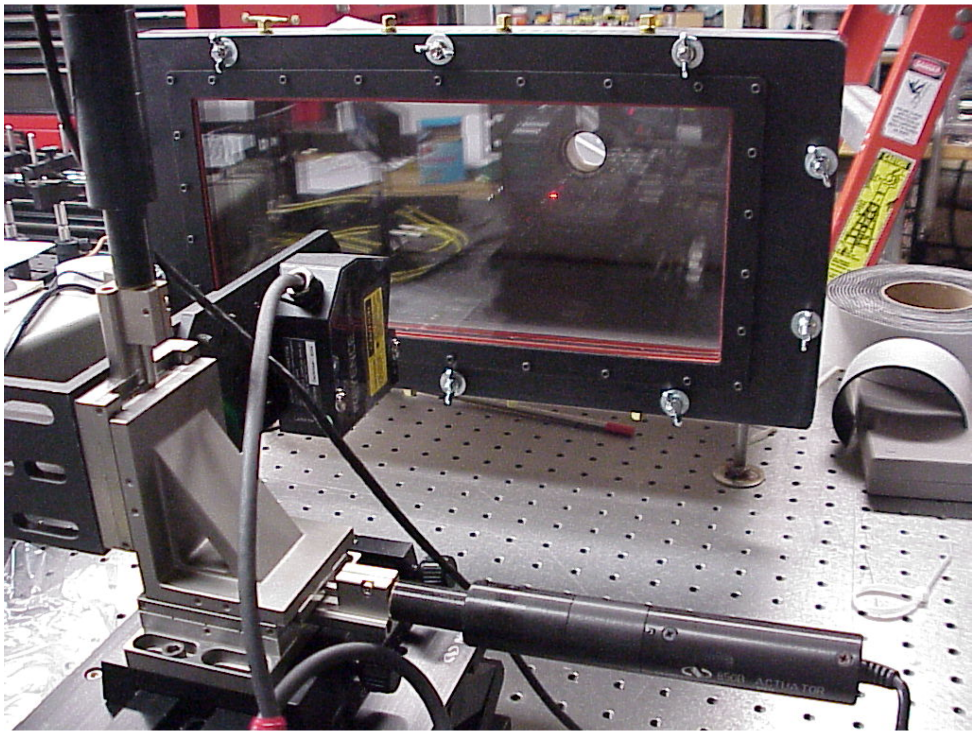
Keyence Navigator Software
- Peak Finding Program
- Data Storage

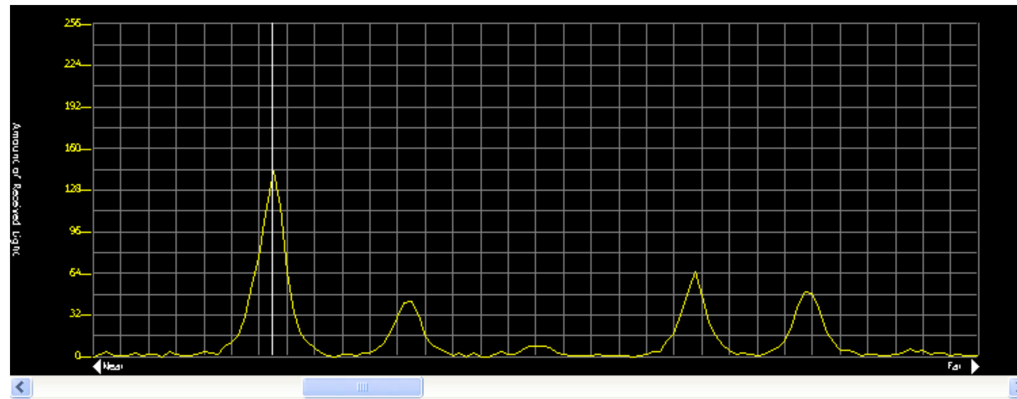
Interface to LabView NOT yet available



Possible Measurement Setup with 2 Sensors

Measurement of Transparent Surfaces

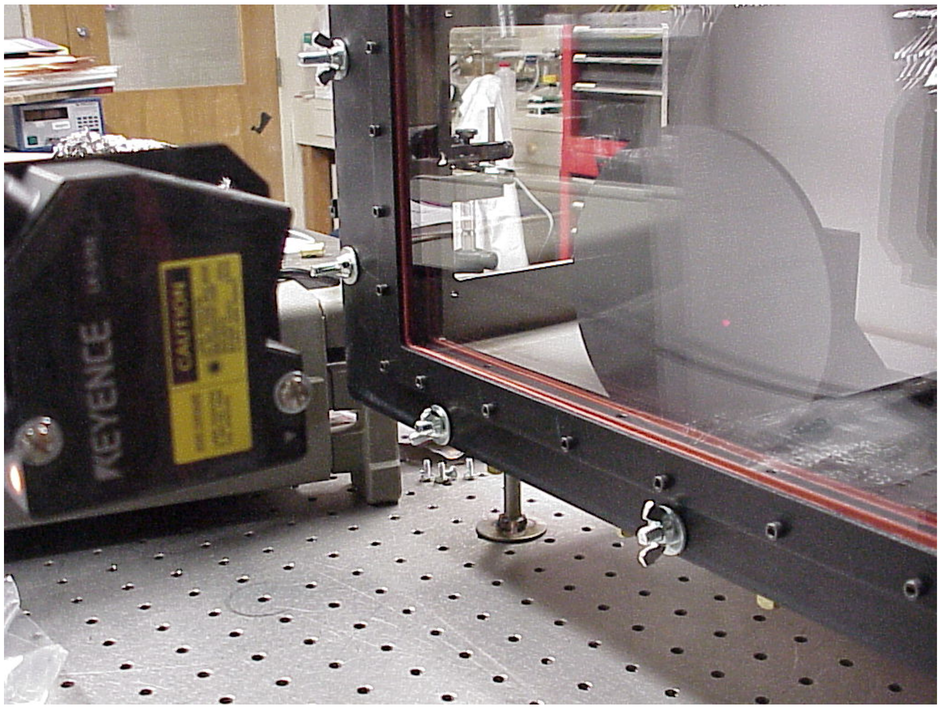




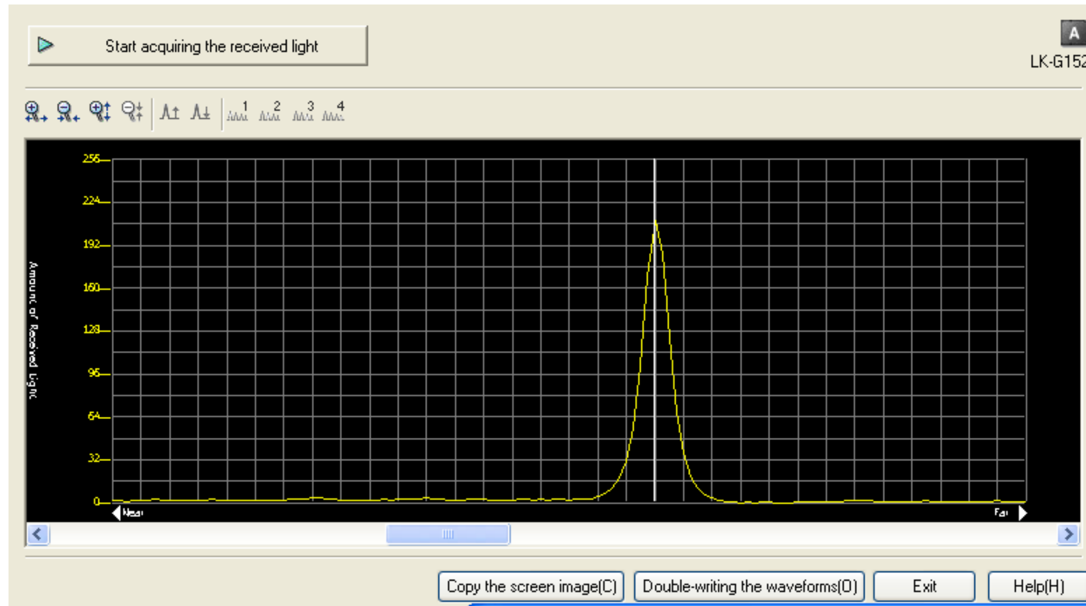
First Glass Second Glass

Long Range LK-G Sensor Mounted on Motorized XY Stage (Newport 425 with 1 inch Travel)

Measurement Through Transparent Surfaces

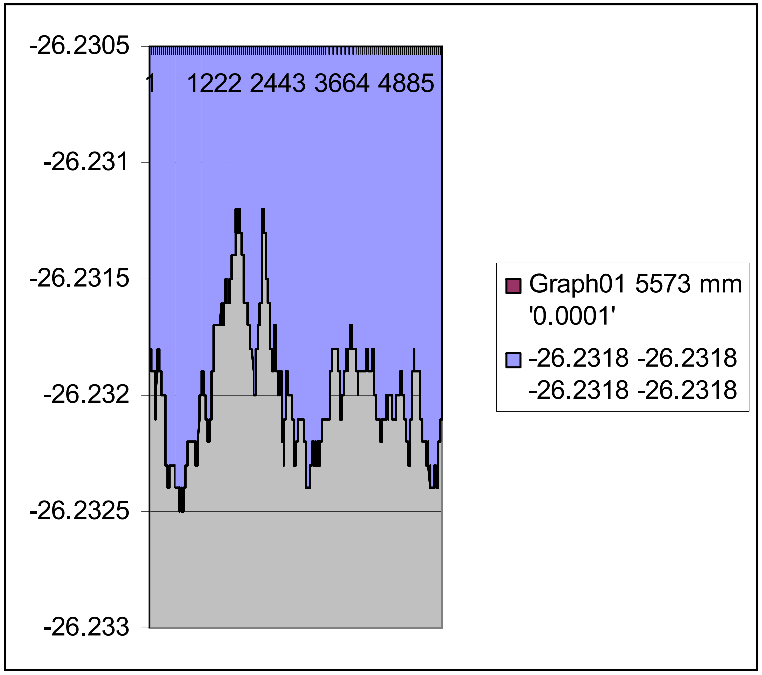


Silicon Carbide Target placed 2.6 cm from the Window



Peak observed with ~0.5 μm resolution

(Auto-scaling Suppresses Peaks associated with Glass Windows)



Measured Distance Variation over Time At a Fixed Spot on the SiC Target

- 15K sampling for each measurement
- Data rate at 2-3 Hz
- $\sigma < 1\ \mu m$

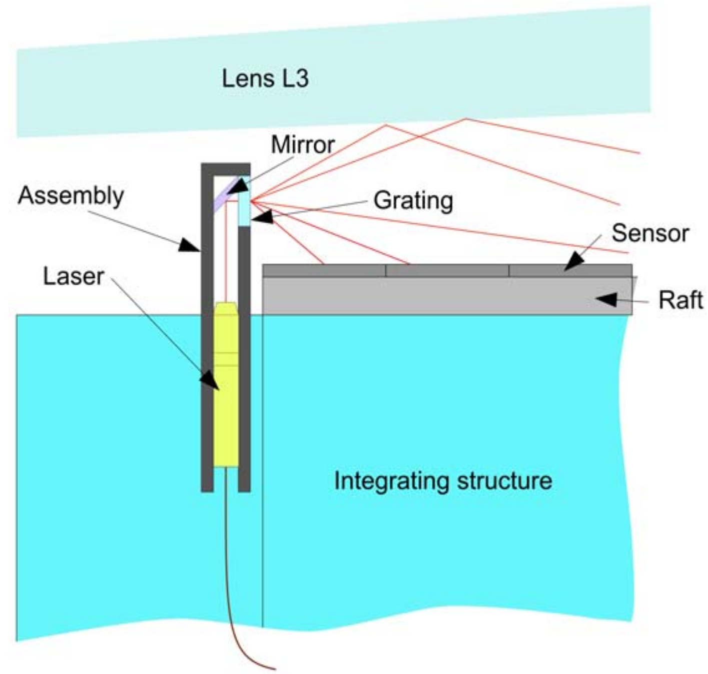
Things To Do:

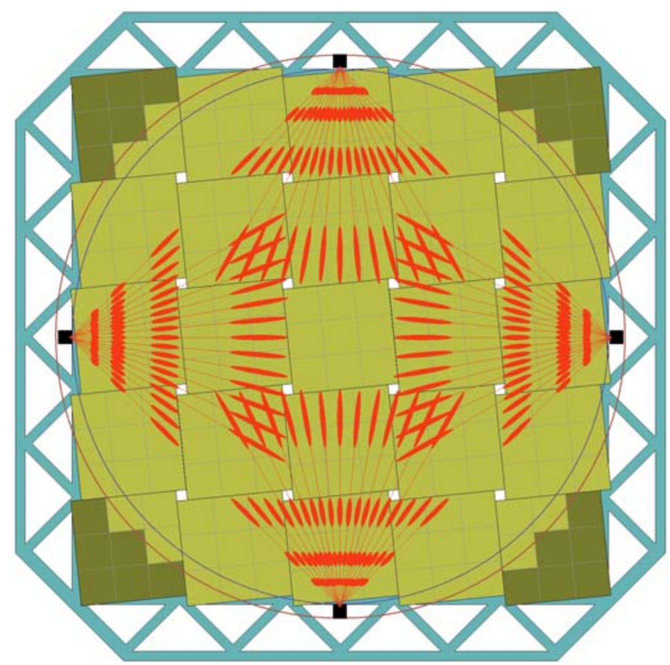
Check Stability of Optical Table, Vibration Isolation
Motorized Stage Calibration and Repeatability
Software Interface between Navigator and Motor Control

Measure Surface of SiC Samples from CoorsTek
(Claimed P-V Variations of order 200 nm)
WARM & COLD

Diffraction Pattern Generators

W Langeveld





- Use a laser assembly and 2D diffraction grating to project unique pattern of ellipses onto FPA.
- Ellipses are centroided by CCD sensors. Vertical motion of FPA can be measured from the spot positions relative to baseline location
- Centroiding Gives ~1/30 Pixel ~ 1/3 microns
- Direct Meas. of CCD Sensor Flatness

Diffraction Pattern Generators

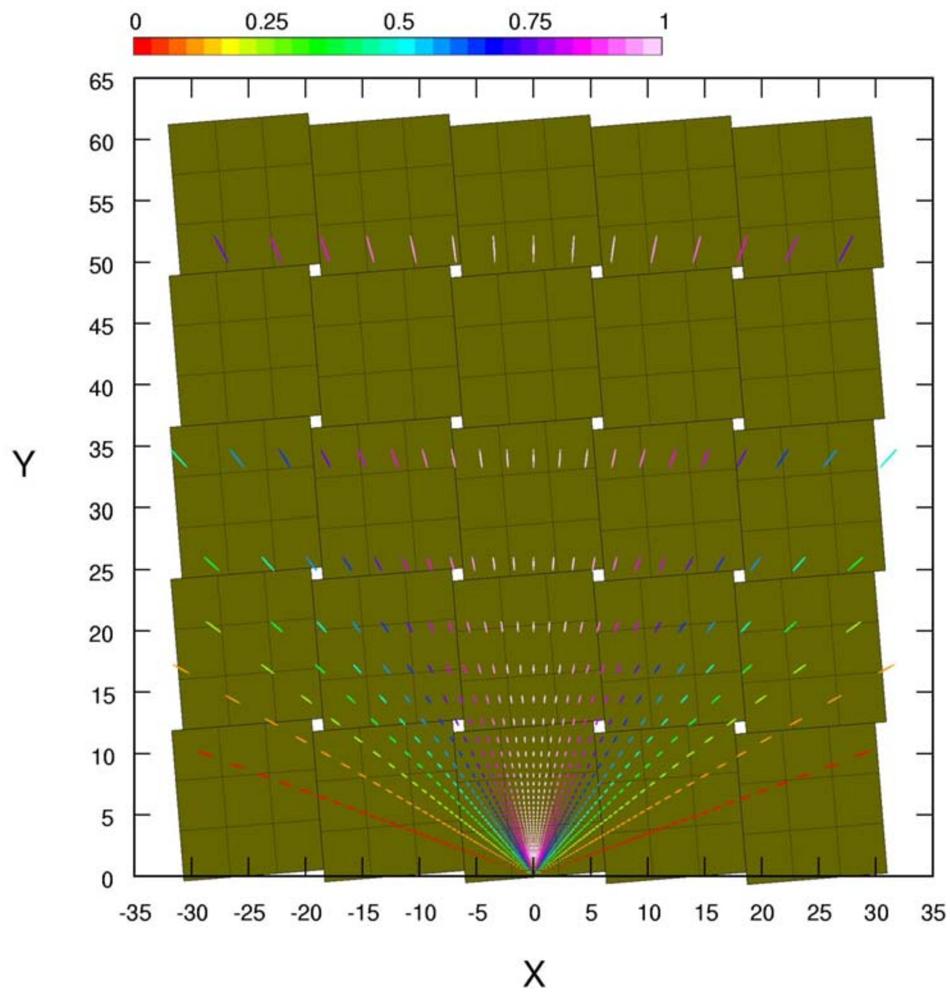
Advantages:

- Lowest hardware cost ←→ Most Software Intensive For Interpretation
- This is the only system that directly tests for FPA flatness if stable & characterizable
- Can be used to detect deflections of L3 by using L3 as a grazing incidence mirror.
- Minimal real estate & power make it good candidate as adjunct system

Potential Problems:

- Unproven method for this application. The practical problems are unknown.
- A live focal plane is required including full readout electronics.
- Stability of the laser and diffraction grating unit with aging & changes in temperature are unknown.
- The positioning of the spot generator with respect to the array must be very stable and-or the spot generation mechanism must be stable enough that global shifts in the spot array position can be compensated within software that recalculates where the spot centroids should be for a flat FPA
- Multiple reflections between the FPA and L3 will complicate the patterns. On the other hand, if correlations between L3 and FPA surface figure with the multiple reflected spot patterns can be solved for, the state of L3 as well as the FPA can be measured.

Diffraction Pattern Generators



Simulation

- Simulation of a single grating, 50 apertures/mm vertically & 150 a/mm horiz.
- Height of pattern origin above FPA is 23 mm.
- Aperture width 0.1 micron leads to (normalized) intensity pattern as shown.
- Laser beam width is 1 mm.
- Get ~1K Usable Spots With 4 Elements

Grating Fabrication

E-beam-Lithographic Gratings made at
Stanford Nanofabrication Facility (SNF)
with the help of Chris Kenny

Liquid Etching of Pattern on Aluminum Sputtered Quartz Wafer
- Pattern made with electron beam
- Control of the Amount of Time Exposed is Critical

After some Trials/Errors,
Usable Grating of 2mm x 2mm Size was Obtained

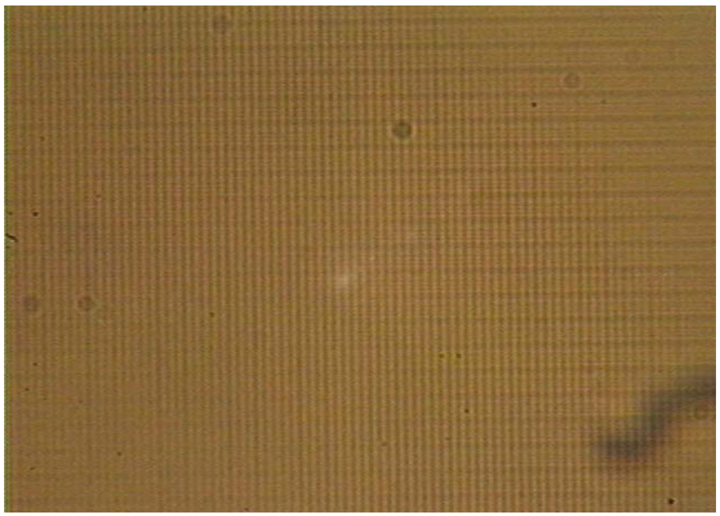
(Pattern was not the Desired one due to an error, but it makes Diffractive Patterns)

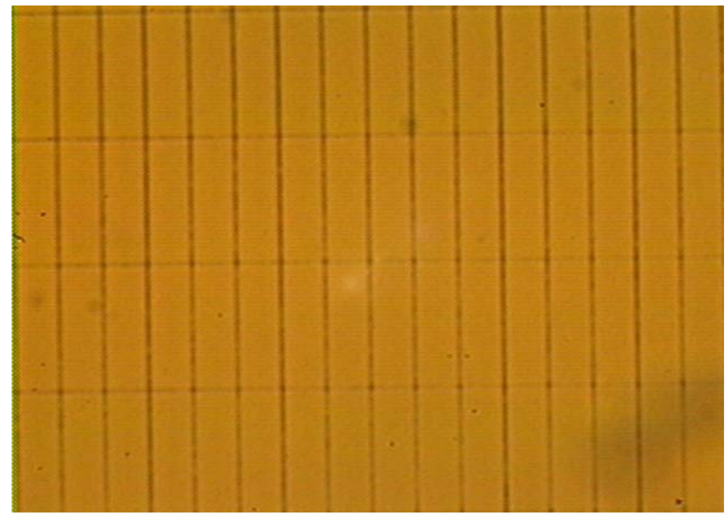
E-beam-Lithographic Gratings

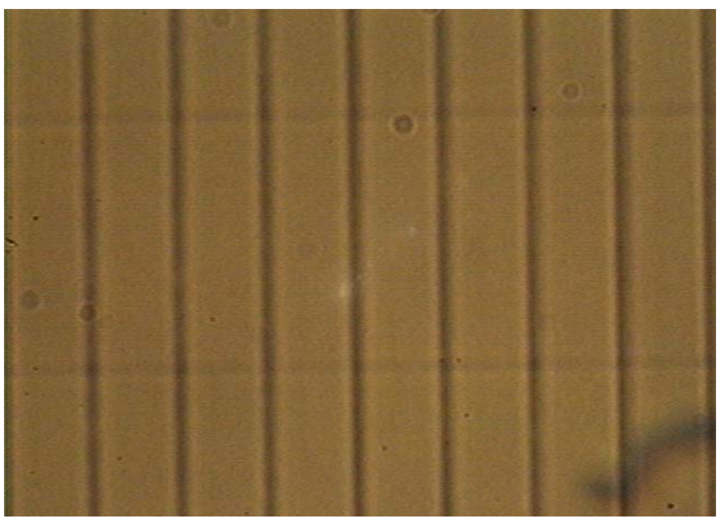
Start with 100 mm diameter quartz wafer with both sides polished

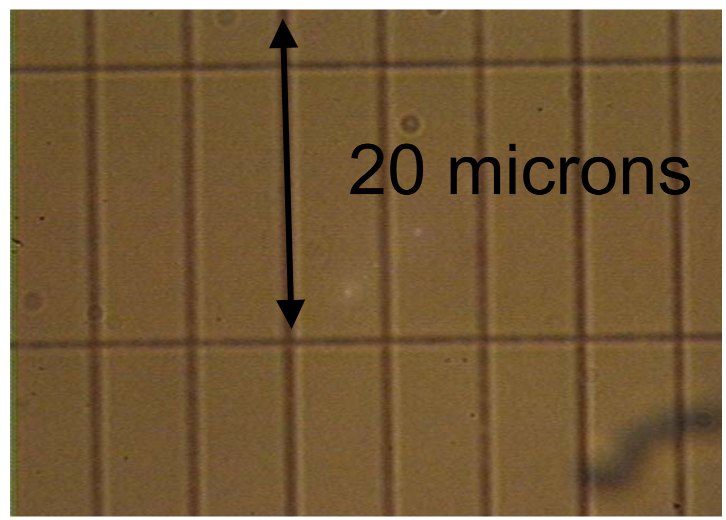
1. Clean/Rinse Cycles with H_2SO_4/H_2O_2, HF/H_2O, $HCl/H_2O_2/H_2O$ at various temperature
2. Sputter deposit aluminum in "Gryphon". Target 70 nm
3. Clean with PRS1000 (standard metal cleaner) and bake at 50^0 C
4. Coat with HDMS (adhesion promoter) on "SVGCOAT"
5. Manual spin coat with 5% 495K MW brand PMMA in Anisole (phenyl methyl ether) at 2000 rpm for 40 seconds. Target 300 nm
6. Measure film thickness using Nanospec Positive Resist recipe: 265.5 nm (center); 266.6 nm (bottom); 264.7 nm (top); 265.6 nm (left)
7. E-beam exposure: 10 kV, 120 $\mu C/cm^2$
8. Develop in MIBK (methyl isobutyl ketone)/IPA (isopropyl alcohol) (volume ratio 1/3) for 30 seconds
9. Perform calibration etches: 300 nm PMMA starts to clear after 17 seconds at edges
10. Plasma etch for 7 seconds to break through oxide
11. Plasma etch for 12 seconds to remove aluminum

Grating Pattern on Wafer Before Etching

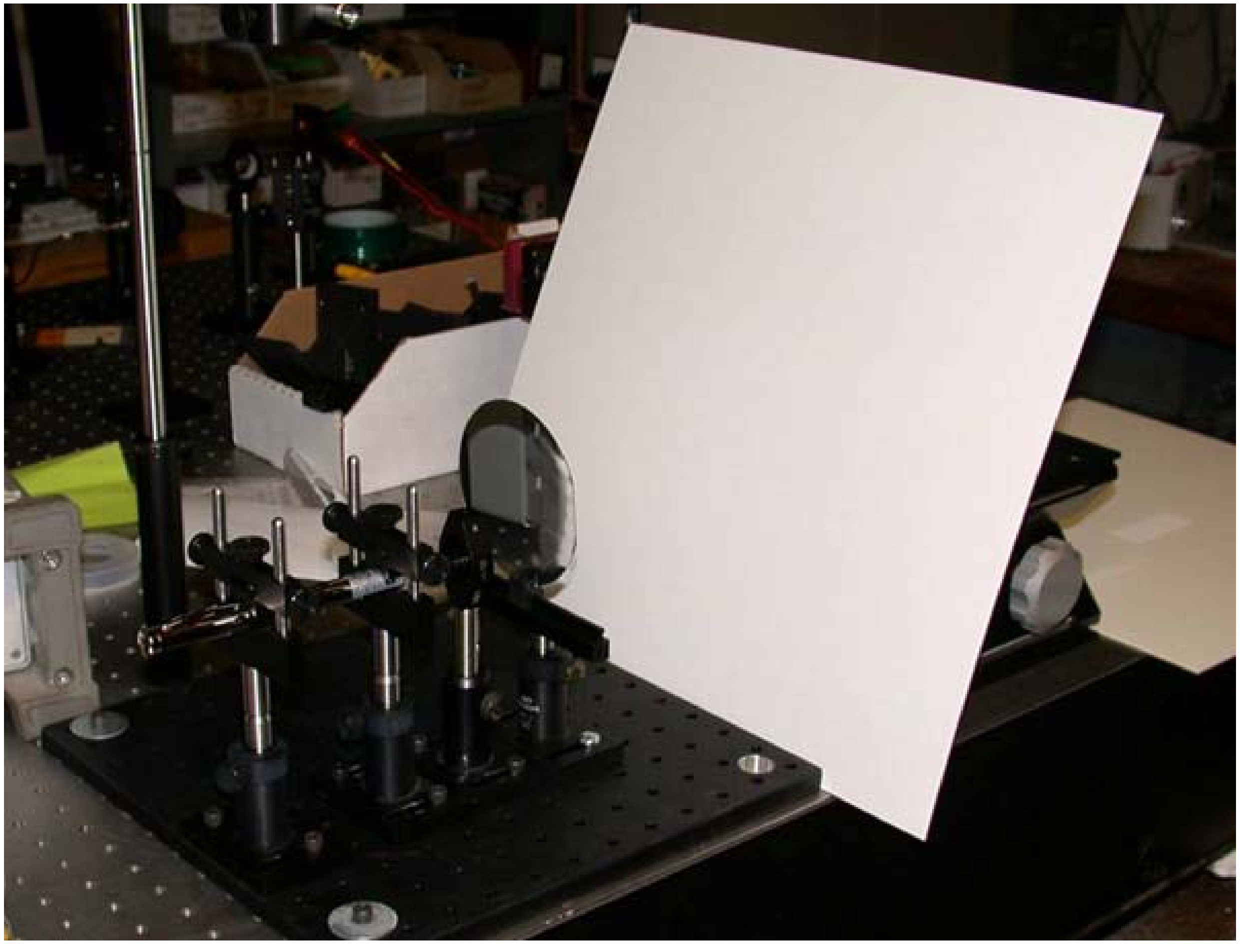








Setup for Demonstration of Principle



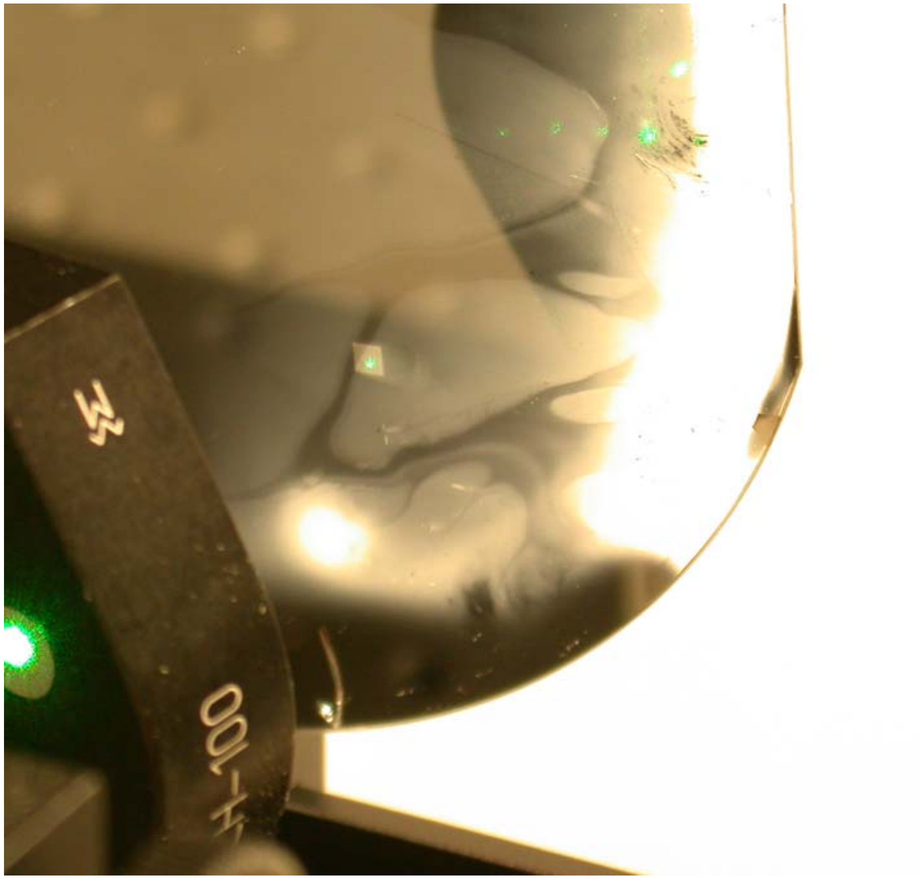
Class IIIa green Laser, 5 mW

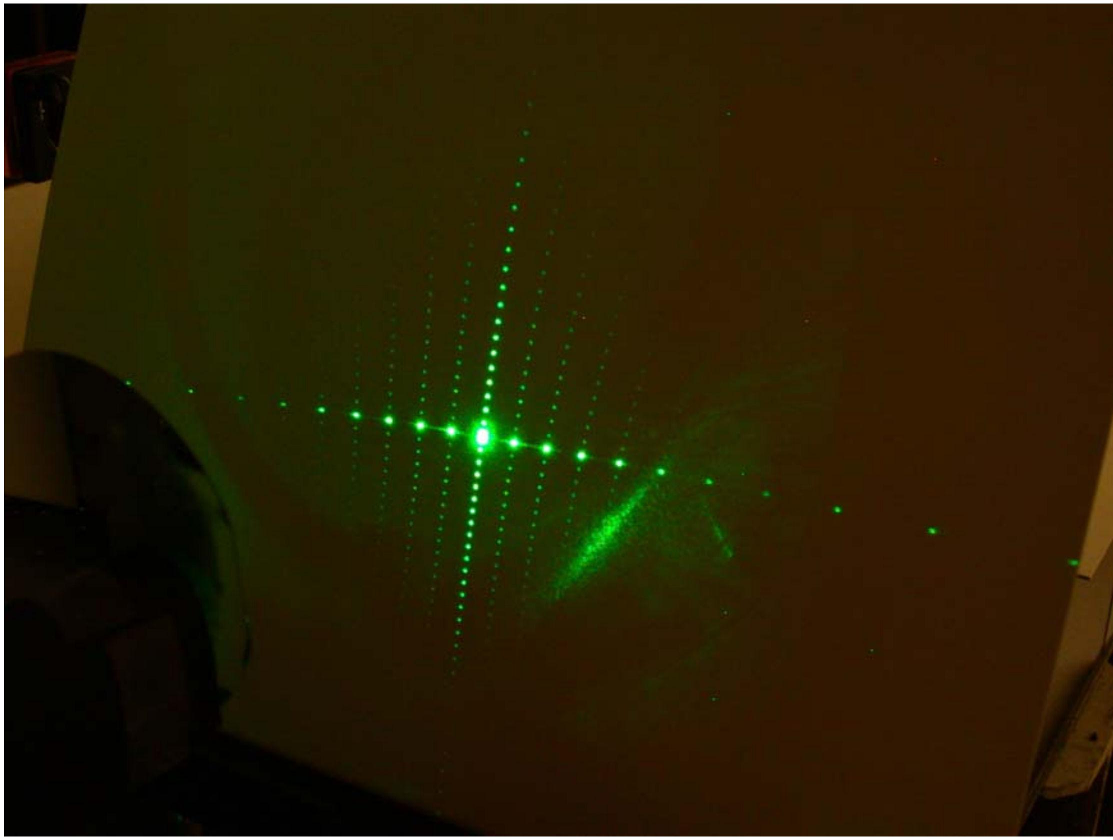
300 micron pin hole

Diffraction grating

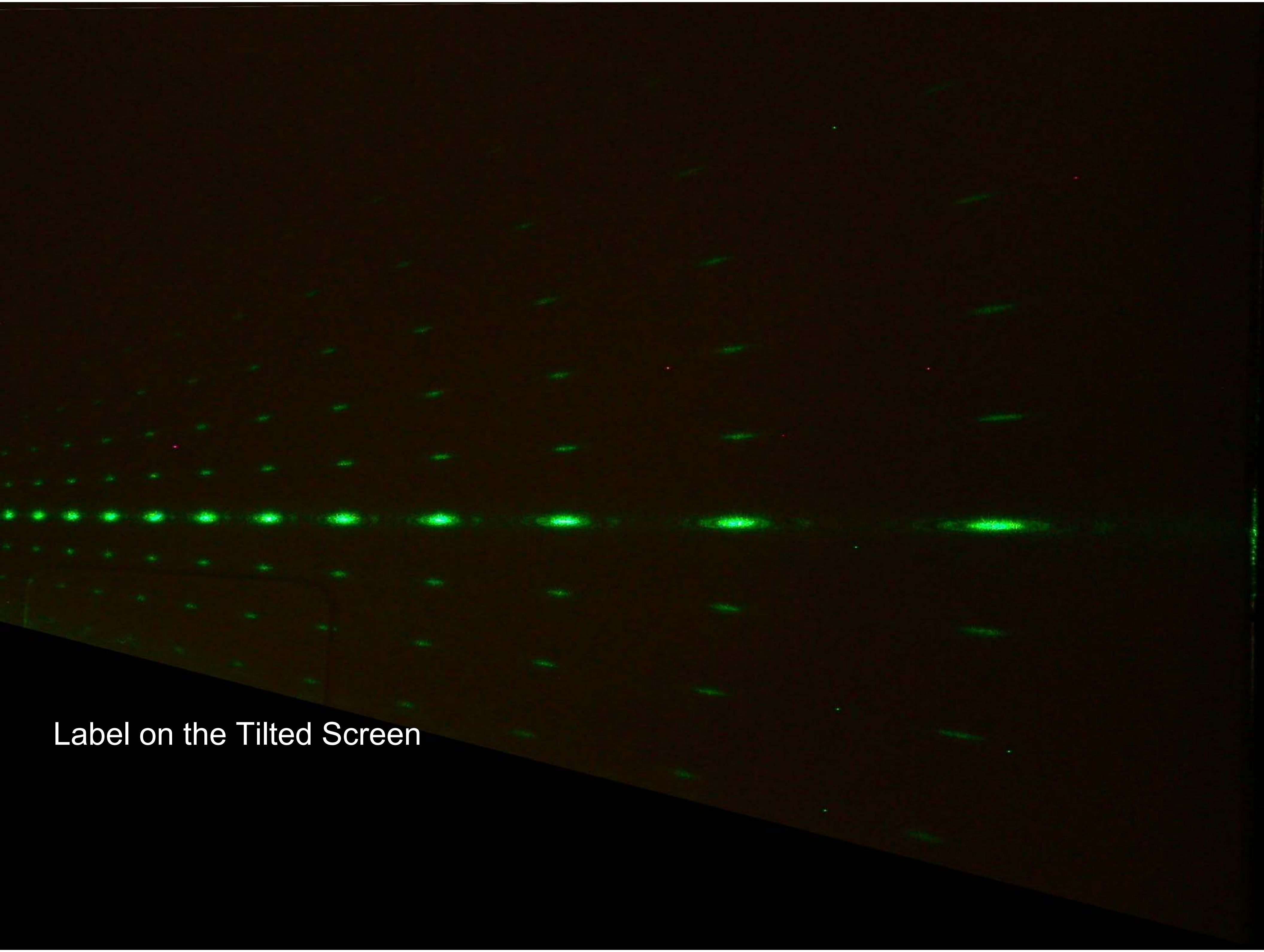
White screen at an angle for pattern display

Image taken with Digital Camera (50 micron pixels) for processing





Pattern with the Screen mostly in Vertical Position


Label on the Tilted Screen

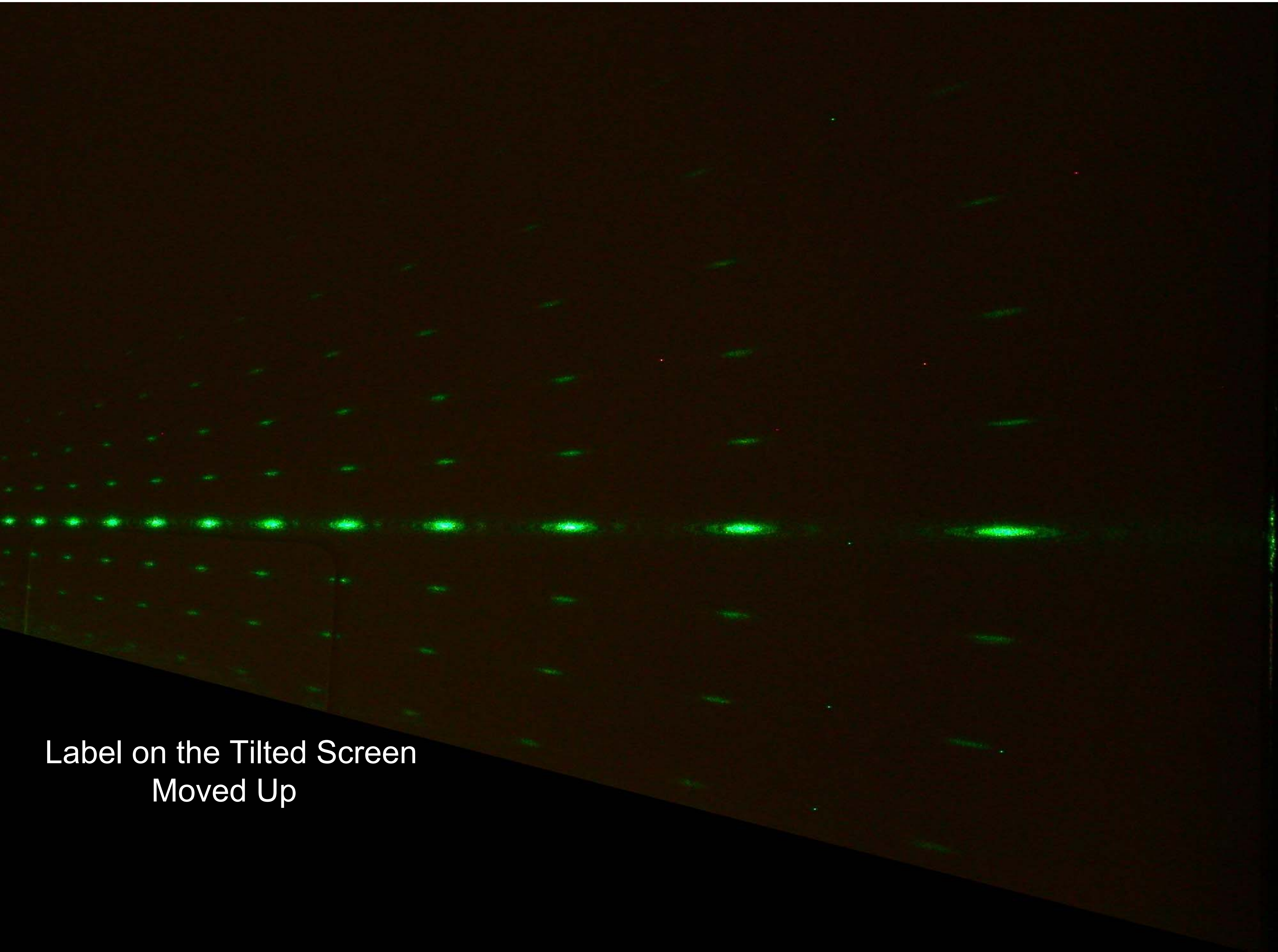

Label on the Tilted Screen
Moved Up

Image Processing

- Find 92 spots in first image, 93 in second
  - But they don't all match
- Match the locations and single out the 7 spots in the changing area
  - Calculate distances from crude average x and y positions
  - Calculate angles from crude shape of ellipse

Distance (pixels)	Angle (rad)	Vertical distance (pixels)	Vertical distance (microns)
4.560 +/- 0.494	0.230	1.067 +/- 0.115	55.863 +/- 6.048
5.249 +/- 0.508	0.250	1.342 +/- 0.130	70.277 +/- 6.794
5.553 +/- 0.521	0.265	1.509 +/- 0.142	79.053 +/- 7.423
6.154 +/- 0.550	0.200	1.247 +/- 0.111	65.307 +/- 5.832
6.816 +/- 0.548	0.183	1.261 +/- 0.101	66.033 +/- 5.313
8.679 +/- 0.620	0.152	1.329 +/- 0.095	69.593 +/- 4.973
3.572 +/- 0.563	0.148	0.533 +/- 0.084	27.904 +/- 4.400

Diffraction Pattern Generators

Verdict on Screen Test

Thickness of Label Measurement with Laser is about 67 microns (55 to 79). Real Thickness was ~98 microns.

Not too bad without any systematic corrections

Very Crude First Try gives ~0.5 Pixel Resolution

Another Round of Grating Fabrication at SNF is Planned

With Right Patterns that are easier to produce

Test with Large Area CCD Camera with AR Coating is Imperative

Understand Effect of Shallow Incident Angle to Focal Plane

Position resolution with pixel size close to LSST CCD's

Capacitive Edge Sensing

Eric Lee

- Proven System at Larger Scale
  - Keck Telescope Alignment: 36 Segments in10 m D Mirror
  - SALT Mirror Alignment: 91 Segments in 11m D Mirror
- Very Good Resolution, but Electronic Noise and Interference Must be Kept Low
- Do we have Room in FPA/Int.Structure?
- New Development: Analog Devices AD7745/46
  - Capacitance to Digital Converter (CDC) in Single Chip
  - 2 Ch. 24-bit Sigma-Delta architecture with 20 aF Resol.
  - Integrated Clock, Reference, Mux, Calibration, Temperature Sensor
  - Low Power 1 mA Max; 5 -90 Hz Data Rate
  - **$5**

AD7746 Evaluation Board

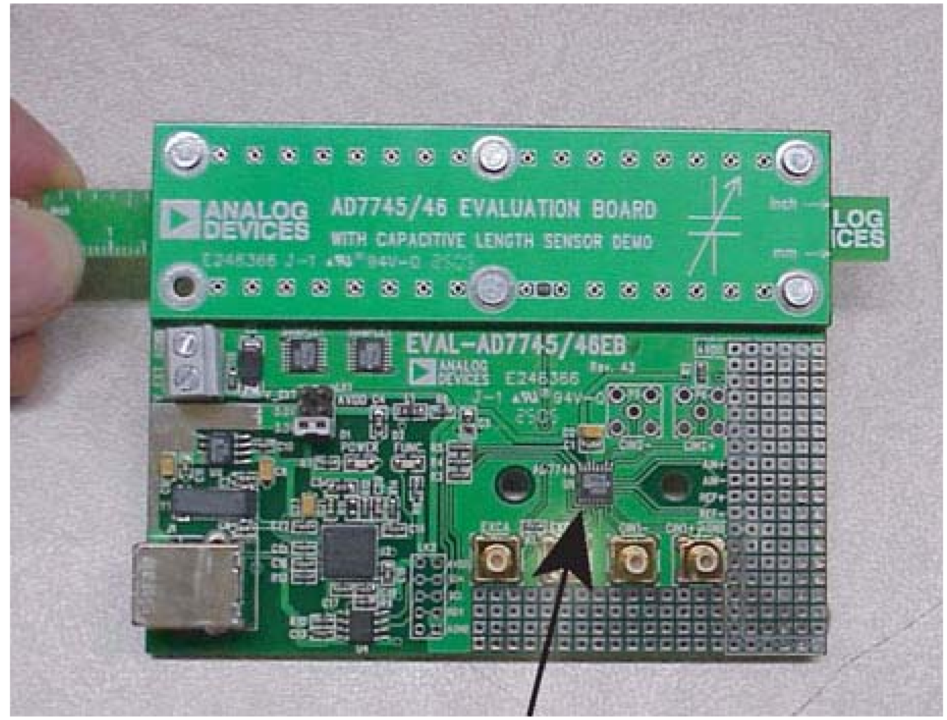
Preliminary Test Result

Data Readout via USB Port / Windows PC

Attach a 4 pF Capacitor

Noise level of 0.2 fF.
0.4 fF/hour drift probably due to
capacitor temperature change

Interference observed with 2 boards
next to each other, due to long leads
on the capacitors



AD 7746 Chip

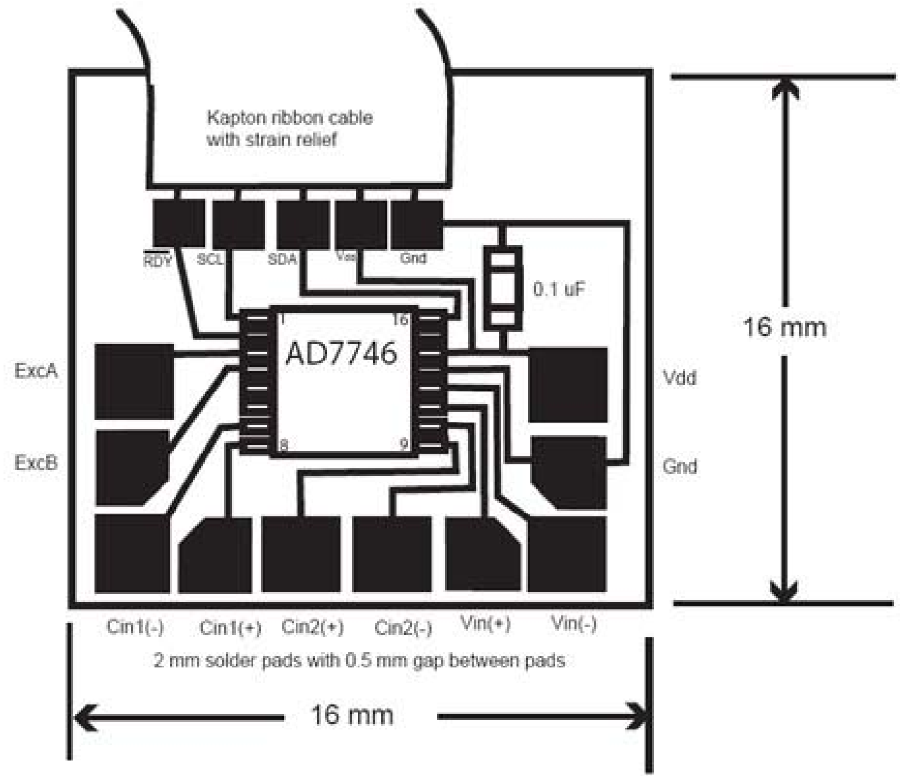
MINIMIZE DISTANCE BETWEEN CAPACITIVE PLATES AND CDC

AD7746 Chip Module

Take CDC off Evaluation Board and Surface mount on a small PC Board

Digital Signal Output on Kapton Ribbon Cable

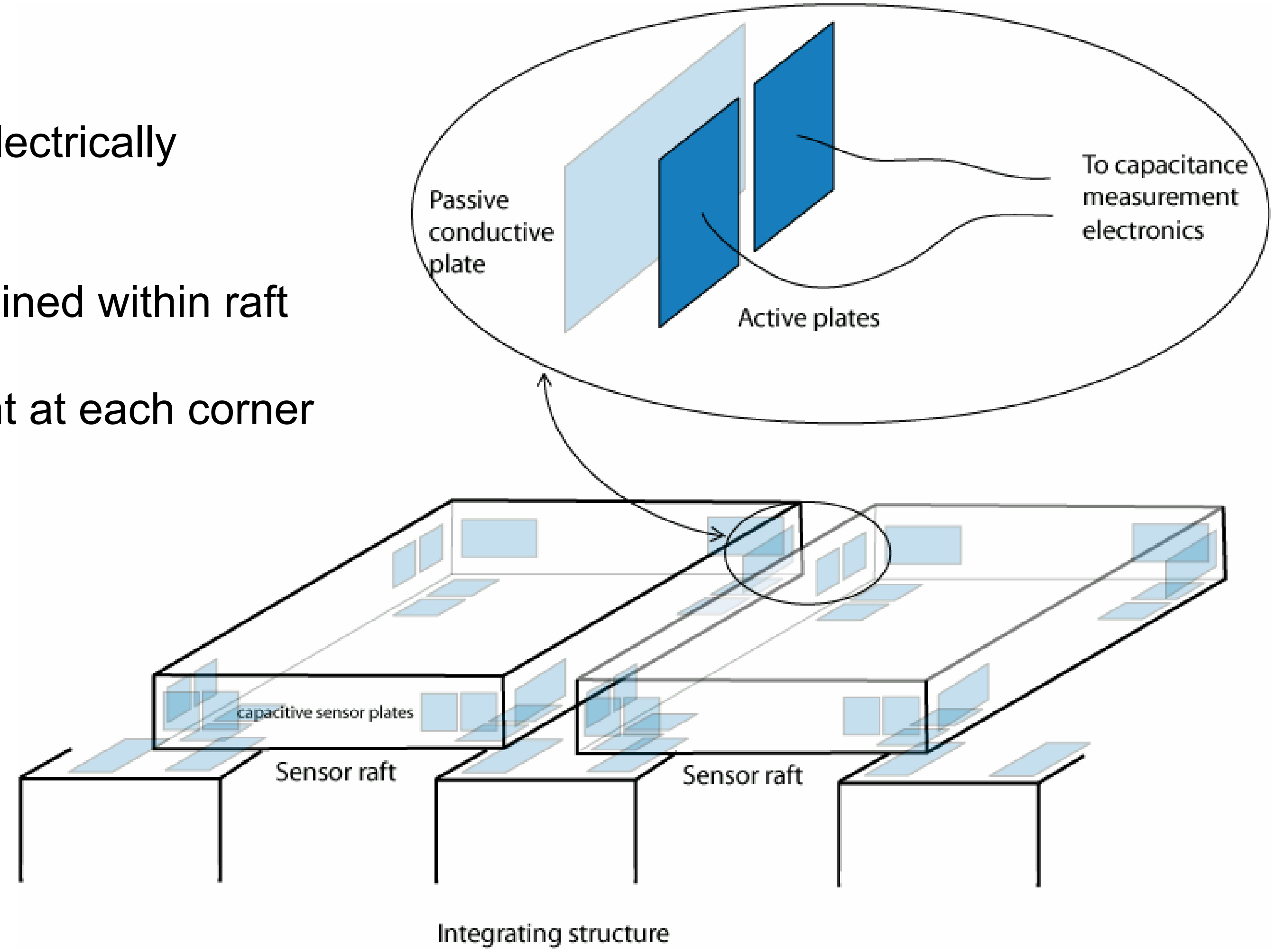
Being Fabricated by SLAC Electronics Group: This Week



Capacitive Edge Sensing

LSST IMPLEMENTATION

- Paired active plates facing an electrically floating passive conductive plate
- Measurement electronics contained within raft
- Three axis (X,Y,Z) measurement at each corner



Capacitive Edge Sensing

- High Precision & Small Form Factor Solution Has been Found
- Noise/Interference Test with New Small PC Board
- Cold Test: AD7746 Specification -40^0 C to 175^0 C
  (Possible to use External Temp reading for calibration)
- Precision/Linearity Test with Capacitive Plates attached to Mockup Rafts on XY Stage
- Design of Capacitive Plate Locations/Shapes and Measurement Algorithm Development (S Sun)
  Following Matlab Simulation Study for Optical Straightedge
  (H Carey, T Thurston)

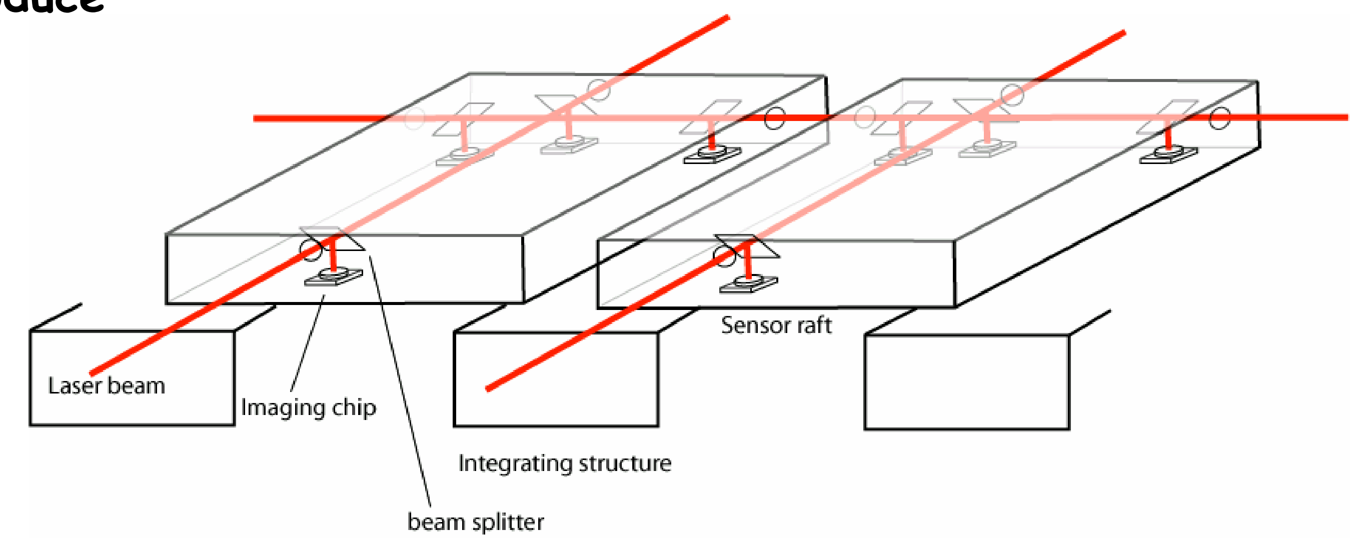
Optical Straightedge

An array of lasers is mounted in the dewar and fires through thru-slots machined into the rafts.

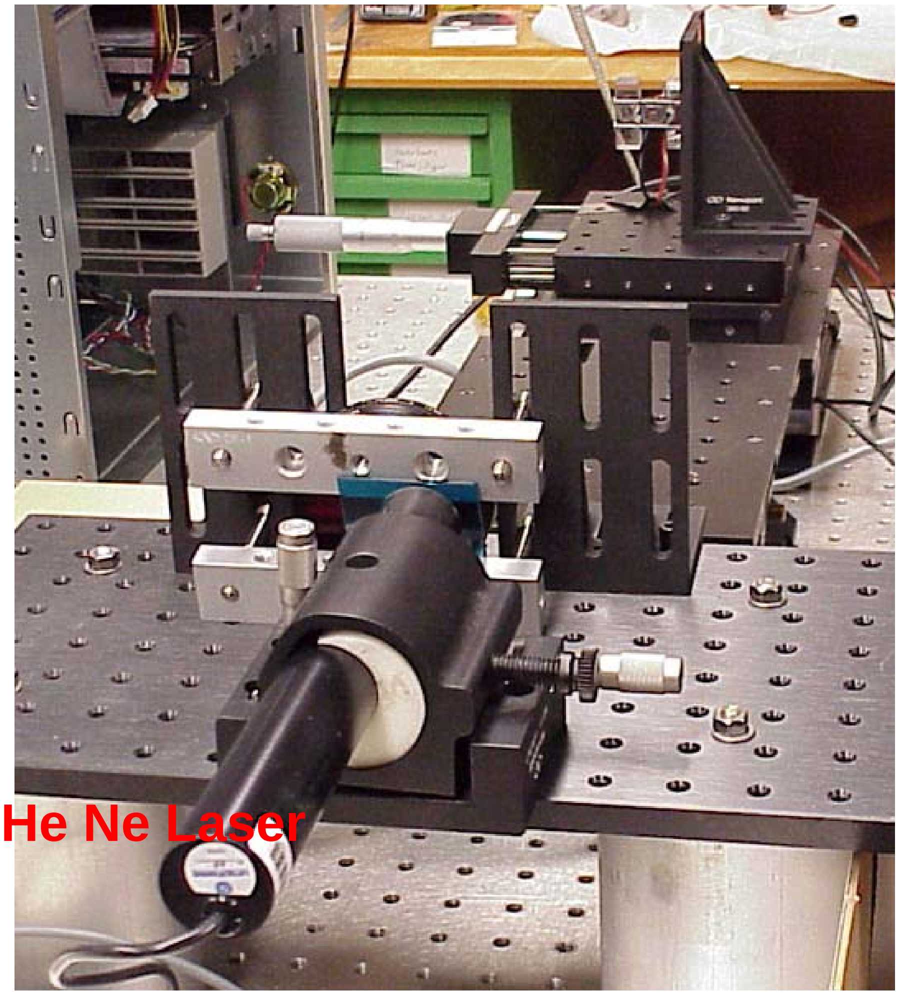
Within the rafts are mounted beam splitters that pick off a small fraction of the laser light and direct it towards an imaging sensor also mounted within the raft.

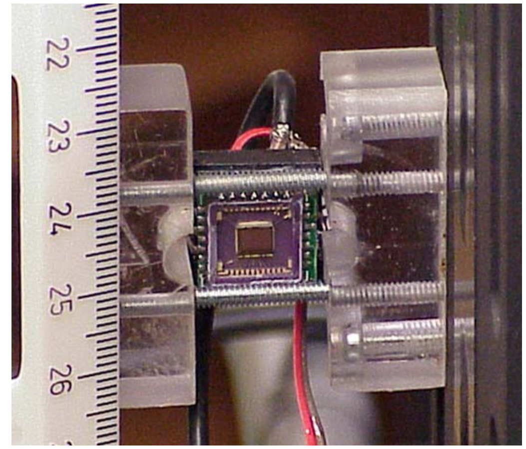
Shifts in the raft with respect to these reference beams produce changes in the location of the centroided laser spots.

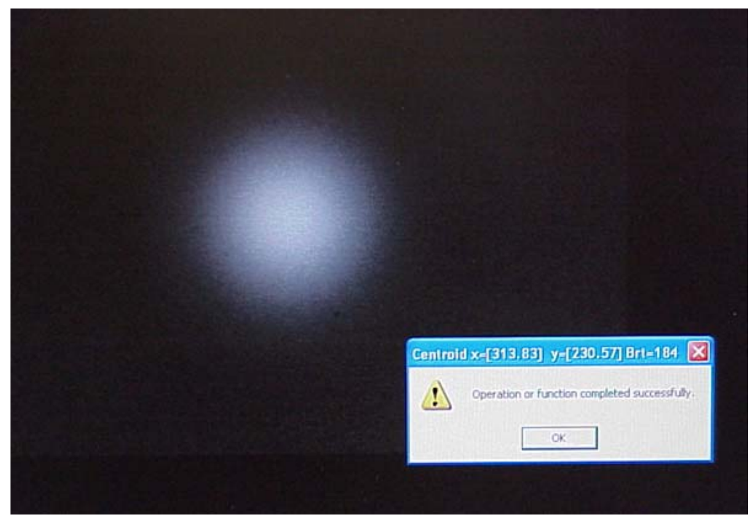
Each raft is interrogated by beams in orthogonal directions so as to detect displacements in x-y-z as well as in rotation.



Simple Laser Centroiding Test Setup







Laser Spot Centroiding Test

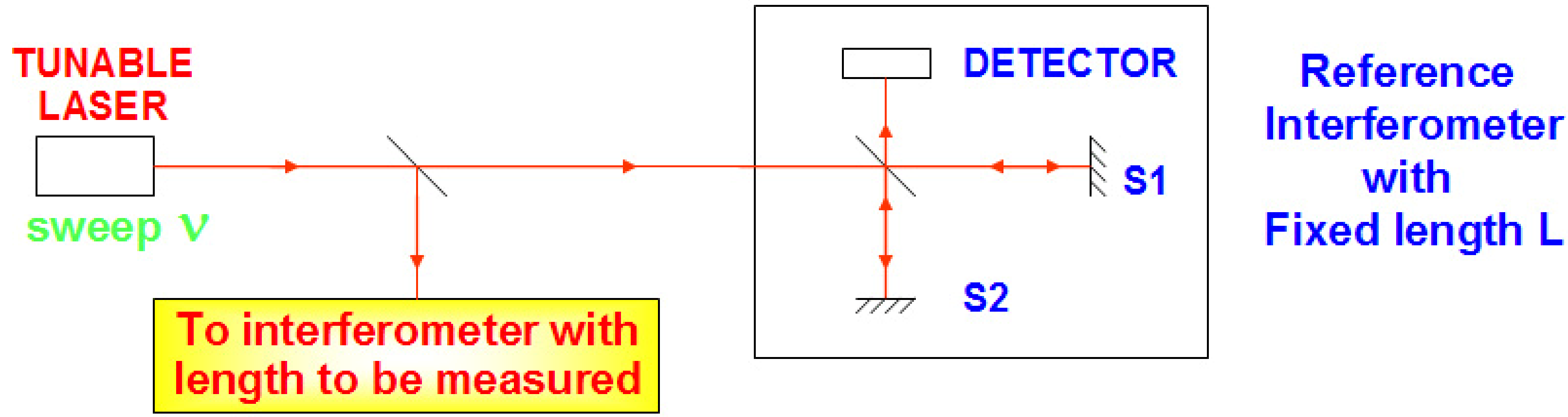
- He-Ne Laser at ~ 1m away from CCD Camera
- Front Glass of CCD Camera removed to eliminate Fringing
- Data Translation DT3155 Frame Grabber
- Centroiding Program (in C) Developed for Frac. Charge Search Exp on Windows XP / Visual Studio C++

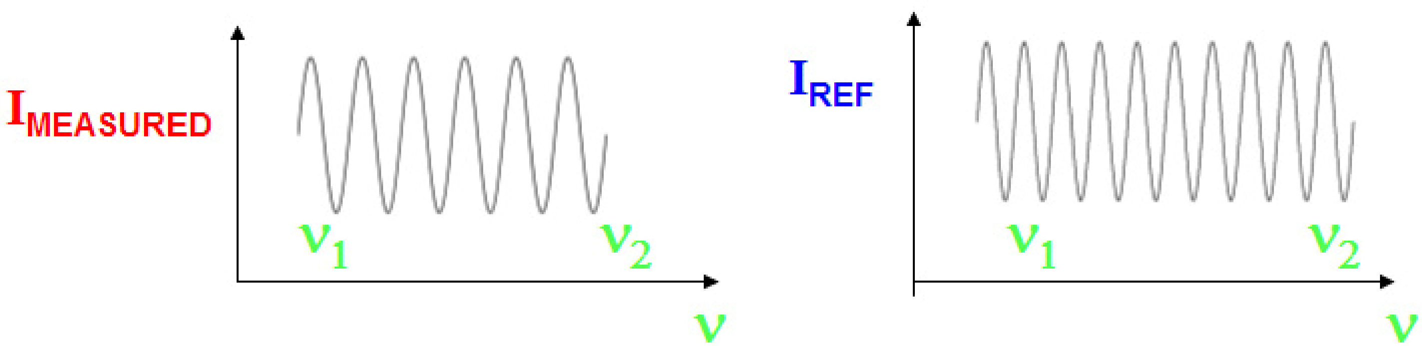
Preliminary Result: Centroid Position Resolution ~2 μm

Observe Large Laser Beam Jitter as much as 100 μm
(Inexpensive Diode Lasers have beam shapes not suitable for centroiding and also move in tens of μm)

Will need Fiber Coupled Solid State Lasers (expensive) for Stable Beam Profile

FSI Length Measurement





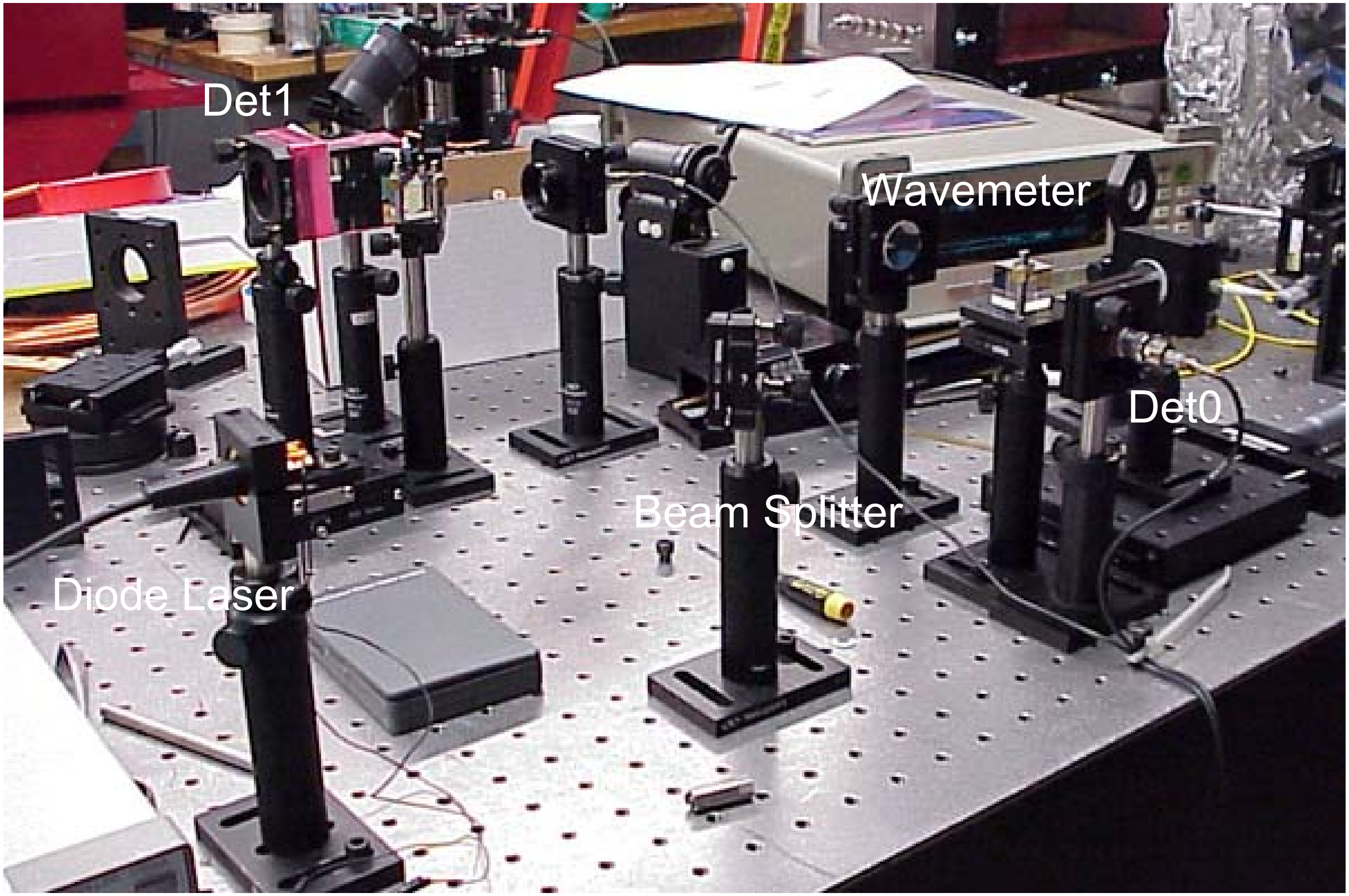
$\Delta\Phi = [2\pi/c]\mathbf{D}\Delta\nu$ $\quad$ $\Delta\vartheta = [2\pi/c]\mathbf{L}\Delta\nu$

Ratio of phase change = Ratio of lengths

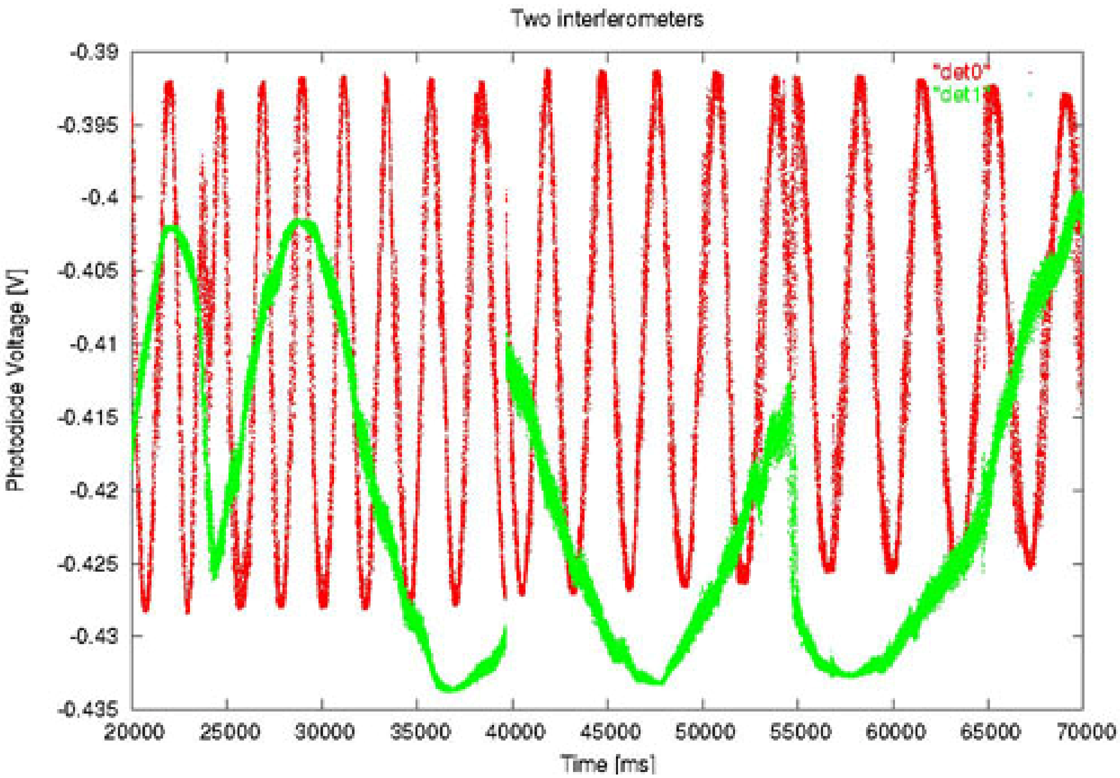
FSI Test Station

- 650 nm Semiconductor Diode Laser
- Kapton Heater Tape to Induce Frequency Change
- HP 86120B Multi-Wavelength Meter
    - Range: 700 – 1650 nm
    - Absolute Accuracy of +/- 3 ppm
- Two Interferometers
    - Det0: Distance being measured (1.0 cm)
        - Mounted on Linear Stage
    - Det1: Reference Distance (0.2 cm)
- Photodiode Detector to Measure beam intensity
- NI-PCI-6221 DAQ Card
- LabView 7 on Windows PC

FSI Test Station



Example Measurements



Det0 has ~5 times Faster Oscillation than Det1

Diode Laser Mode-Hopping Problem Can't be Solved…

FSI Test Station

- Plan to Add Inexpensive *used* Frequency Changing Laser

- Considering 1500 nm Wavelength that can be used while the CCD Sensors are ON

  Possible Tool for Alignment of Various Camera/Telescope Components over 2 m ranges
  (e.g. Atlas Inner Detector Alignment)

- More Measurement to Come Soon

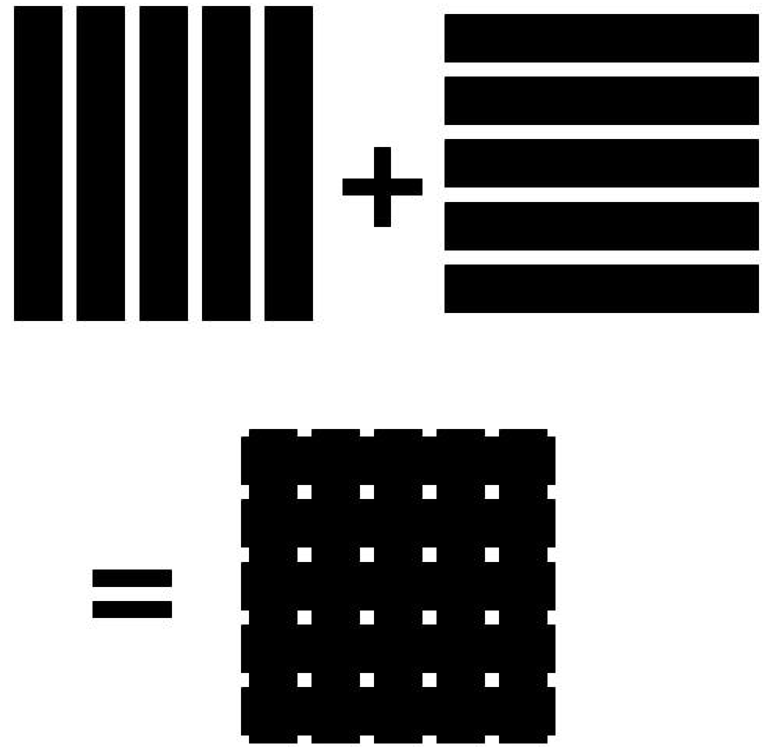
Summary

- R&D Test Stations are Up and Running
  Allowing Quantitative Evaluations of
  Various In-Situ Metrology Methods

- Capacitive Edge Sensing looks Most Promising for
  Raft-Raft & Raft-Int.Str. Alignment Measurements

- Diffractive Pattern on CCD Sensors could provide Direct Measurements Complementary to Other Methods

- Cold Test Box is almost ready to Use



- What we should have made:

- What we made: