Calibration of Nanoindentation Data

Elaine Rhoades, Embry-Riddle Aeronautical University
Mentor: Matthew Abernathy

August 20, 2013

LIGO Livingston Observatory
SURF Seminar Day, Session I

Project Relation to LIGO

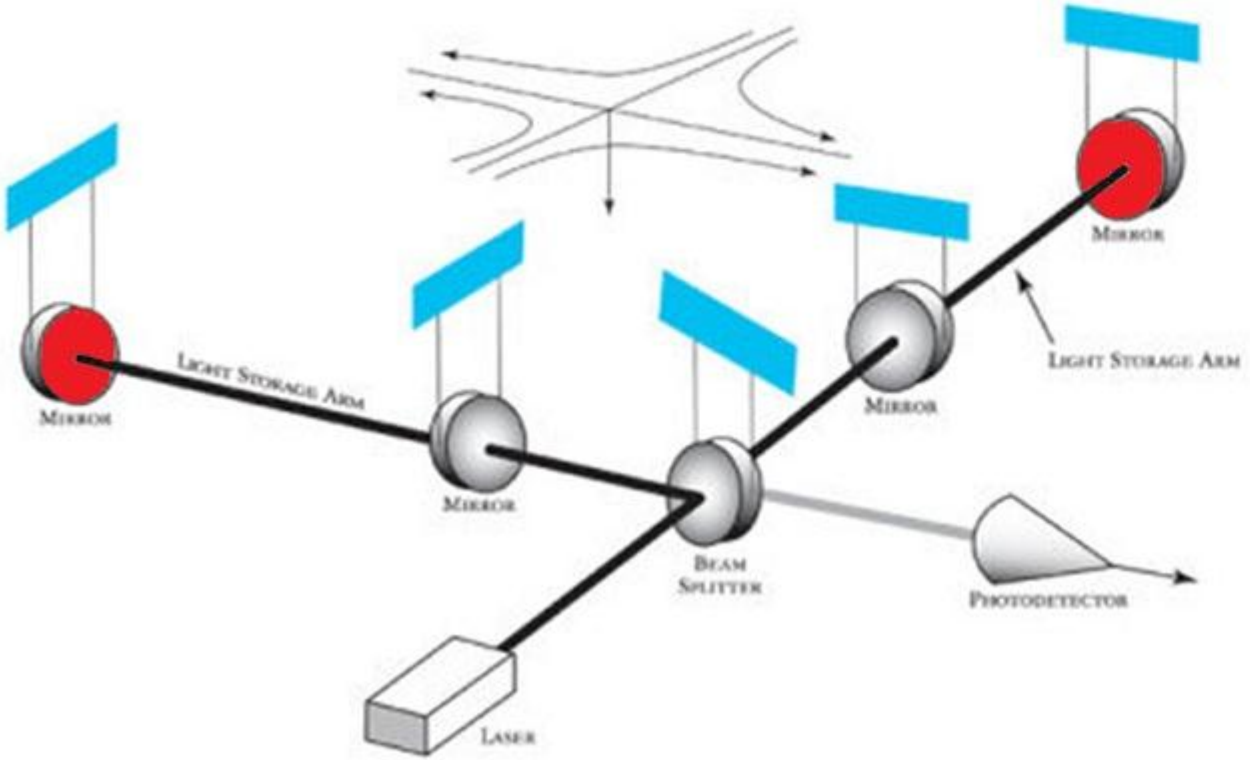


Photo credit: LIGO

Noise Sources in Coatings

- Three main sources of noise from the coatings:
  - » Brownian
  - » Thermo-elastic
  - » Thermo-refractive

Brownian Noise

- Brownian thermal noise from a multilayer mirror:

$$S_x(f) = \frac{2k_BT}{\pi^{3/2}f}\frac{1}{\omega Y}\left\{\phi_{\text{substrate}} + \frac{1}{\sqrt{\pi}}\frac{d}{\omega}\left(\frac{Y'}{Y}\phi_{\parallel} + \frac{Y}{Y'}\phi_{\perp}\right)\right\}$$

where k_b is the Boltzmann constant, T is temperature, f is frequency, Y is the Young's modulus of the substrate, Y' is the Young's modulus of coating, d is the thickness of the coating, ω is the radius of the laser beam at $1/e^2$ of maximum light intensity, ϕ are the mechanical losses of the substrate, and the parallel and perpendicular directions of the coating

- Assuming $\phi_{\parallel}$ and $\phi_{\perp}$ are equal, and setting Y'=72 GPa and Y=140 GPa, changing Y' by 20% causes the noise to change by approximately 12%.

Ways to Measure Young's Modulus

- Acoustics
  - » Good for finding mechanical properties of thin films (on the order of microns)
- Nanoindentation
  - » Good for finding mechanical properties on the atomic scale
- Purpose
  - » Determine if thin film and atomic mechanical properties of a material are the same as the bulk properties

Nanoindentation

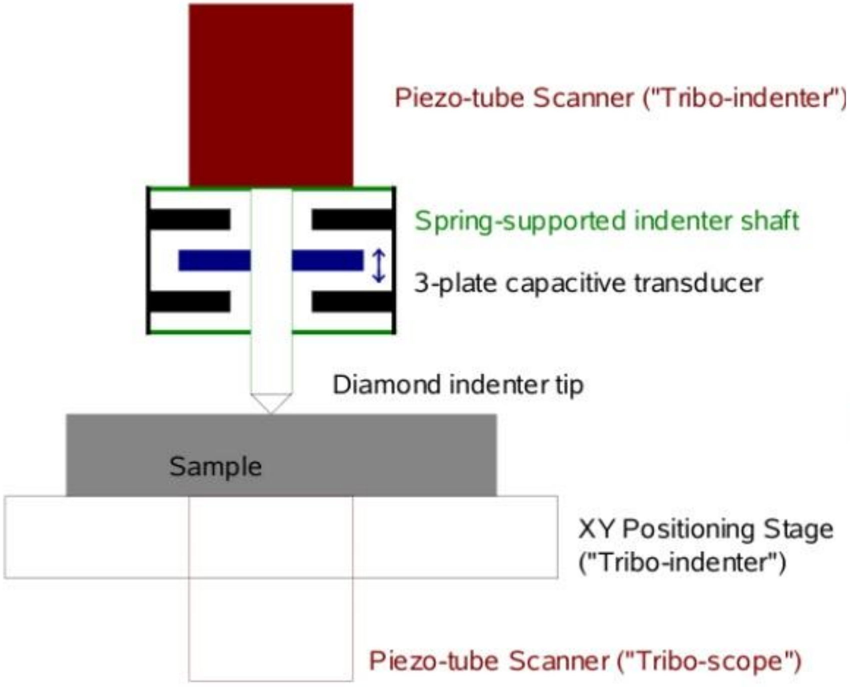
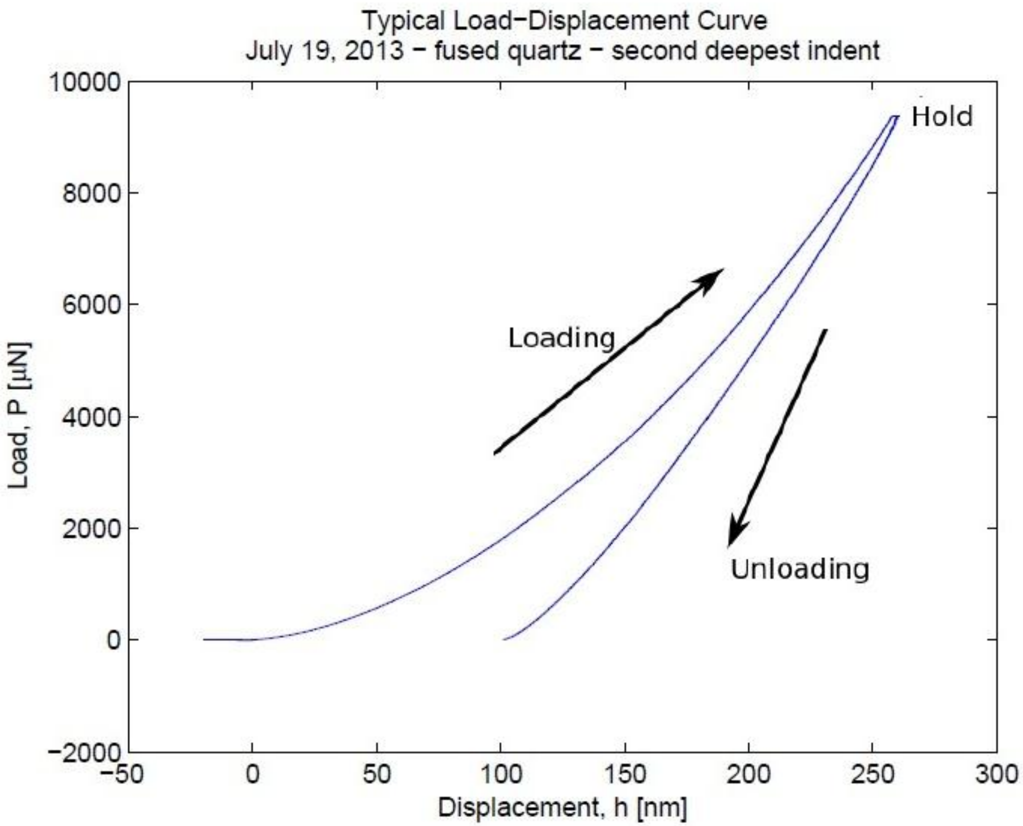


Photo credit: M. Oyen



Nanoindentation

- Two parameters of the nanoindentation system that affect sensitivity are variable: machine compliance and area function of the indenter tip
- Variation of 10% of the machine compliance causes a 9.2% variation of the Young's modulus
- Variation of 10% of the area function causes a 4.7% variation of the Young's modulus

Calibration

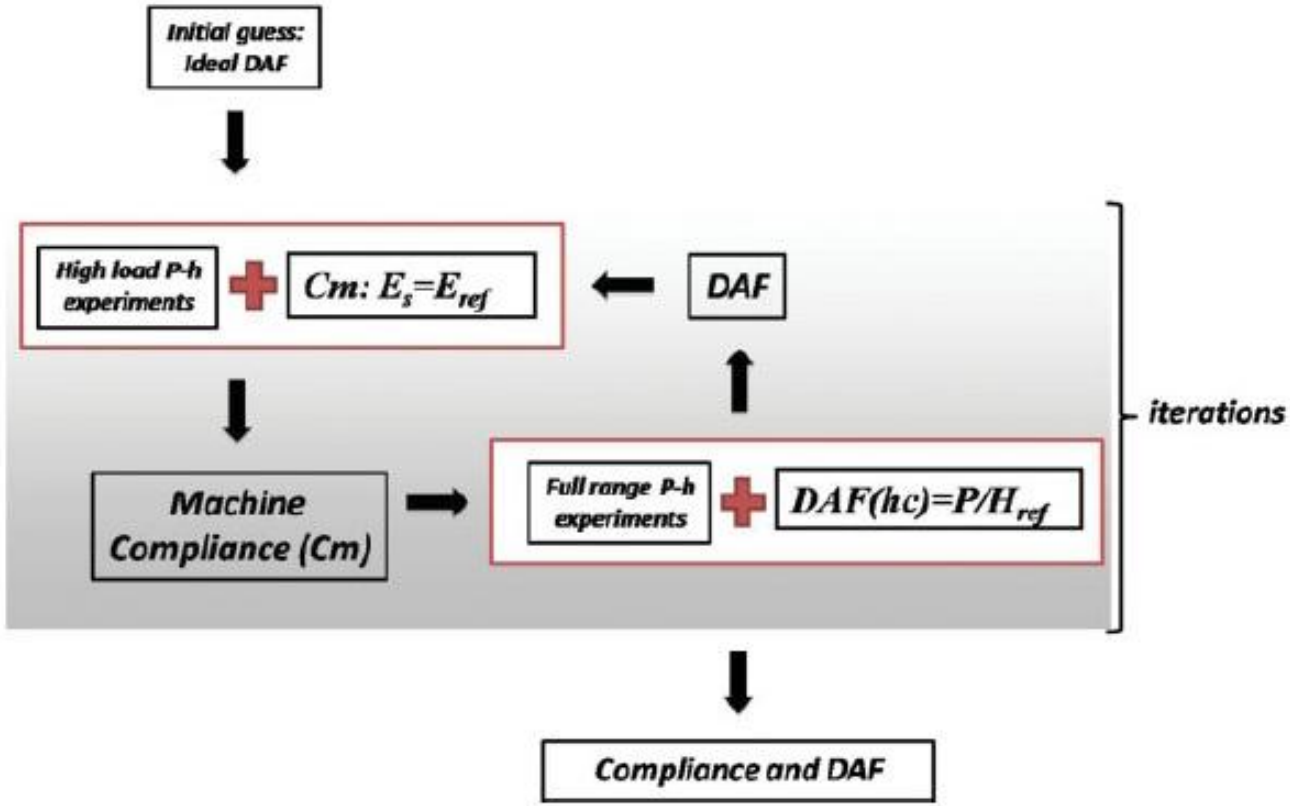


Photo credit: Barone et al., *Microsc. Res. Techniq*. 73:1001, 2010

Calibration

- Calibration is done on a material of known properties.
  - » Fused quartz is the standard calibration material.
- Calibration check: reverse analysis
  - » Run calibration analysis on a fused quartz data set, assuming the known value of the Young's modulus, E = 72 GPa
  - » Apply the calibration and run a Young's modulus analysis
  - » Should get the same number as the input value, with tolerance for rounding errors
- For each reverse analysis completed, results were consistent with the input value

Future Work

- Complete Young's modulus analysis for layered samples
  - » Analysis following the method of Song and Pharr
  - » Include Hay model to remove substrate effects
- Compare results from Young's modulus analysis of nanoindentation with fully analyzed results from Embry-Riddle acoustics group to uniquely determine Young's modulus and Poisson's ratio

Acknowledgements

- LIGO and LSC
- California Institute of Technology
- Matt Abernathy
- Andri Gretarsson and Michele Zanolin at Embry-Riddle Aeronautical University
- Tamaryn Shean and the Oyen group at Cambridge University
- Lucas Meza and the Greer group at Caltech

References

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Nanoindentation Equations

- Unloading data relation:

$$P = \alpha(h - h_f)^m$$

- Contact stiffness:

$$S = \frac{\mathrm{d}P}{\mathrm{d}h} = \frac{2}{\sqrt{\pi}} E_r \sqrt{A}$$

- Reduced Young's modulus:

$$\frac{1}{E_r} = \frac{(1-\nu_s^2)}{E_s} + \frac{(1-\nu_i^2)}{E_i}$$

- 6 term area function

$$A(h) = C_0 h^2 + C_1 h + C_2 h^{1/2} + C_3 h^{1/4} + C_4 h^{1/8} + C_5 h^{1/16}$$

Nanoindentation Equations

- Modeling load frame and specimen as two springs in series, total compliance of the system is

$$C = C_{\text{machine}} + C_{\text{specimen}}$$

- Since specimen compliance is the inverse of contact stiffness, the final equation is

$$C = C_{\text{machine}} + \frac{\sqrt{\pi}}{2E_r}\frac{1}{\sqrt{A}}$$

Calibration Methods

- Calculating machine compliance can be done:
  - » Graphically, by fitting the second equation on slide 15; the intercept is the machine compliance
  - » Analytically, by calculating both sides of the second equation on slide 14, and taking the average difference
- Applying the machine compliance can be done:
  - » To the load
  - » To the displacement

Calibration Results

Date	Calibration method	Young's modulus
July 19	Graphical, load	71.72 ± 1.89
July 19	Analytical, load	73.69 ± 1.79
July 19	Graphical, displacement	71.67 ± 1.88
July 19	Analytical, displacement	73.47 ± 1.72
August 5	Graphical, load	74.90 ± 2.64
August 5	Analytical, load	75.54 ± 2.53
August 5	Graphical, displacement	74.95 ± 2.49
August 5	Analytical, displacement	75.35 ± 2.47

Future Work - Comparison