Measurement of Wire Sag in a Vibrating Wire Setup*

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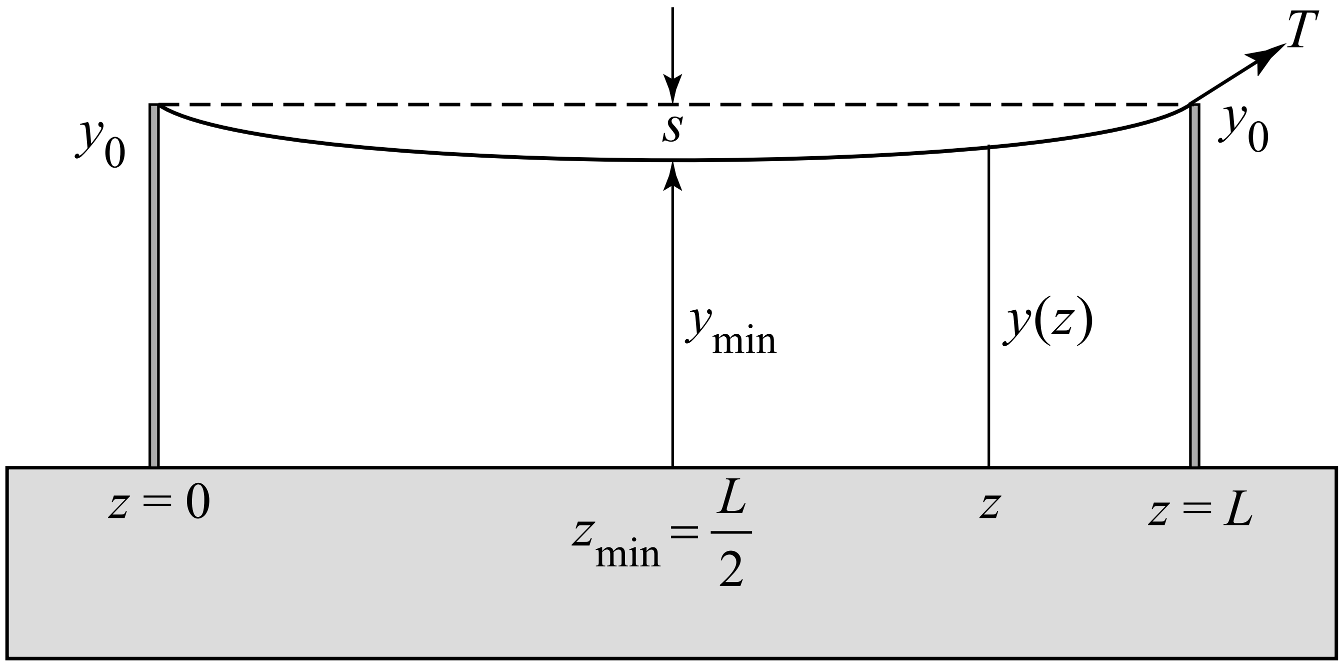
Introduction

- NSLS-II requires a very tight tolerance on the relative alignment of quadrupoles and sextupoles on a girder, which is ~ 6 m long.
- Although individual magnets could be fiducialized using a variety of techniques, one is ultimately limited by the survey accuracy (50-100 μm) for the final installation.
- Based on the accuracy required, and the overall length of the girders, the vibrating wire technique developed at Cornell was chosen for aligning magnets to each other.
- Cu-Be wire sags 500-600 μm for ~6 m length. So, accurate calculation of the sag correction is essential.
- How well does the sag formula work?

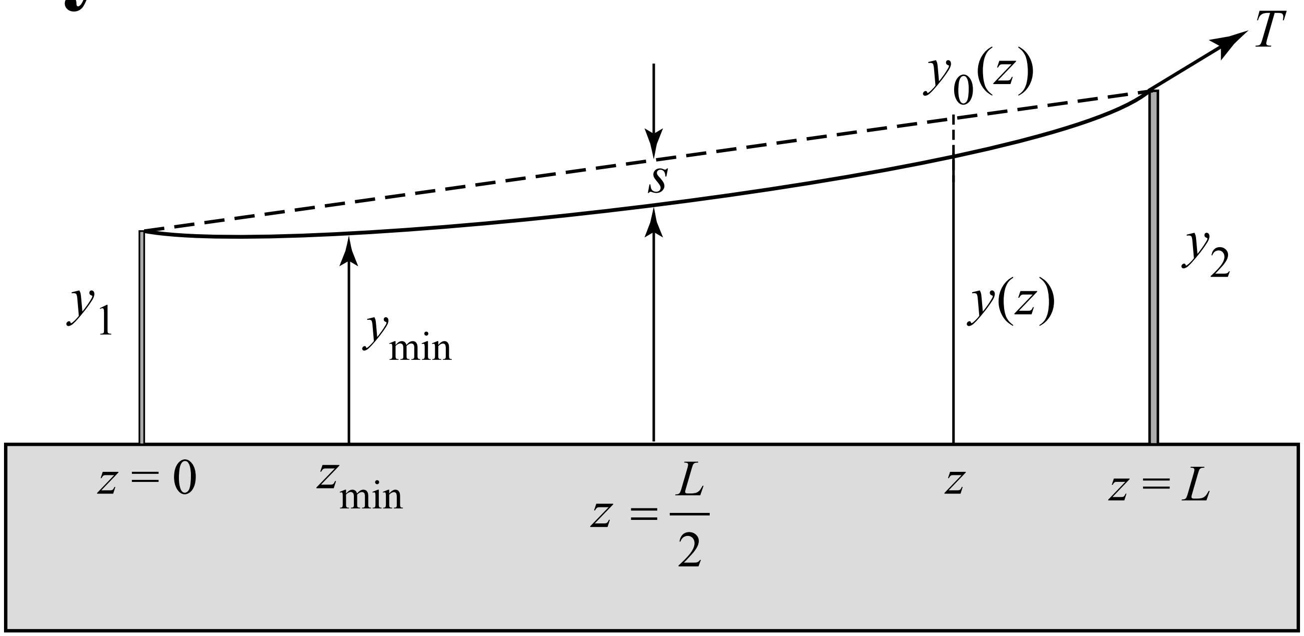
Wire Sag: Symmetric Case



$$y(z) = \left(\frac{m_\ell g}{2T}\right) z(z - L) + y_0 \qquad z_{\min} = \frac{L}{2} \qquad f_1 = \left(\frac{1}{2L}\right)\sqrt{\frac{T}{m_\ell}}$$

$$\boxed{\text{Sag} = s = (y_0 - y_{\min}) = \left(\frac{m_\ell g L^2}{8T}\right) = \frac{g}{32 f_1^2}}$$

Asymmetric Case: How to Define Sag?



$$y_0(z) = \frac{y_2 - y_1}{L} z + y_1$$

$$y(z) = \left(\frac{m_\ell g}{2T}\right) z(z-L) + \frac{y_2 - y_1}{L} z + y_1$$

$$z_{min} = \frac{L}{2}\left[1 - \frac{8(y_2 - y_1) f_1^2}{g}\right]$$

If we define "sag" as departure from straight line at $z = z_{min}$, then it is given by:

$$y_0(z_{min}) - y_{min} = \frac{g}{32 f_1^2} - \frac{2 f_1^2 (y_2 - y_1)^2}{g}$$

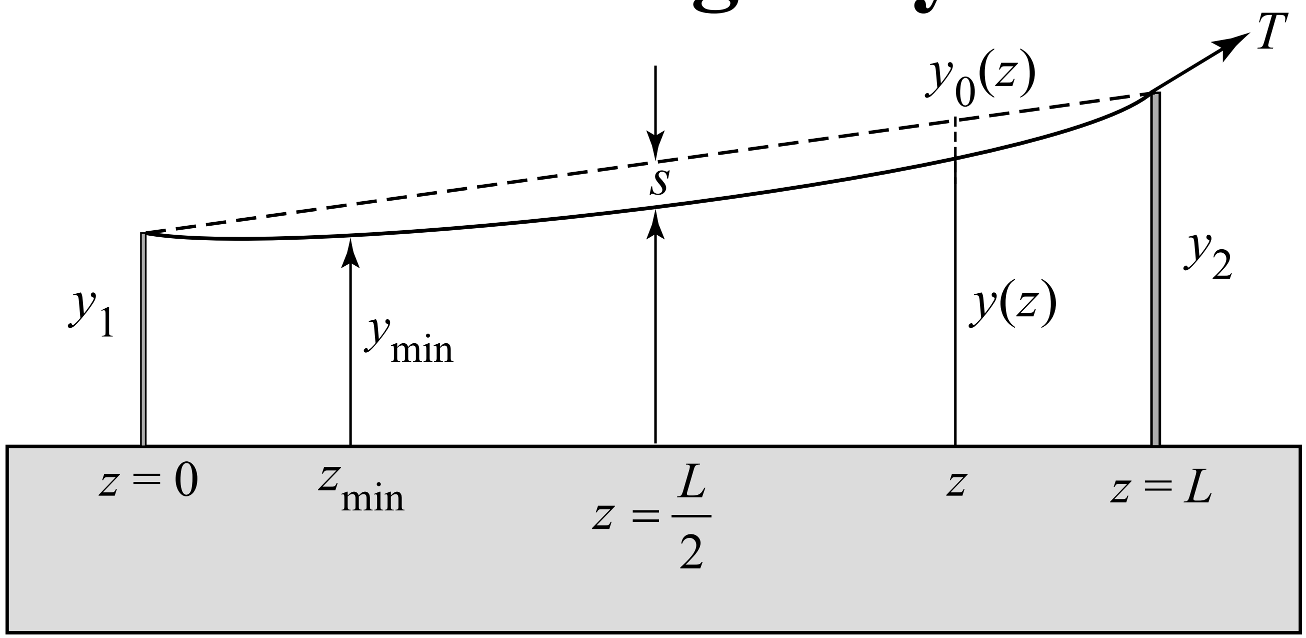
Note that z_{min} may be outside the wire!

For $y_2 - y_1 = 0.25$ mm, $L = 6$ m, $f_1 = 22$ Hz:

z_{min} differs from $L/2$ by ~ 30 cm

Correction term in "sag" is ~ 6 μm

Definition of Sag: Asymmetric Case



$$y_0(z) = \frac{y_2 - y_1}{L} z + y_1$$

$$y_0(z) - y(z) = \left(\frac{m_\ell g}{2T}\right) z(z - L)$$

Deviation from straight line at any position.
This has the same form as the symmetric case.

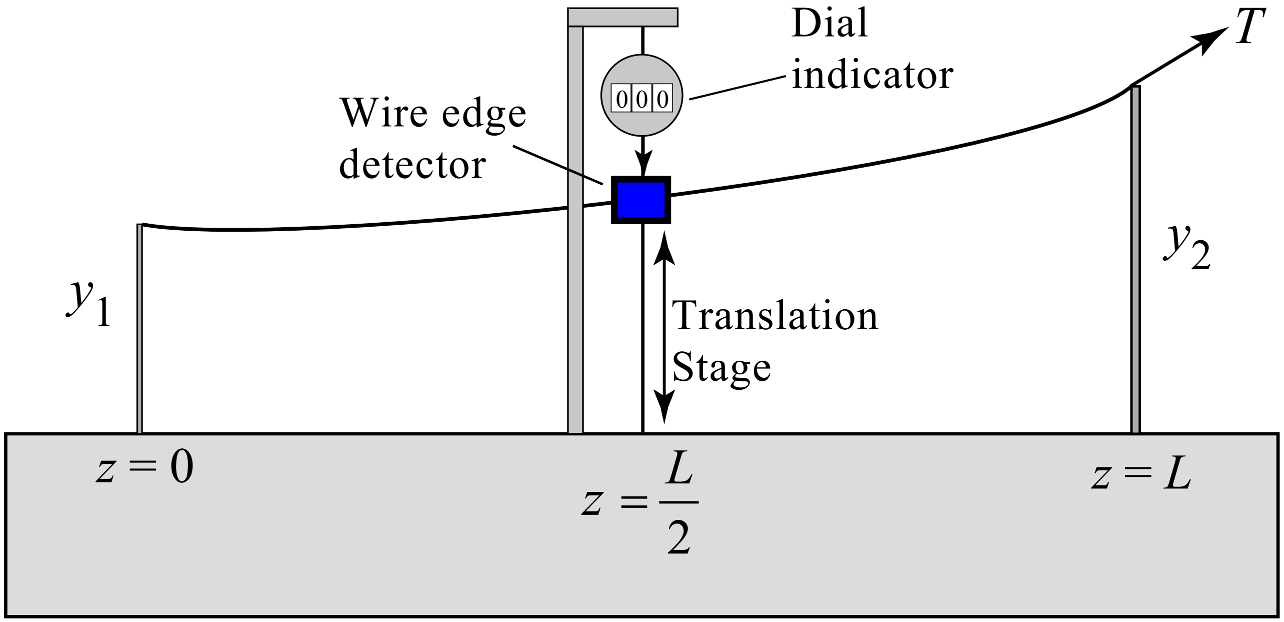
If we define “sag” as the maximum departure from a straight line then:

$$\text{Sag} = s = \left[y_0(z) - y(z)\right]_{\max} = \left(\frac{m_\ell g L^2}{8T}\right) = \frac{g}{32 f_1^2}$$

Same as the symmetric case

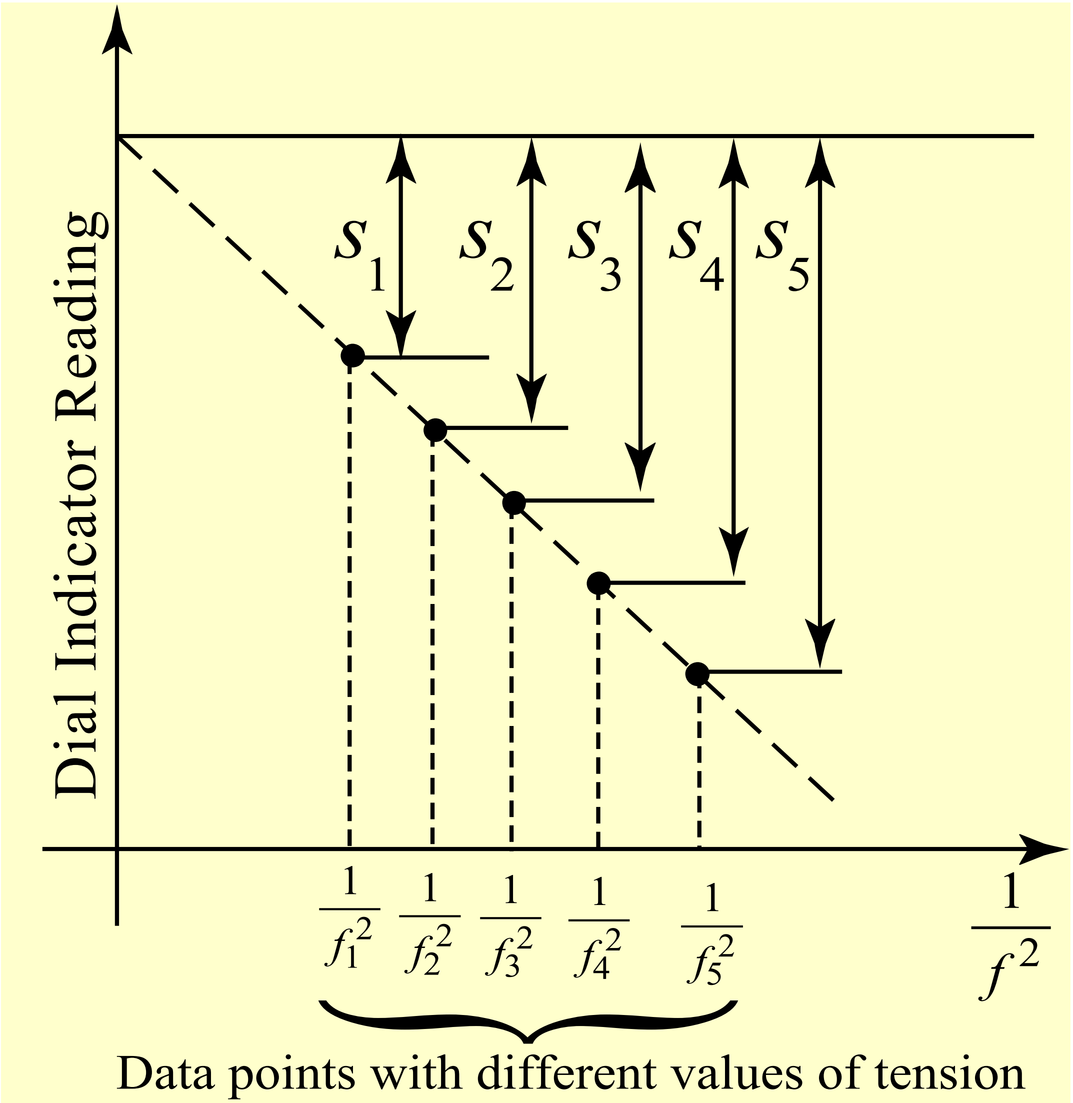
Maximum departure from straight line always occurs at the midpoint.

Measurement of Sag: Concept



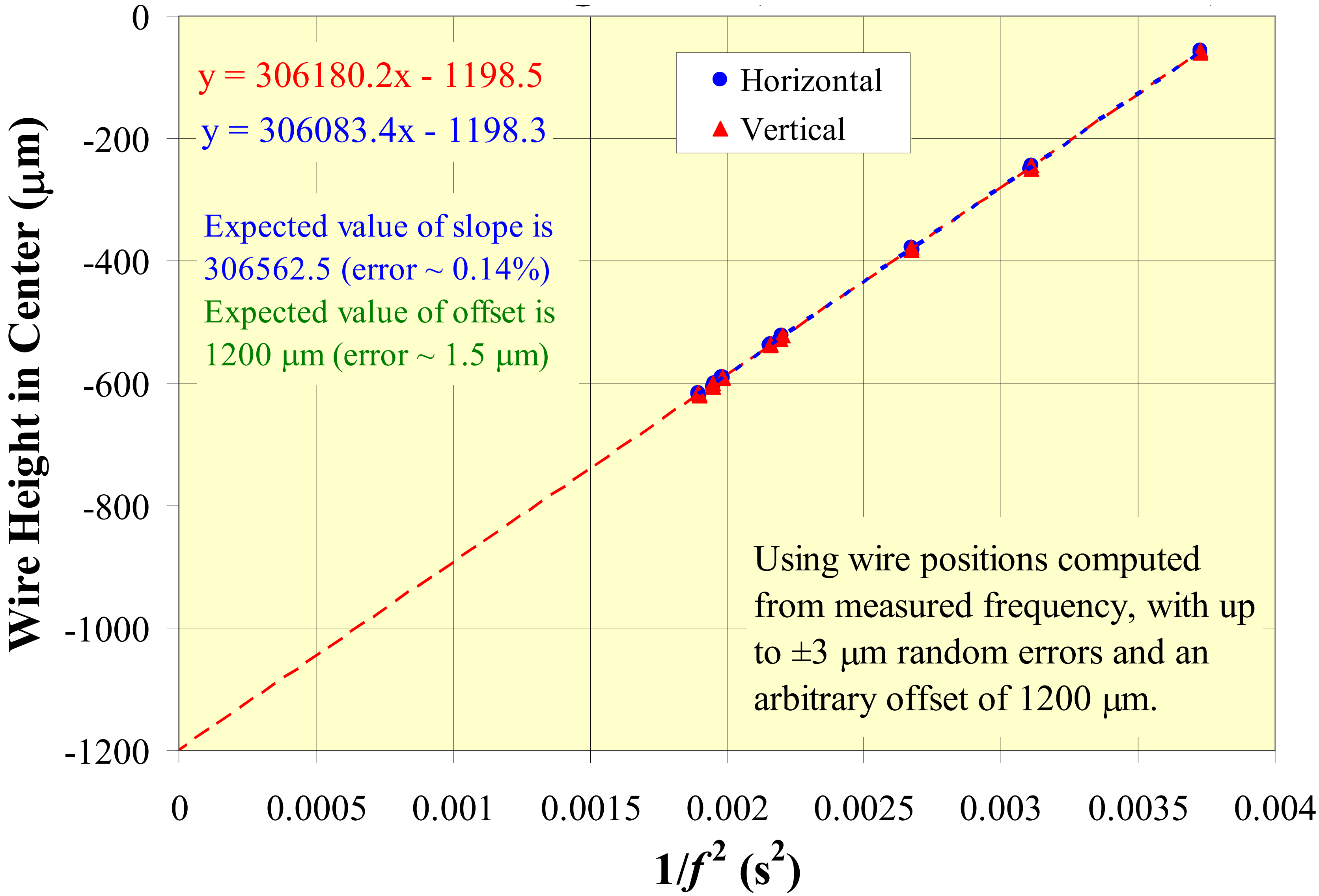
- Set up a wire position detector mounted on a translation stage at the mid point.
- For a given tension, adjust position of detector until null output is obtained.
- Change the tension, and adjust detector again. Measure the amount moved using digital dial indicators.
- Study as a function of tension (or resonant frequency) and compare to theory.

Measurement of Sag: Analysis Concept

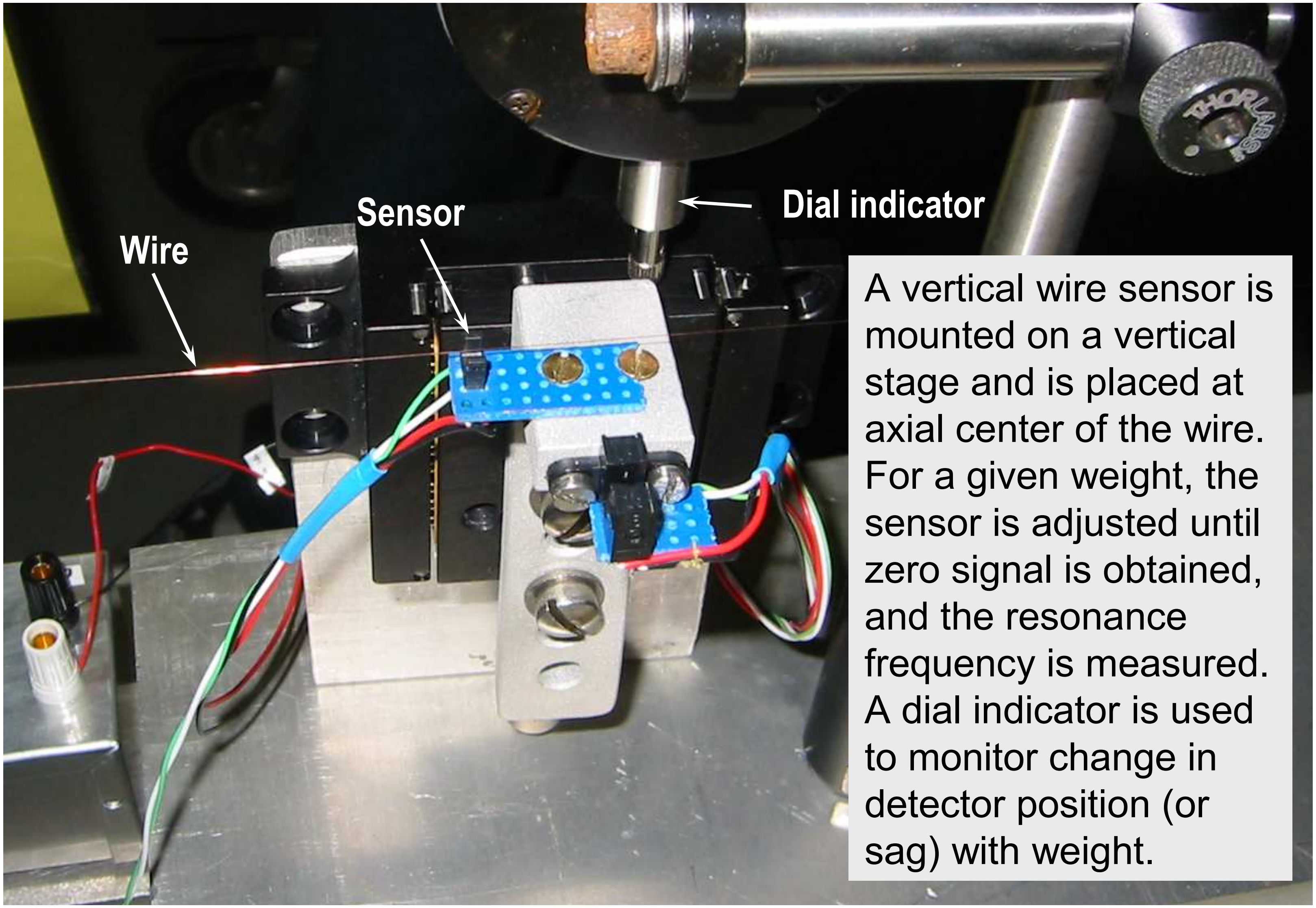


- Vary tension and measure the resonant frequency and the change in wire height.
- Plot dial indicator reading vs. $1/f^2$, which should give a straight line.
- Extrapolate to infinite tension. The difference between the intercept and any given dial reading gives the absolute value of sag for that tension (or frequency).
- Compare to formula.

Wire Sag: Simulation with Random Errors

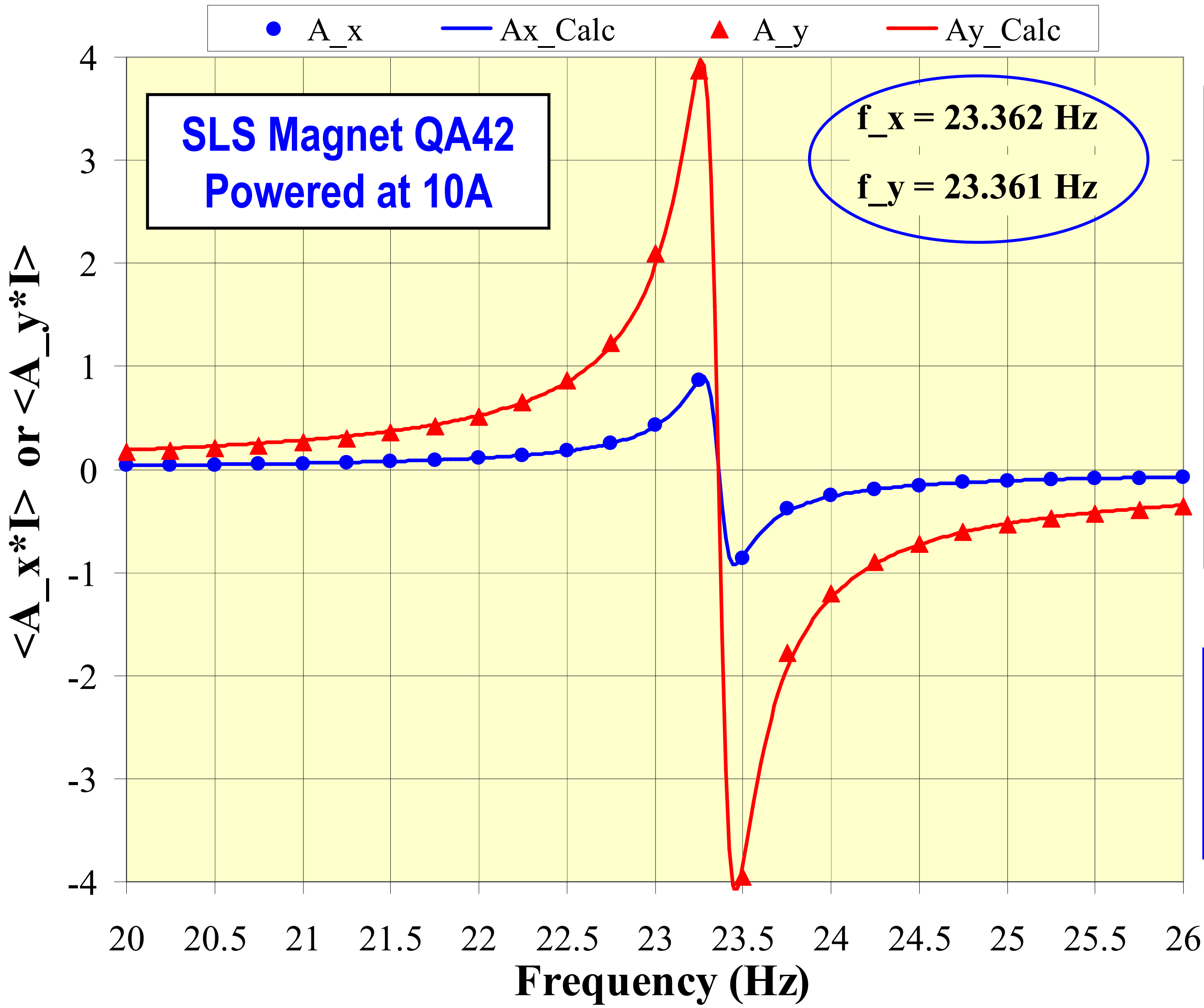


Experimental Setup for Sag Measurements



A vertical wire sensor is mounted on a vertical stage and is placed at axial center of the wire. For a given weight, the sensor is adjusted until zero signal is obtained, and the resonance frequency is measured. A dial indicator is used to monitor change in detector position (or sag) with weight.

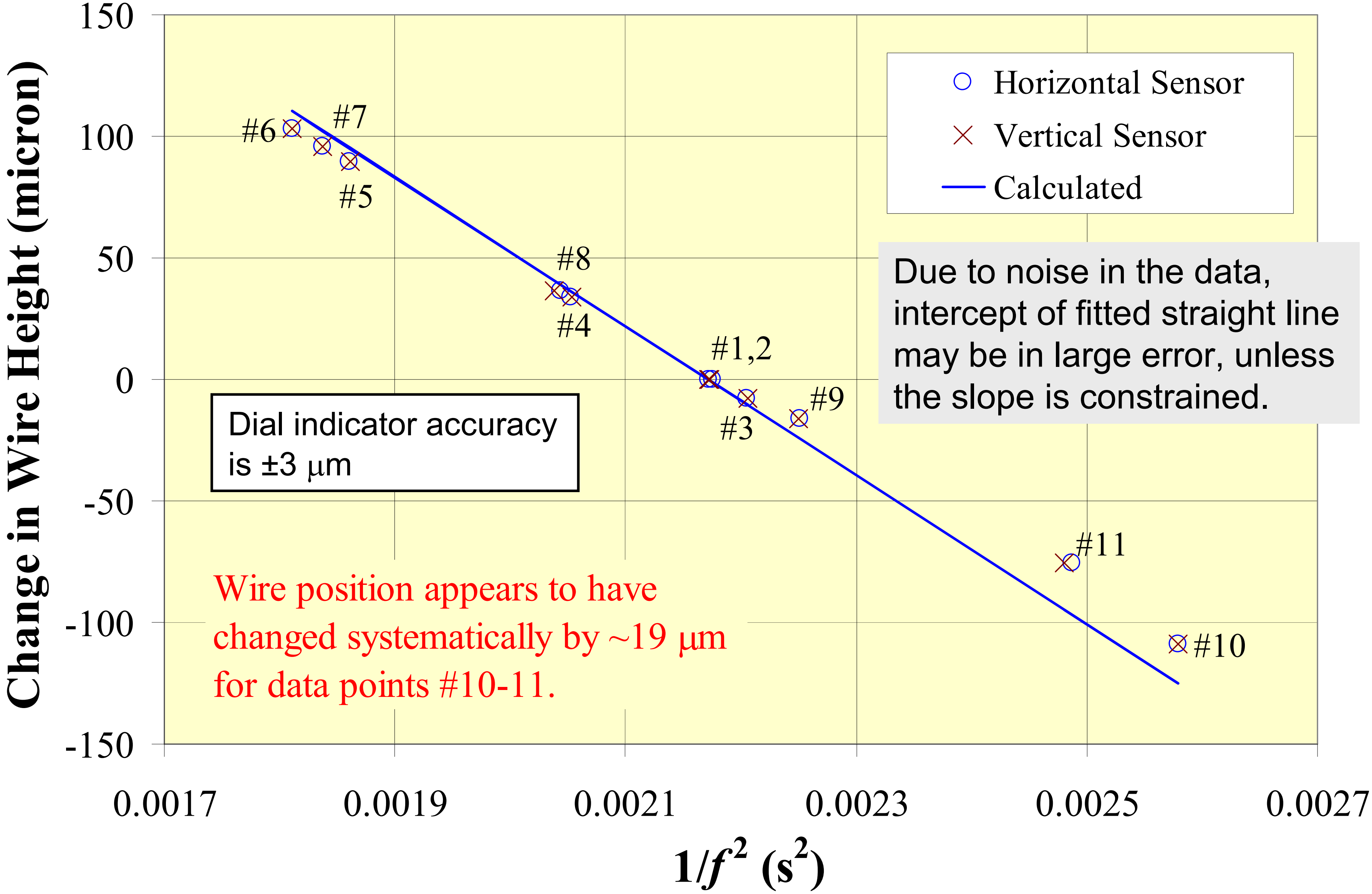
Accuracy of Resonant Frequency

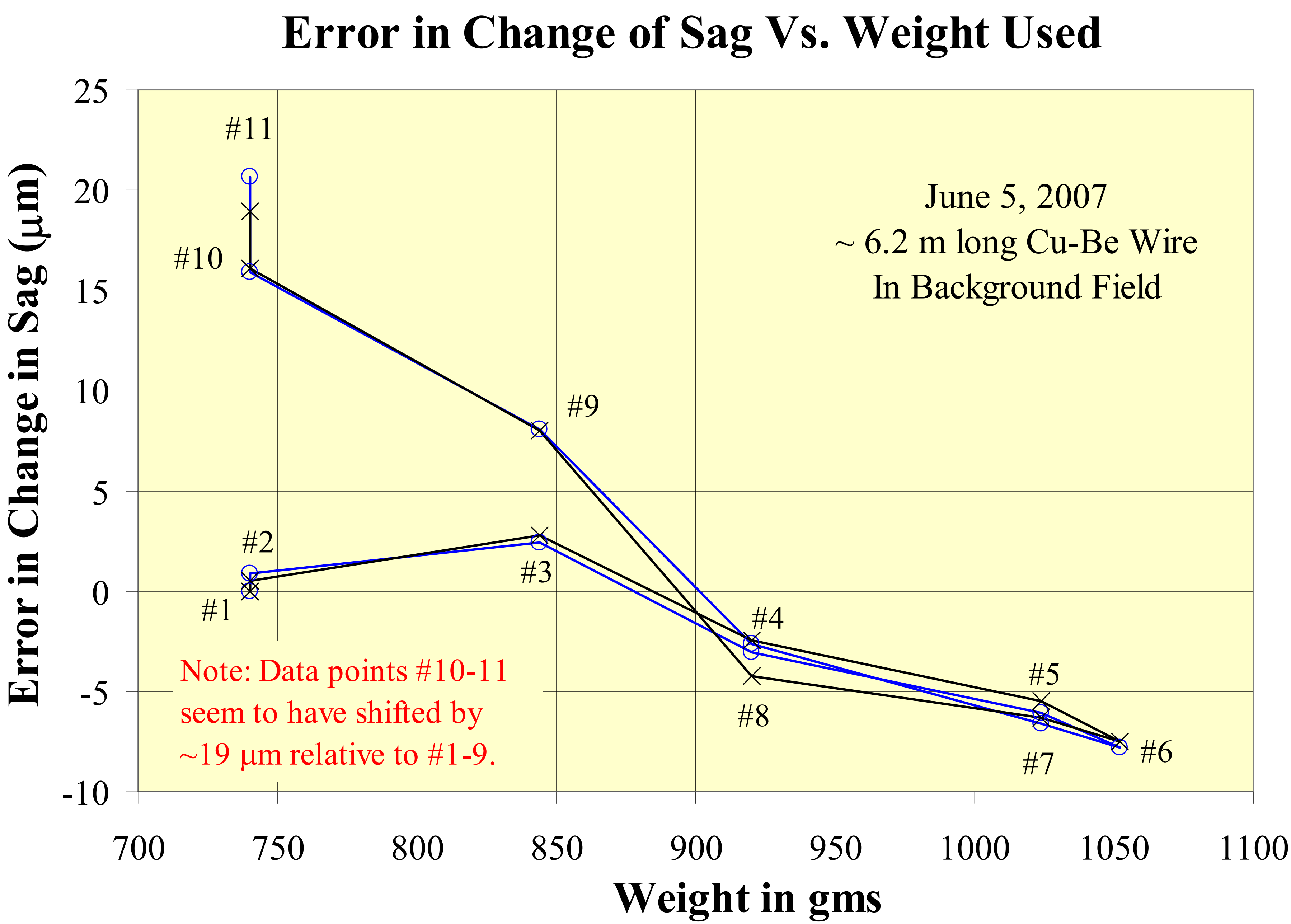


Correction for large wire sag (500 to 600 microns for ~6.2 m length) is very important, which in turn requires a very precise knowlege of resonant frequency.

$$Sag = \frac{g}{32 f^2}$$

Sag: Measured Vs. Calculated





Error in Change of Sag Vs. Weight Used
June 5, 2007
~ 6.2 m long Cu-Be Wire
In Background Field
Note: Data points #10-11
seem to have shifted by
~19 µm relative to #1-9.
#11
#10
#9
#2
#3
#1
#4
#8
#5
#7
#6
Error in Change in Sag (µm)
Weight in gms
25
20
15
10
5
0
-5
-10
700
750
800
850
900
950
1000
1050
1100

Summary

- Accurate estimation of sag is critical for precise alignment of multipoles on a girder for NSLS-II.
- A simple set up was used to measure changes in sag as a function of applied tension.
- Noise in the data due to dial indicator resolution, detector noise, wire vibrations, etc. was up to ±5 μm in wire height.
- An unconstrained fit to the data gives large uncertainty in the intercept, or the absolute value of the sag. The change from one tension to another, however, generally agreed with theory.
- The set up was not very robust mechanically and unexpected changes in wire position were sometimes seen.
- The experiment will be repeated with a better set up when the R&D vibrating wire system at BNL will be operational.