Progress of the development of an ultra-low-noise laser Doppler displacement meter for synchrotron radiation applications with sub-nanometer resolution

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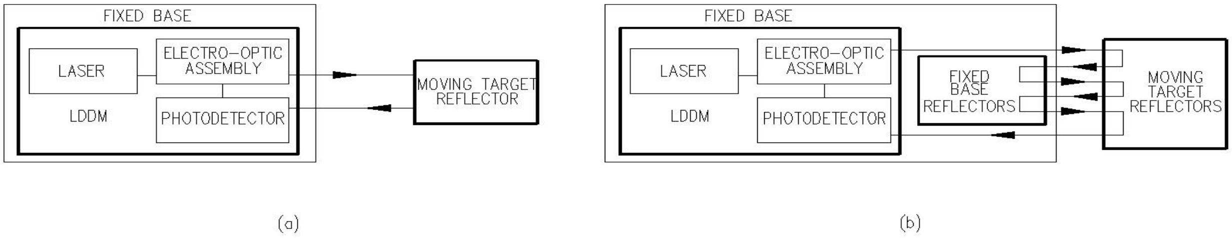
Abstract

To perform a sub-nanometer level measurement with centimeters measuring range, Argonne National Laboratory (ANL) developed special self-aligning multiple-reflection optics to extend its measuring resolution and improve the laser Doppler displacement meter (LDDM) signal-to-noise ratio one order of magnitude or more [1-3]. This technique has been applied to today's hard x-ray nanoprobes successfully [4]. However, for the next generation of hard x-ray nanoprobe using multilayer Laue lenses (MLLs) with 1 – 2 nanometer x-ray focusing capability [5], the multiple-reflection optics will face design difficulties due to MLL's restricted alignment space. A DOE Cooperative Research and Development Agreement (CRADA) between ANL and Optodyne, Inc. has been established to develop a prototype LDDM system with ultra-low noise level for linear measurements to sub-nanometer resolution for synchrotron radiation applications. To achieve higher signal to noise ratio, we have improved the heterodyne efficiency and reduced the detector shot noises by proper shielding and a low-pass filter. In this paper, we present the preliminary test results of this new LDDM system using ANL-developed single/multiple-reflection optics and weak-link stage techniques [6,7]

Introduction

Since 1997, a prototype laser Doppler linear encoder (LDLE) with multiple reflections has been developed at the APS. With a customized commercial laser Doppler displacement meter (LDDM), this novel linear encoder achieved sub-angstrom sensitivity in a 300-mm measuring range. The laser Doppler displacement meter is based on the principles of radar, the Doppler effect, and optical heterodyning. We have chosen a LDDM as our basic system, not only because of its high resolution and high measuring speed (2 m/s) but also because of its unique performance independent of polarization, which provides the convenience to create a novel multiple-reflection-based optical design to attain sub-angstrom linear resolution extension.



(a)

(b)

FIGURE 1. Left: Schematic of the laser Doppler displacement measurement system. Right: Schematic of the laser Doppler displacement measurement system with multiple-reflection optics [7].

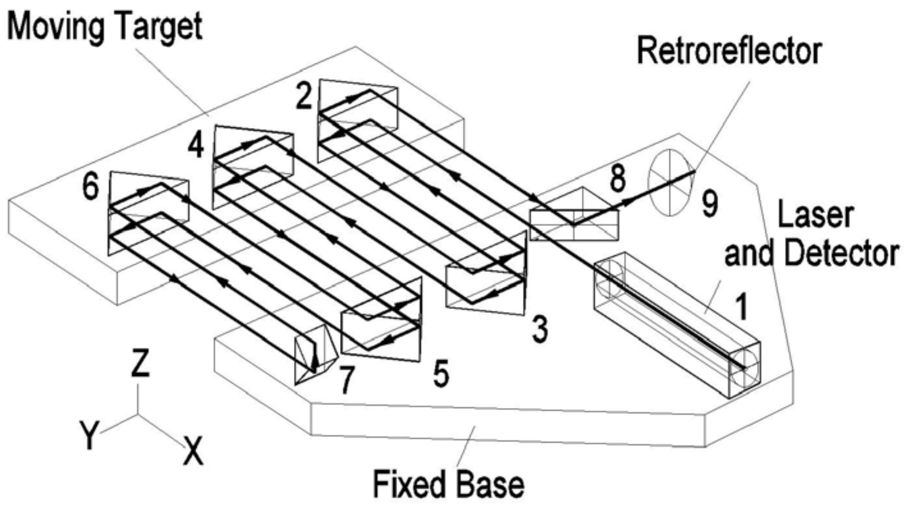
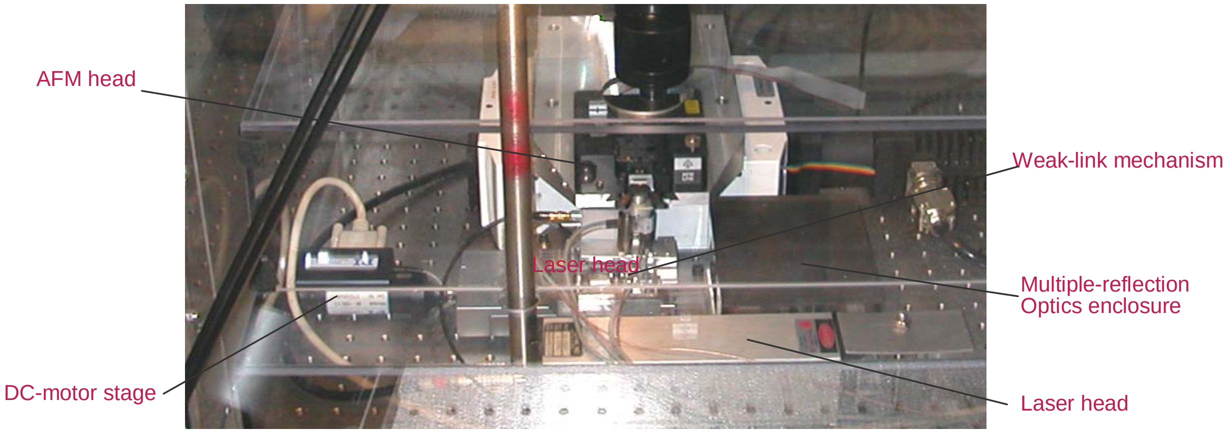


FIGURE 2. Configuration of a self-aligning twenty-four reflection optical design. In this figure, item 1 is the frequency-stabilized laser source with heterodyning detector, items 2 – 8 are right-angle prisms, and item 9 is the end retroreflector [7].



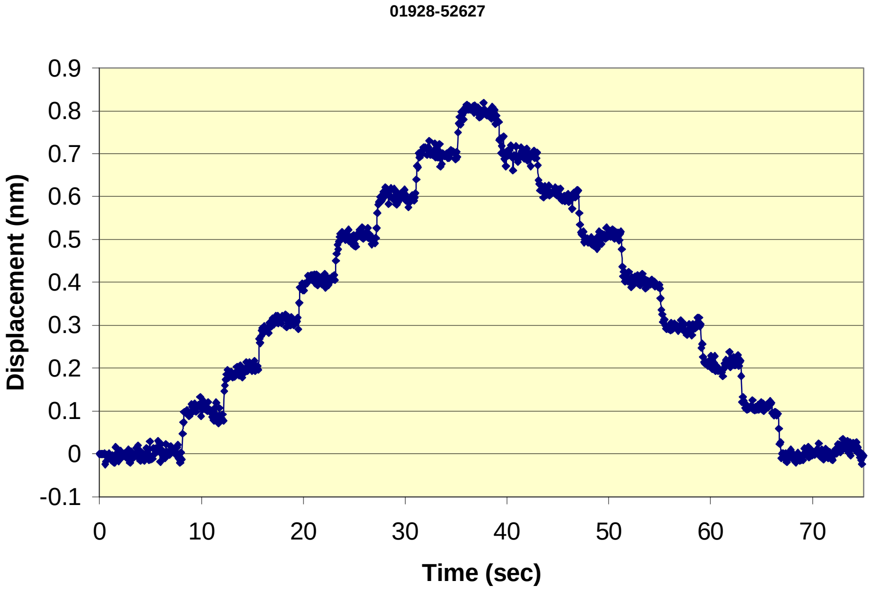


FIGURE 3. Top: Photograph of the one-dimensional closed-loop linear stage system for an atomic force microscope with a twelve-bounce optical resolution extension assembly and DSP-based control system. Bottom: A series of 1-angstrom steps demonstrated with this one-dimensional stage system [7].

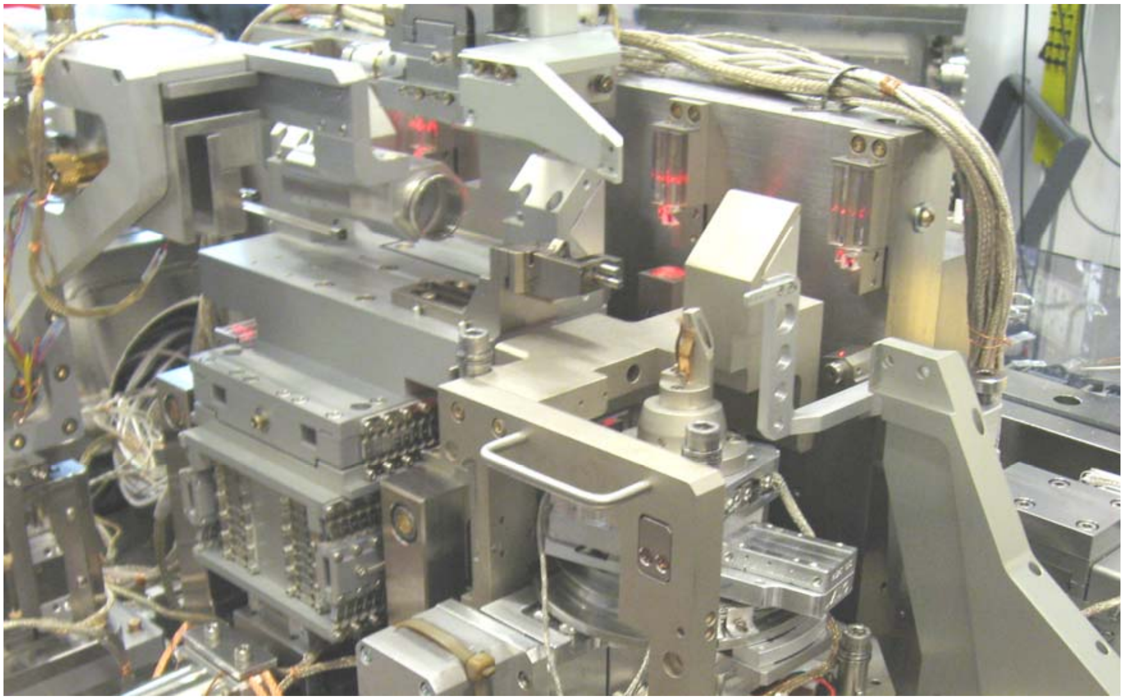


FIGURE 4. Photograph of the laser encoded scanning stage system for the ANL CNM hard x-ray nanoprobe with eight-bounce optical resolution extension assembly at APS Sector 26 [4].

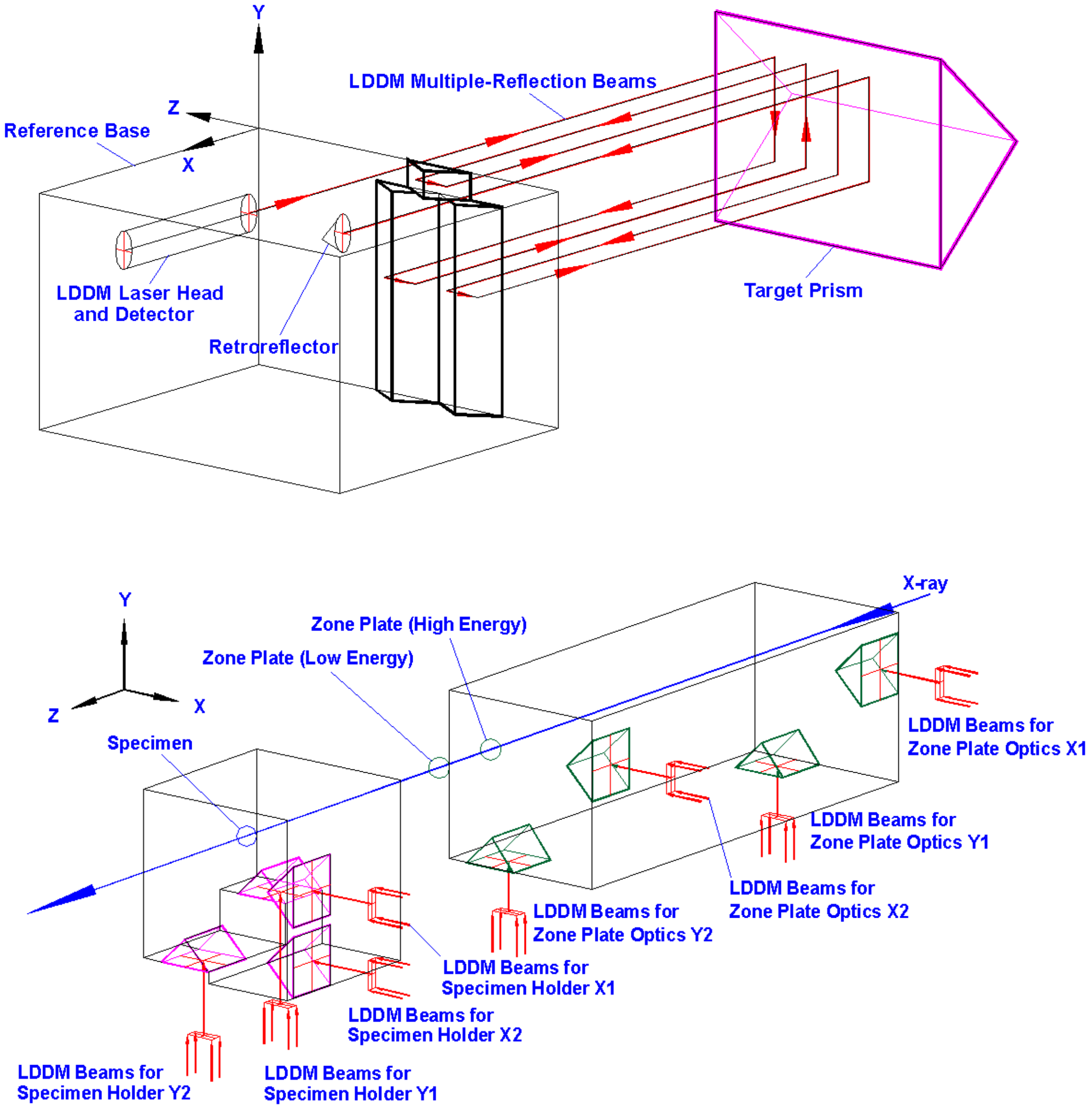
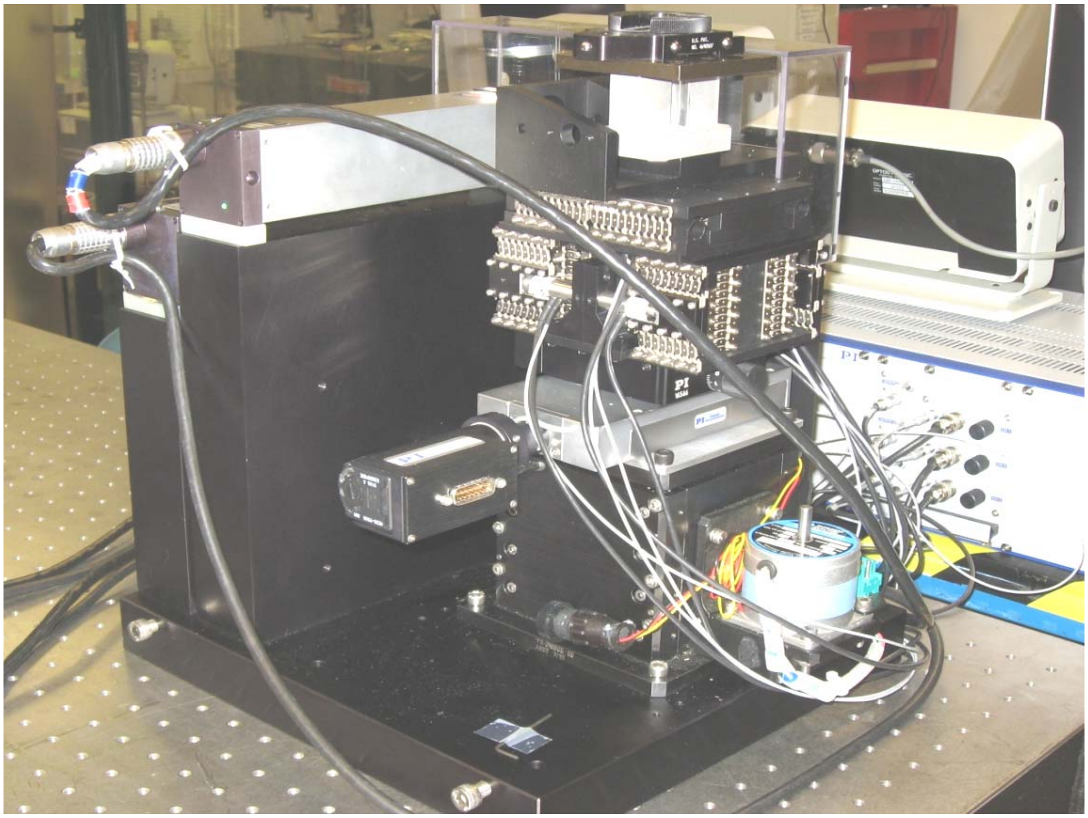


FIGURE 5. Schematic of the eight-bounce self-aligning multiple-reflection optical design. With same LDDM laser source and detector electronics, this optical path provides eight times greater resolution [4].



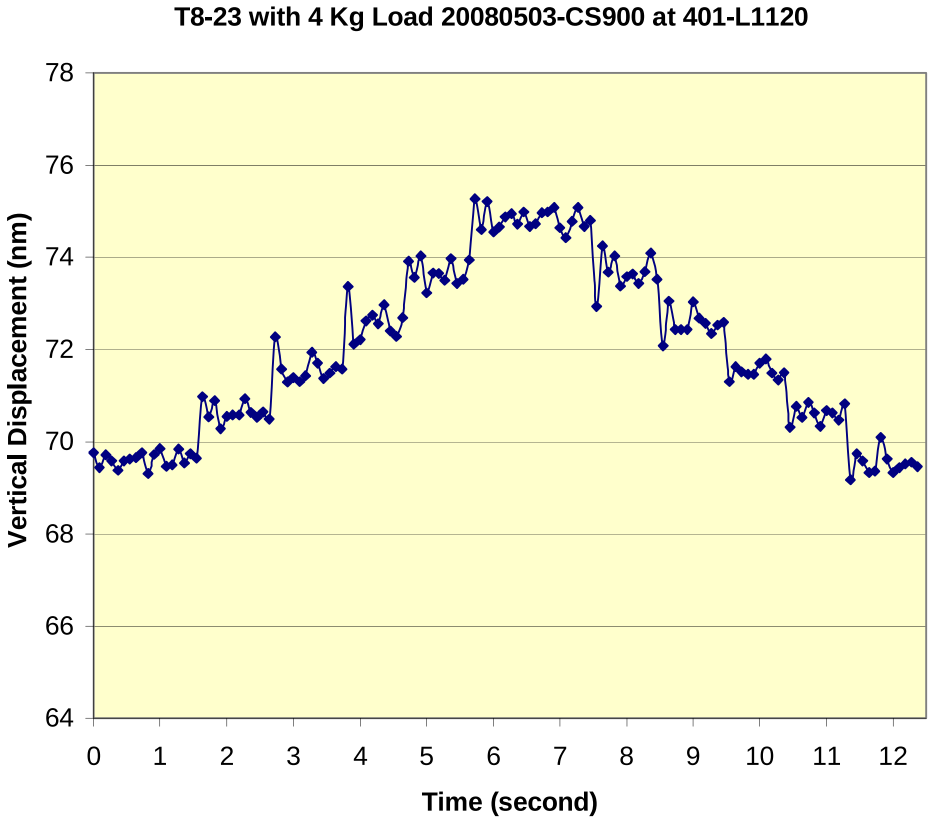

T8-23 with 4 Kg Load 20080503-CS900 at 401-L1120
Vertical Displacement (nm)
78
76
74
72
70
68
66
64
0
1
2
3
4
5
6
7
8
9
10
11
12
Time (second)

FIGURE 6, Top: Photograph of a 2-D nanopositioning diagnostic setup to support the ANL CNM nanoprobe instrument commissioning process at the APS. Bottom, A series of 1-nm steps generated by the APS-designed T8-23 ultraprecision weak-link stage on top of the original T2-24 high-stiffness motor-driven stage with a 4-kg load under LDDM closed-loop control using eight-bounce optical resolution extension assembly [8].

The comparison between the homodyne and heterodyne scheme

There are two basic schemes to retrieve the laser interference signal, the homodyne and the heterodyne scheme. We believe the heterodyne is superior to achieve higher resolution. Here is a comparison of these two schemes.

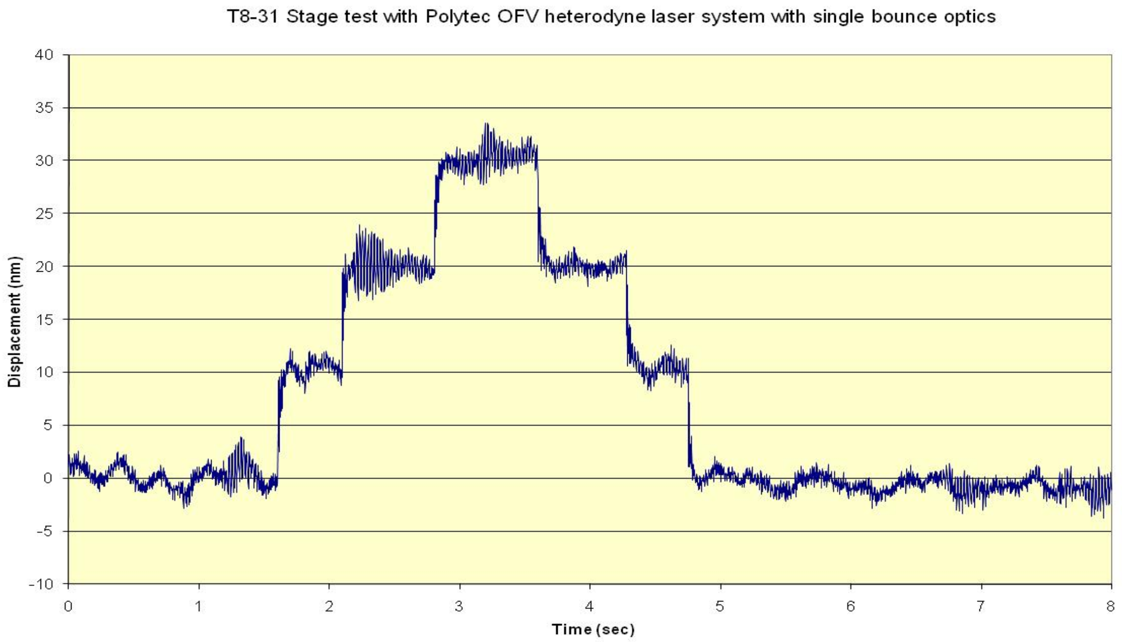
The homodyne scheme using single laser frequency is amplitude modulated. It requires 2 detectors to determine the movement direction. Hence the alignment is more difficult and the signal strength is lower. Since it is amplitude modulated, it is more sensitive to the noise pickup and amplitude variations.

The heterodyne scheme using two laser frequencies is frequency modulated. The movement direction is determined by the increasing or decreasing of the beat frequency. Hence only 1 detector is needed. The alignment is relatively easy and the signal strength is higher. Since it is frequency modulated, it is less sensitive to the noise pickup and amplitude variations

Preliminary test results with improved heterodyne efficiency and detector shielding

To achieve higher signal to noise ratio, we have improved the heterodyne efficiency and reduced the detector shot noises by proper shielding and a low-pass filter. Preliminary test results show that the phase signal to noise ratio of the new LDDM prototype system is improving significantly.

A DOE CRADA between ANL and Optodyne, Inc. has been established and is in progress to develop a new LDDM prototype system with ultra-low noise level for linear measurements to sub-nanometer resolution for synchrotron radiation applications.



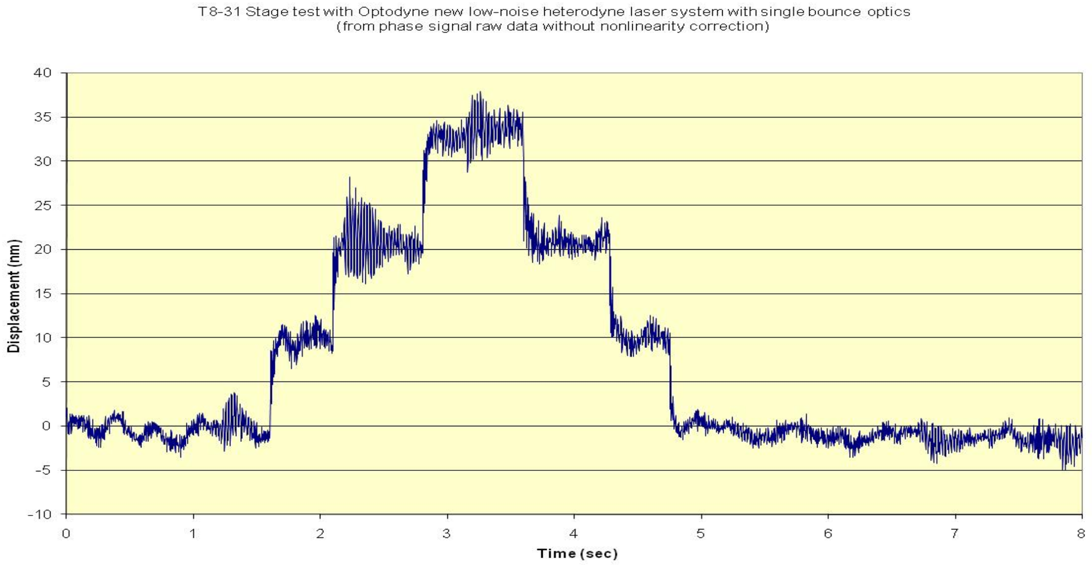


FIGURE 7, Top, Test setup for laser encoder noise level side by side comparison using APS T8-31 weak-link stage. Middle, 10-nm steps displacement output from Polytec OFV heterodyne laser displacement meter system with single-bounce optics. Bottom, 10-nm steps displacement output from Optodyne new low-noise heterodyne laser displacement meter system with single-bounce optics.

Acknowledgments

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References:

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