Measurements with Capacitance Gage for Sub-Nanometer Thermal Expansion Characterization

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MTI Instruments contracted an independent Metrology expert to test and verify the performance of a new high resolution capacitance gauge. The Accumeasure HD has passed in house testing where its performance was tested against a commercial laser interferometer (See Application Note). Optical Metrology Solutions was chosen based on their extensive experience and proximity to MTI's manufacturing plant.

Optical Metrology Solutions (OMS) Task:

OMS was tasked with designing a challenging experiment to verify the accuracy and resolution of the MTI Accumeasure HD capacitance system that could also be encountered in a typical customer application. The experimental setup and results are as follows:

The image on the left demonstrates what can happen to astronomical images without temperature compensation

Measurements with Capacitance Gage for Sub-Nanometer Thermal Expansion Characterization

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Optical Metrology Solutions

EXPERIMENTAL ABSTRACT

The ability to measure small thermal expansions of precision components can be critical to the performance of precision instruments such as optical telescopes. This white paper explores the ability of MTI's HD capacitance gage to measure expansion of optical elements in the sub-nanometer range.

DISCUSSION

Setup

To explore the ability to measure very small thermal expansions of a ceramic material, we used a 6-millimeter thick, optical mirror with an unprotected gold coating. Many low expansion materials, such as Zerodur, are well characterized materials used for critical optical mirror applications because of their low coefficient of thermal expansion of 0.1 x 10 -6. With a 6mm thick mirror, a change of 0.1 degrees C would create a change in mirror thickness of only 60 pico-meters. For a glass mirror the expansion is only about 6 to 10 nanometers for 0.1 degree C change. Stability at these levels is very difficult to achieve, but in some critical applications, such changes may cause an optical system to blur or lose resolution. Capacitance probes have the potential to measure such low changes over a small measurement range. In order to explore the ability to measure such a small change, we developed a test fixture using a low expansion ceramic material to hold the mirror and probe within less than 50 microns of each other so as to be in range of the capacitance probe. The MTI capacitance probe chosen was an ASP-50M-CTA which has a 50 um measuring range. The mating capacitance amplifier is the MTI Accumeasure HD which is designed to have very high resolution. The probe and amplifier were linearized on an air bearing stage using a glass encoder scale with 100nm accuracy.

The setup is shown in **FIGURE 1:** The fixture stand consisted of a holder for the mirror which supported the mirror from the bottom leaving the mirror free to expand upward. A similar holder supported the probe from the bottom, removing any expansion of the probe case from the measurement. The two support plates where connected with three rods made of the same very low expansion ceramic material. The mirror was instrumented with three thermocouples around the exposed side of the mirror using heat conducting adhesive, as well as one thermistor used for feedback to a thermal electric device attached to the back of the mirror for heating. A ground wire needed for the operation of the capacitance probe was attached to the gold surface of the mirror using an electrical conducting adhesive.

By providing local heating to the back of the mirror and keeping the system isolated from room "breezes", the mirror should slowly expand with little expansion of the ceramic support structure, permitting measurement of the mirror growth during heating by the capacitance probe. Only the amount of the support structure between the mirror back and the base of the probe would contribute to any changes from the ceramic support. The thermal couple sensors monitor the heat distribution in the mirror to verify that uneven tilt does not occur, and also as an input to calculating the theoretical expansion of the mirror to compare against the reading from the probe.

The system was checked in stages to verify operation of the various sensors. First just small heating was applied to verify the mirror appeared to heat uniformly and that all thermocouples were operating consistently. The thermal couples were read using an Omega HH520, four channel handheld data logger thermometer (the 4th channel being used to monitor the air environment surrounding the structure). A box of 2-inch thick Styrofoam was used to isolate the whole test unit from room thermal variations. The heating was done using an Omega TE-8-0.45-1.3 thermal electric module and TC-720 controller. An Omega MP-3189 Thermistor was attached to the 4th or 12 O'clock position (with the thermo couples at 3, 6, and 9 o'clock positions) on the side of the mirror for feedback to the thermo-electric control unit. The whole system was placed on a vibration isolated optics table using passively air isolation.

Results

As a first simple test, the temperature of the mirror was raised about 1.5 degrees C then allowed to fall

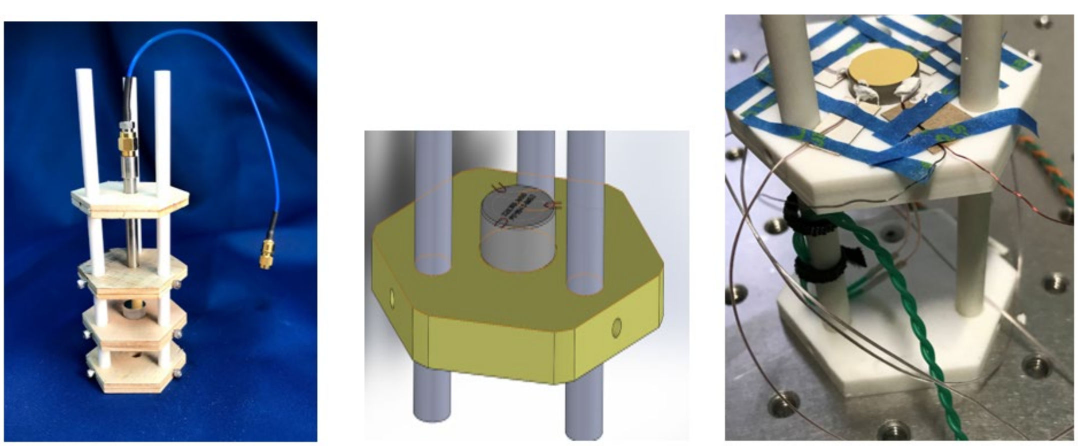


FIGURE 1.

Mockup of the stand to hold the probe and mirror (left and center) then instrumented with thermal couples and thermal electric system (right).

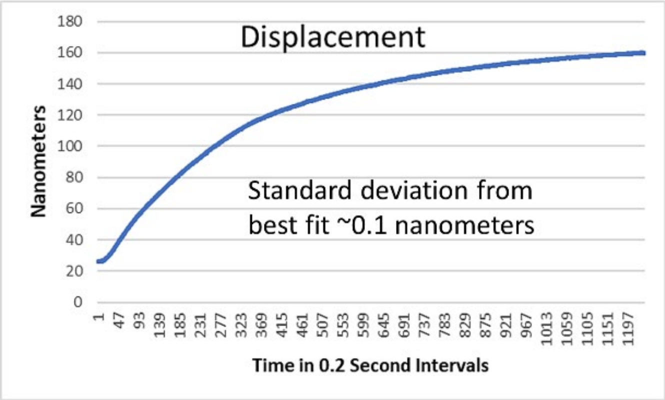


FIGURE 2. *Mirror Expansion vs Time*

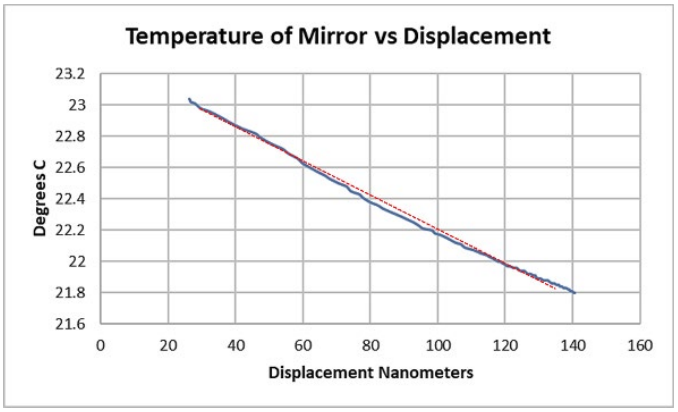


FIGURE 3. *The change of the mirror thickness closely follows the temperature change.*

naturally. The heating controller uses pulse width modulation for regulating the heating which was found to introduce some noise into the stability of the temperature ramp. By turning off the heating, the thermal noise was minimized. A graph of the mirror expansion versus time is shown in **FIGURE 2** and expansion versus temperature in **FIGURE 3.** Note: The capacitance sensor is measuring the gap from the probe to the mirror so as the mirror contracts with the temperature drop, the gap increases proportionally and the gap is what is plotted here. The measured change of the mirror surface contains whatever the expansion factor is from the mounting structure, as well as any expansion of the probe tip which is very close to the mirror surface.

As expected, the measured effective mirror expansion (contraction for temperature decrease) closely followed the temperature change in a nearly linear fashion. The total displacement was about 90 nanometers for 1 degree C change. The effective change was about 8.9 nanometers per 0.1 degree C change. The total time of the change was about 3 minutes. For the 6-millimeter thick mirror, this represented an effective thermal coefficient of about 15 x 10 -6 /C, which is close to the typical number for glass.

We attempted to make small temperature step changes using a dwell at each level of about 15 minutes. Even at this level, the temperature controller tended to oscillate (PWM modulation) in order to produce the desired temperature introducing noise. **FIGURE 4** shows the typical temperature fluctuation for steps of 0.1 C.

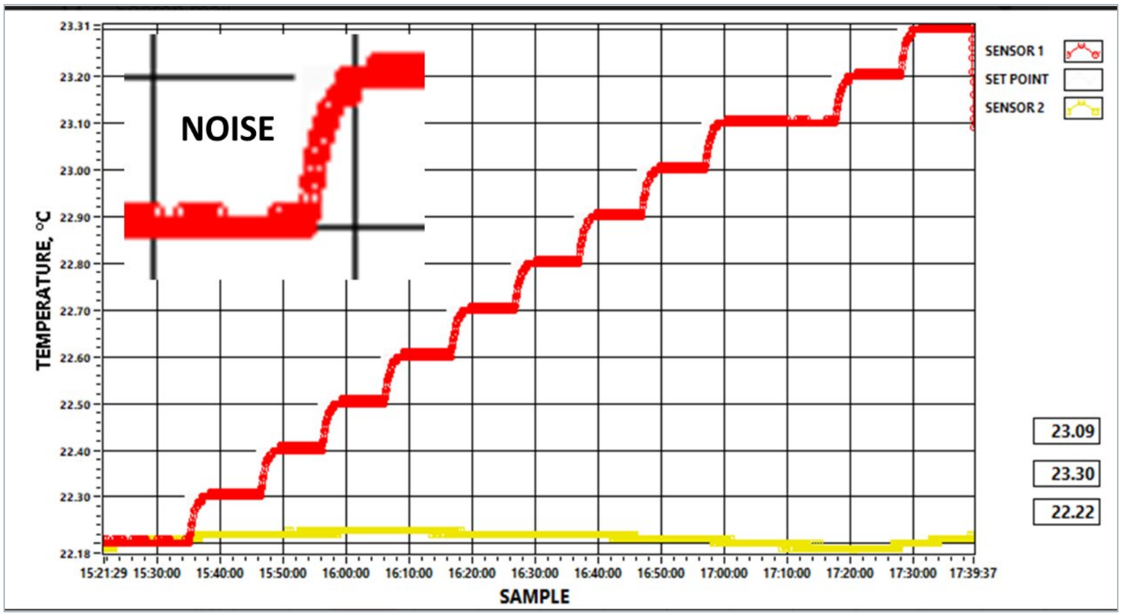


FIGURE 4.

The thermal noise is pronounced even with 0.1C step changes.

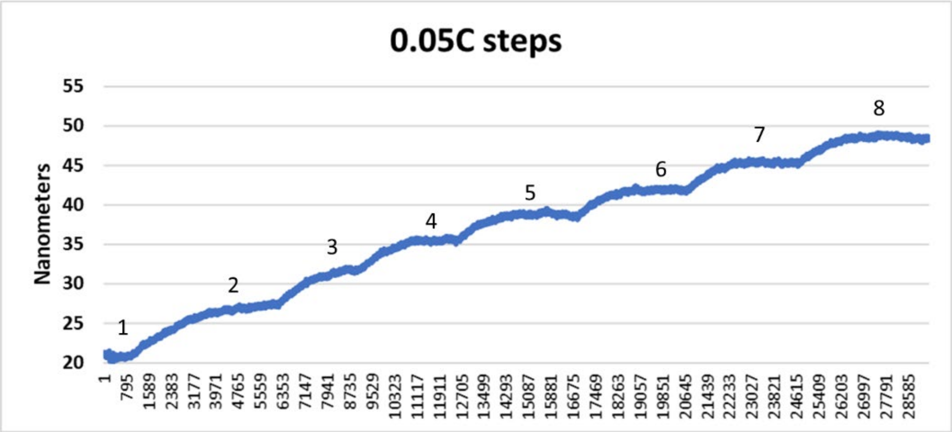


FIGURE 5.

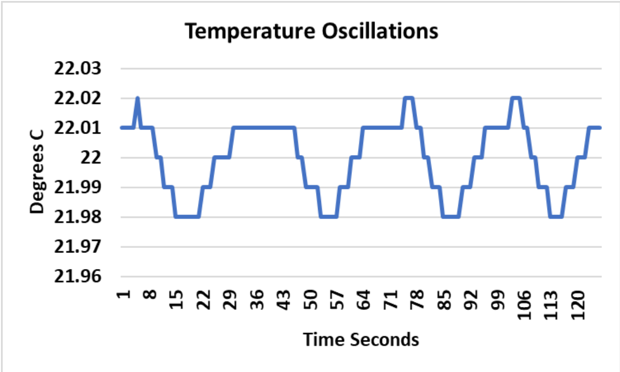
Analysis of range changes for temperature going down at 0.05 degree C step changes.

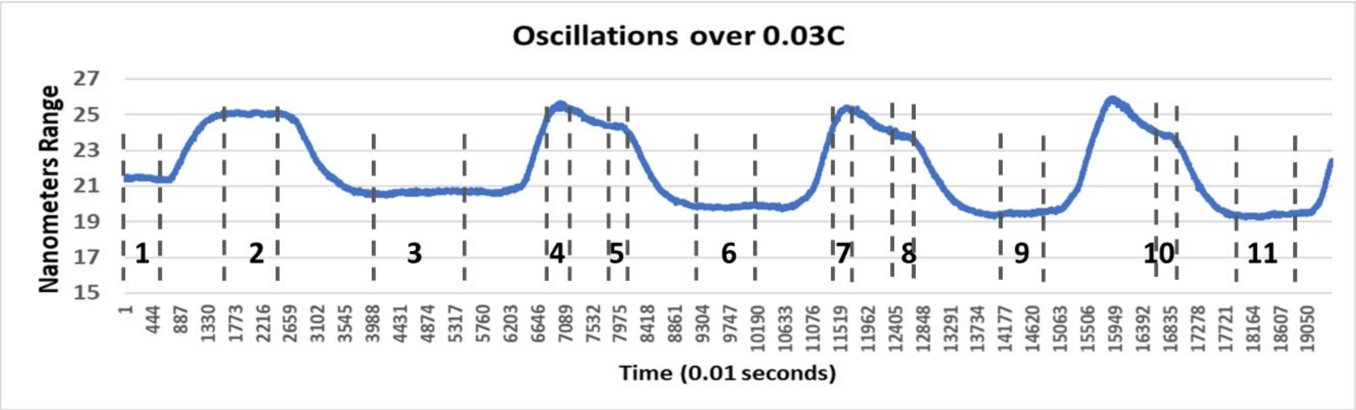
STEP	1	2	3	4	5	6	7	8		
median nm	20.954	26.969	31.566	35.448	38.896	41.887	45.390	48.688		
stdev nm	0.140	0.165	0.155	0.138	0.190	0.154	0.157	0.186	0.161	Average
step nm		3.007	4.597	3.882	3.448	2.991	3.503	3.298	0.803	Variance
step S:N		18.2	29.7	28.1	18.2	19.4	22.3	17.7	22.0	Average

The graph and analysis of each level for a 0.05 C change is shown in **FIGURE 5.** The standard deviation average was around 0.16 nanometers with a variance in the step size of 1.36 nanometers.

It proved difficult to obtain steady temperature changes over an extended length of time. To try to get around this limitation, the controller was set to make a small oscillation in temperature which resulted in the least thermal variation noise. The temperature profile is shown in **FIGURE 6** and the resulting displacement and analysis in

FIGURE 6. *Temperature fluctuations for controller in oscillation.*





Zone	1	2	3	4	5	6	7	8	9	10	11
median nm	21.45	25.06	20.67	25.35	24.37	19.86	25.29	23.81	19.54	23.86	19.42
stdev nm	0.05	0.06	0.06	0.04	0.06	0.06	0.06	0.05	0.07	0.03	0.05
S:N meas	440	445	344	606	433	336	422	459	264	702	374
step nm		3.609	4.389	4.68	0.977	4.512	5.433	1.477	4.273	4.318	4.433
S:N step		64.07	73.04	111.82	17.36	76.44	90.74	28.46	57.62	126.97	85.32
1 sigma pm		56	60	42	56	59	60	52	74	34	52
6 sigma pm		290	309	216	290	304	308	267	382	175	268

FIGURE 7. *A least noise data set from setting the temperature controller into oscillation show consistent steps and noise levels on average around 60 picometers, representing the noise level of the sensor.*

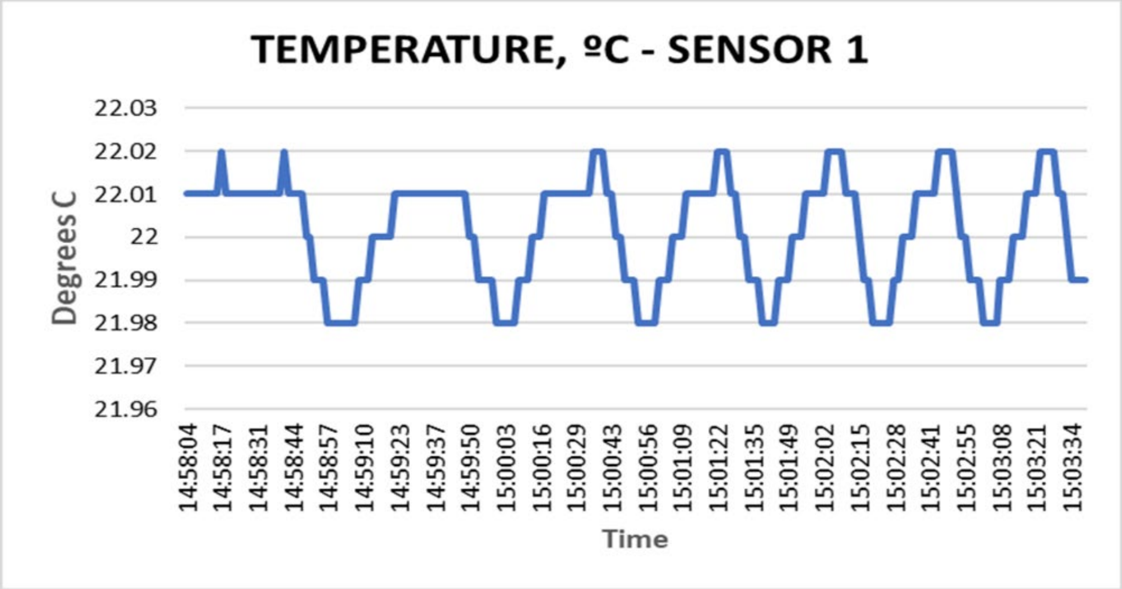


FIGURE 8.

Temperature Oscillations 0ver 0.04 degree C simulating instrument stability test.

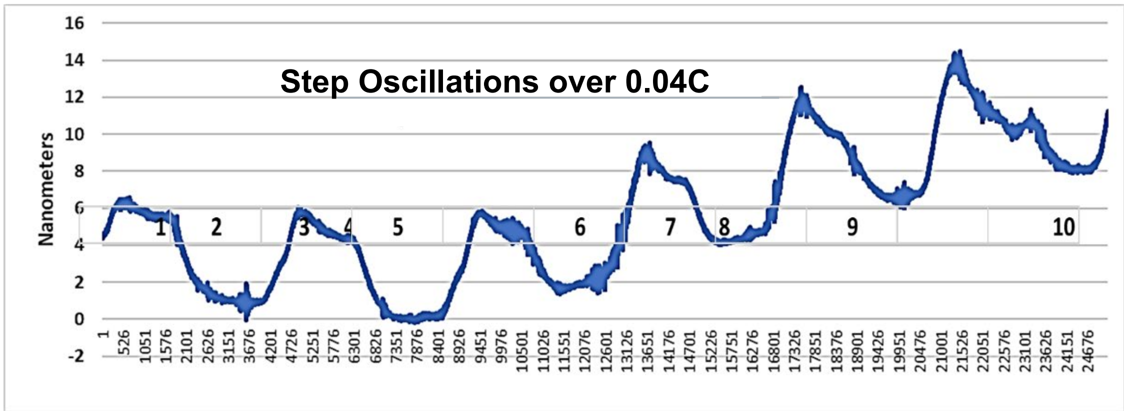


FIGURE 9.

Effective Optical element thickness variations due to temperature changes with an average 1 sigma value of 66 picometers. The thickness change is clearly measurable.

zone	1	2	3	4	5	6	7	8	9	10
Median	5.532	0.987	5.726	4.365	0.156	1.822	7.475	4.216	10.014	8.090
Stdev nm	0.072	0.059	0.050	0.071	0.070	0.079	0.065	0.083	0.049	0.064
S:N	76.8	16.8	114.4	61.1	2.2	22.9	114.7	50.6	203.3	126.2
step nm		4.545	-4.739	1.361	4.209	-1.666	-5.653	3.259	-5.798	1.924

FIGURE 7. This minimum temperature controller noise situation suggests a noise floor for the sensor of around 60 picometers with step sizes under a nanometer clearly measurable with good signal to noise ratio.

A second set of oscillations over 0.04 degrees are shown in **FIGURE 8 AND 9.** This level of sensitivity would be typical of what might be needed to characterize optical elements for a precision instrument such as might be used in aerospace applications.

The average standard deviation of about 69 picometers is consistent with previous runs. This number represents the lower limit on what range changes could be detected by the sensor, with clearly resolvable changes available in the 300 picometer range.

Conclusions

These results conclusively demonstrate the capability of the MTI capacitance HD amplifier, and a 50um range probe to measure the very small distance changes (pico- meters) encountered in a practical application where thickness changes are caused by thermal variation of precision optical elements. The ability to measure such changes at this pico-meter level is difficult to realize with most other metrology tools except at high expense such as a laser interferometer. Additionally, the capacitive measurements correlated to the expected mirror changes as computed from the normal thermal coefficients of expansions of the test materials used in this experiment further verifying the results.

Some of Optical Metrology Solutions qualifications:

Kevin Harding: President

About Kevin Harding: 39 years of experience in optics, vision, metrology; editor and primary author of the CRC Handbook of Optical Dimensional Metrology; member of the Society of Photo-Optical Instrumentation Engineers (SPIE) for 30+ years (fellow, instructor, and past president), recipient of the President's Award from SPIE; SME Young Engineer & Eli Whitney Award; Sr. Member, MVA Chair, AIA Leadership Award, Engineering Society of Detroit Leadership Author with more than 150 papers, 5 book chapters, and over 80 patents in optics/metrology; more than 80 Tutorials taught, Optics and Lighting for Machine Vision, Metrology, Optics for Non-Optics People; 3D Optical Metrology Expertise; Quality Systems, six sigma methods, Optical System Design, Machine Vision System Development, Analysis Optical Metrology Application Engineering/ Technology/Market Evaluations; Deep technical knowledge commercial (and non) optical gages (1- 2-3D) Extensive Government and Industry proposal and contract experience. Work Experience Includes: University of Dayton Research Institute, Industrial Technology Institute (Director: Cost, Quality, Productivity), GE Global Research (Principal Engineer).

Robert Tait: Partner

About Robert Tait: Over 37 years of experience in Vision, Automation; Frequent Speaker; Instructor: Vision Show, Automate, NI Week Worked with several company startups (electronics inspection) Expertise: Machine Vision System/ Automation Integration, Lab View Programming, Automation Control Lighting/Imaging/controls integration/Shop hardening, Collaborative Robots. Work Experience includes: University of Dayton Research Institute (at WPAFB), Industrial Technology Institute, Intelligent Reasoning Systems Inc, Dimension Data, GE Global Research.

Afterword

MTI would like to thank Optical Metrology Solutions for their hard work in creating and carrying out this experiment. It was gratifying to see OMS reached a similar conclusion from MTI's experimental verification when testing piezo stage displacements down to pico-meter levels. (Reference: MTI's Accumeasure HD Amplifier vs. SmarAct's PicoScale Interferometer)

About the MTI Instruments Accumeasure D200HD

The MTI Instruments Accumeasure D200HD is a two-channel, picometer scale, capacitance based, displacement measurement instrument for conductive targets. The D200HD achieves very high resolution with the aid of external preamplifiers that are located close to the probes that eliminate parasitic capacitance effects which cause noise. Digital communication is provided via Ethernet or USB. The bandwidth and range extension of the probes are digitally programmable. Resolutions as low as 20pm may be achieved with a 10um range probe. Visit our site to see more details on the Accumeasure D200HD.