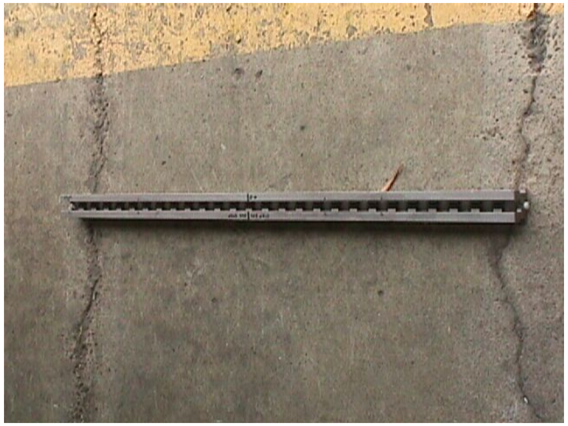
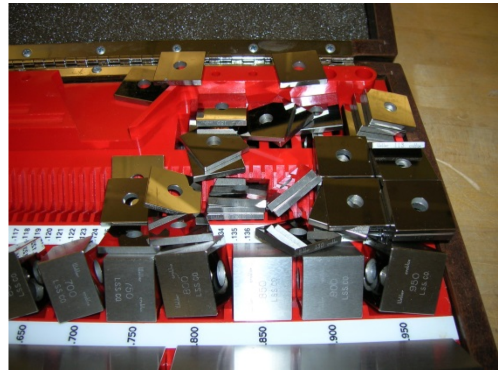
Dimensional Metrology

Ted Doiron
Dimensional Metrology Group

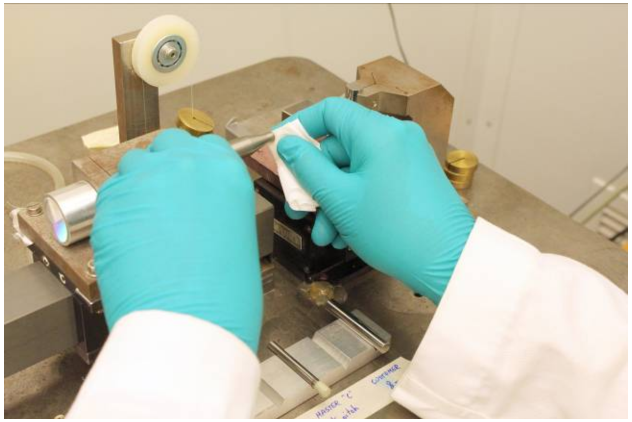
Shipping





Most cases are designed to protect the gages in the lab, not for shipping. On the left, the box has allowed a high stakes billiards game with precision gages. Wires, on the other hand, are in separate tubes.

Cleaning and Handling



We use gloves, everything from cotton to various polymers. The only requirement is that there is no latex.

We have two size ball tongs. Ethanol is used for cleaning, along with lint free paper.

Generic Uncertainty Budget

1) Long Term Reproducibility
2) Master Gage Calibration
3) Thermal Expansion
4) Elastic Deformation
5) Scale Calibration
6) Instrument Geometry
7) Artifact Effects

Generic Uncertainty Budget

for Dimensional Metrology

1. Long Term Reproducibility
2. Master Gage Uncertainty
3. Thermal Expansion
    a. Thermometer calibration
    b. Coefficient of thermal expansion (CTE)
    c. Thermal gradients
4. Elastic Deformation
    a. Probe contact deformation
    b. Fixturing Effects
5. Scale Calibration
    a. Sensor calibration
    b. Environmental compensation
6. Instrument Geometry
    a. Abbe offset and instrument geometry errors
    b. Scale and gage alignment
7. Artifact Geometry

    Flatness, parallelism, roundness

Coefficient of Thermal Expansion (CTE)

$$\Delta L = \alpha(T-20)\,L$$

- Measurement not made at exactly 20 °C needs thermal expansion correction using an assumed CTE, α.
- The uncertainty in this coefficient is a source of uncertainty.

SOURCES OF COMPARATOR MEASUREMENT ERROR

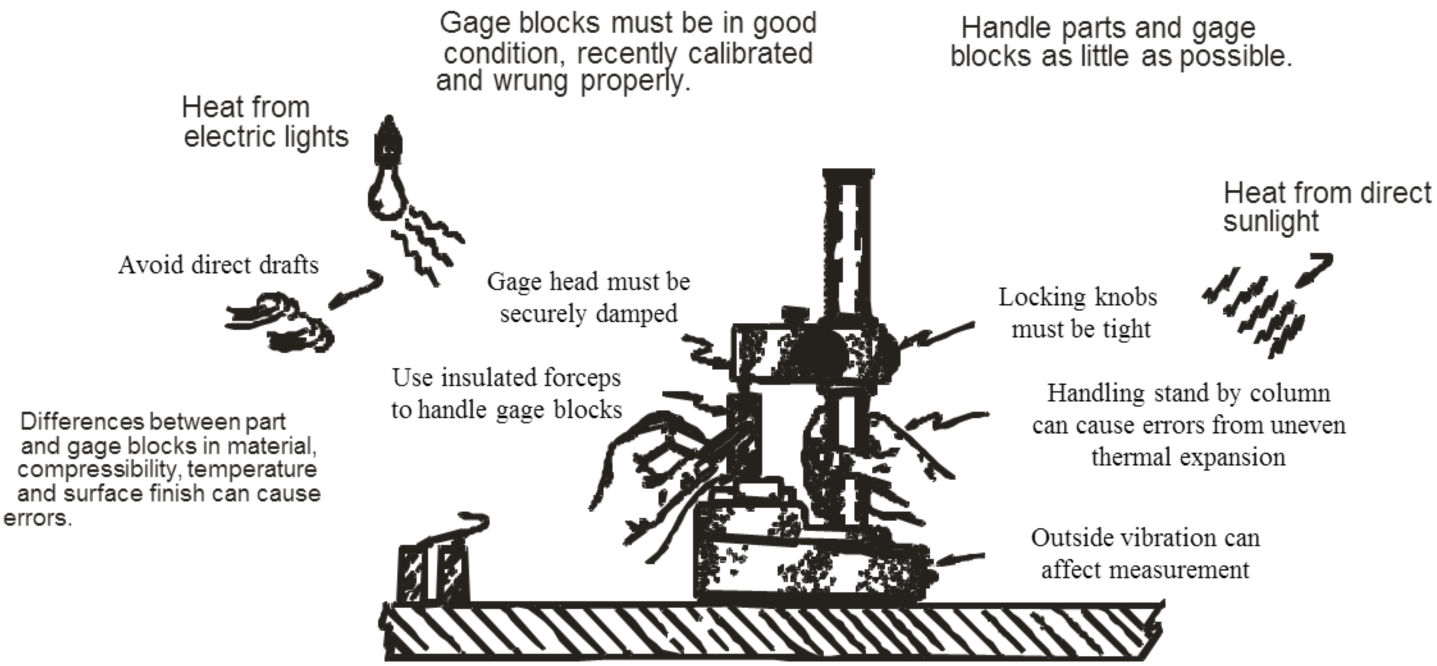
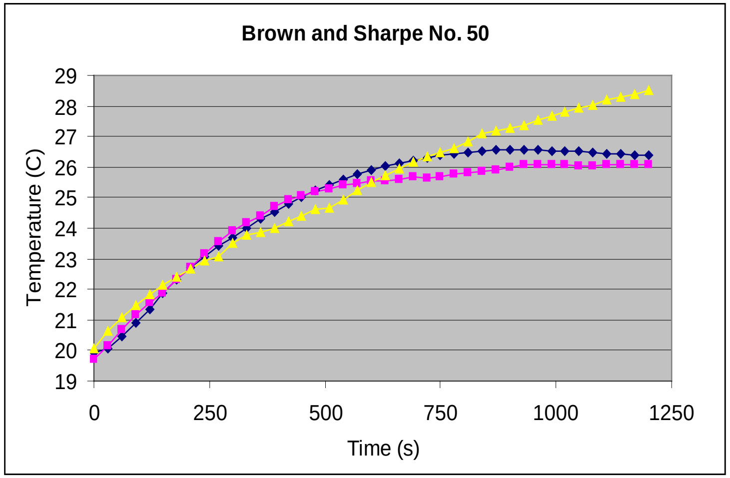
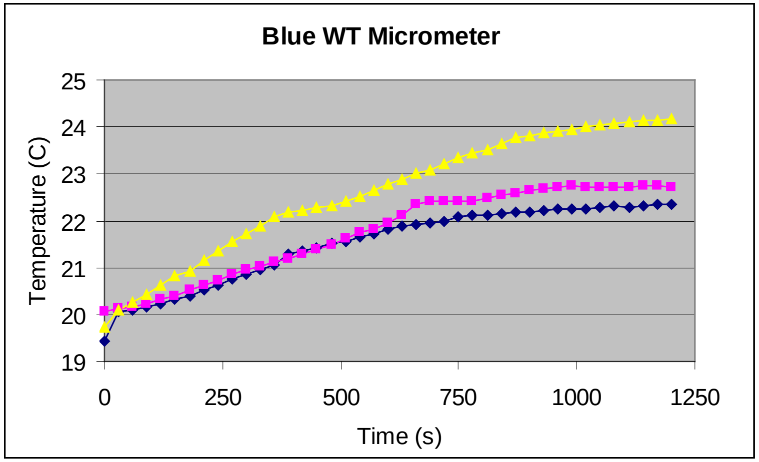


Figure 11-37. All sources of potential errors should be consciously investigated whenever a high precision measurement is made.

These graphs show three trials each for two separate micrometers, the first is a 0-1 inch and the second a 1-2 inch. Neither had a plastic insulating plate on the frame.





Using a thermal expansion coefficient of 12 PPM/°C and the fact that the maximum range of the Brown and Sharpe #50 micrometer is two inches, the error in measurement caused by a shift of 6 °C is 3.07 μm. The same test with a micrometer with a thermal insulating plate reduced the effect considerably.

Operator Heat Control

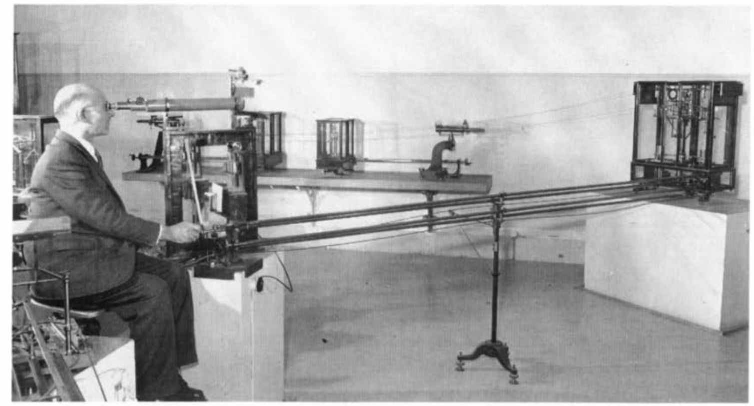
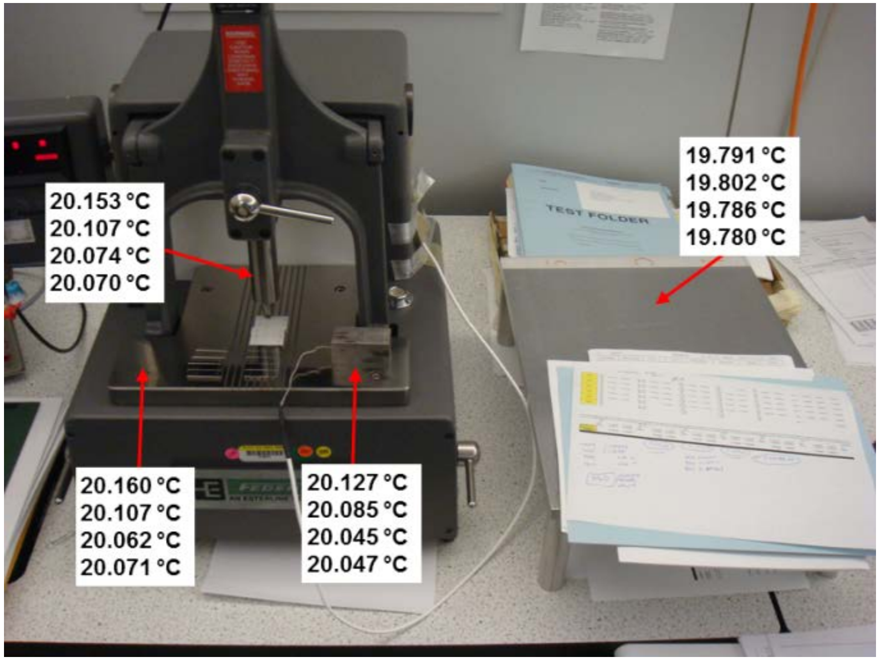


Plate 34: Albert Bonhoure operating the Ruprecht No.1 balance in Room 5 of the Observatoire, date unknown but probably in the 1940s or 1950s; all balances were operated at a distance to avoid heating by close proximity of the operator. (*Courtesy BIPM*.)

Here are the two most obvious ways of controlling body heat. On the left is my boss years ago, Ralph Veale. The use of heat shield clothing was used up until a few years ago. The picture on the right is from Terry Quinn's marvelous book "From Artefacts to Atoms"

Spatial Temperature Variations

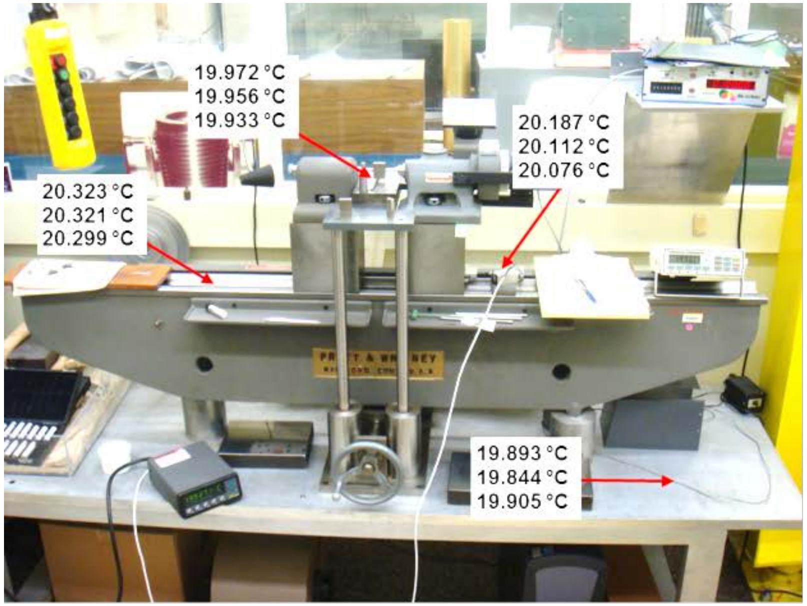
$$\delta(L) = \alpha \cdot L \cdot \delta\left(T_{gage} - T_{master}\right)$$

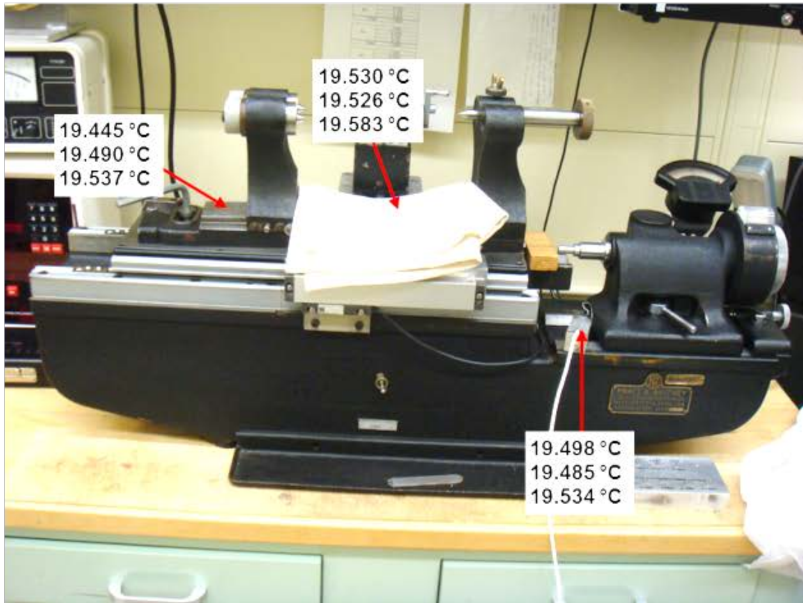


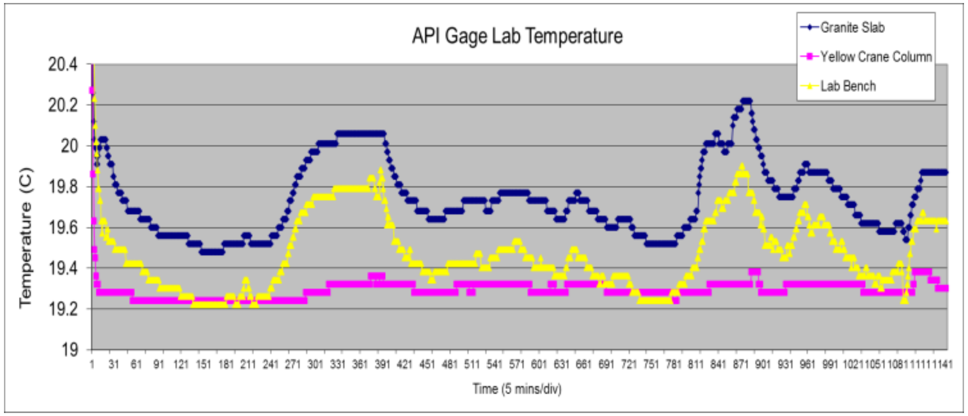
Here we have the aluminum soaking tray next to the comparator. While only separated by a few inches the temperature differs from the comparator by 0.3 ºC.

For blocks over 25 mm extra soaking time is required or the check standard test will fail.

On the actual platen the temperature variation is generally much smaller, generally holding under 0.030 ºC across the entire platen, and less among the blocks as measured (note blocks under the contact are touching).

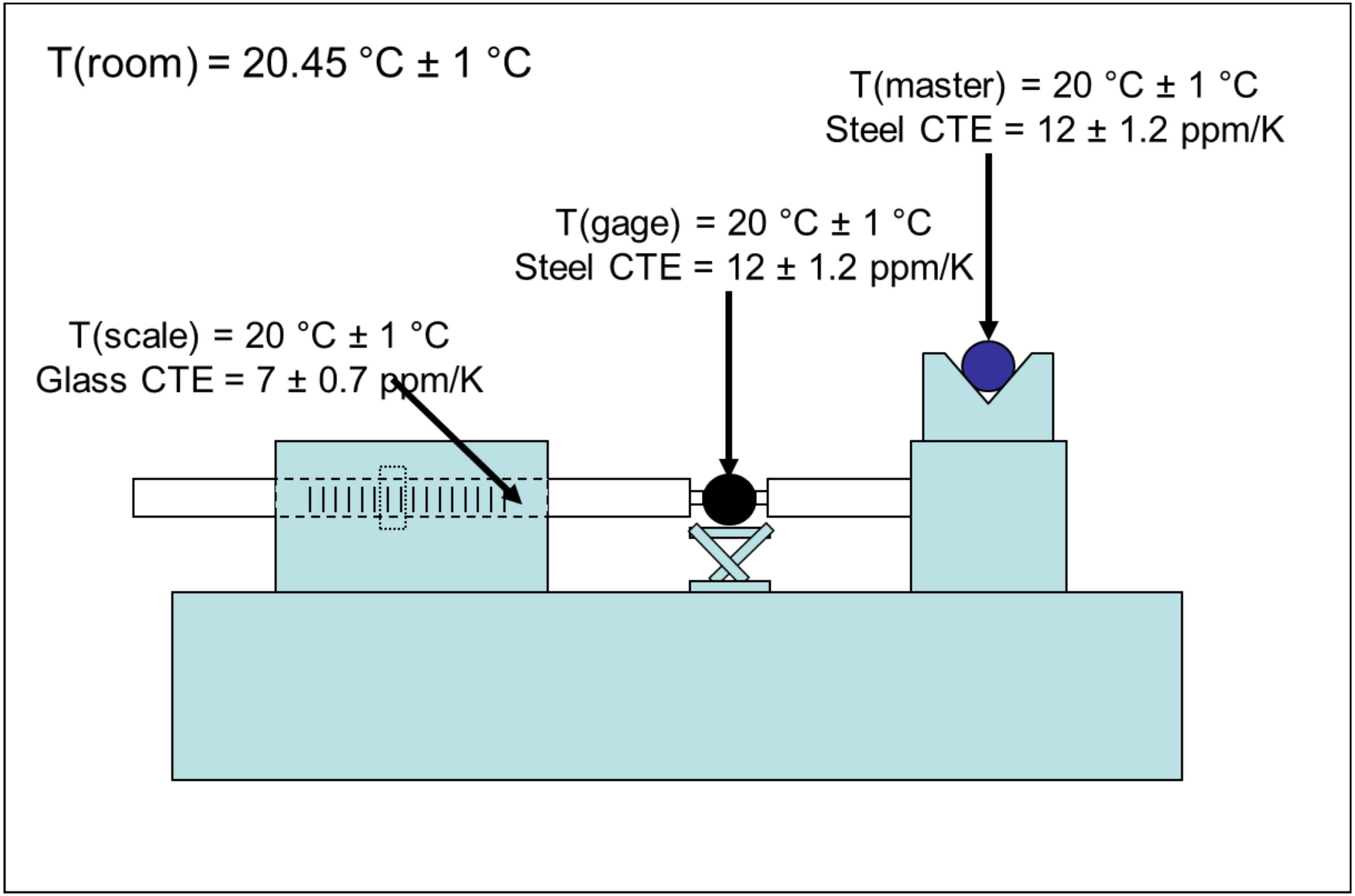






In our conventional labs, where the temperature is controlled to about 0.5 ºC we see temperature differences of about that size. Large machines have a large thermal mass, effectively filtering the temperature changes..

Example 1: 100 mm plug gage calibrated using a 100 mm master plug on a long range UMM. Lab has one thermometer to monitor room which has an uncertainty of 1 °C.



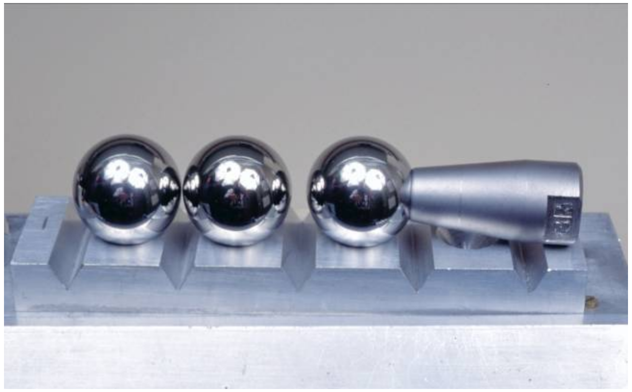
Heat Transfer Equation

$$Q = -hA(T - T_s)$$

Heat Transfer Mechanism	h in W/(m^2-K)
Mechanical Contact	100 - 4,000
Free Convection of Gasses	5 – 30
Forced Convection of Gasses	50 - 150
Radiative Transfer	1 - 10

Here T is the temperature of the object, T_s is the temperature of the environment, A is the area of contact and h is a constant that depends on the details of the heat transfer mechanism. Even when there are two or more types of heat transfer involved, the heat transfer follows the equation closely with some effective “h”.

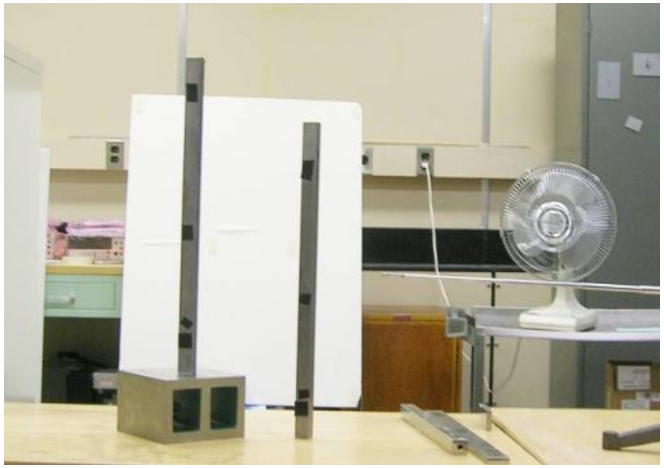
Thermal Equilibrium

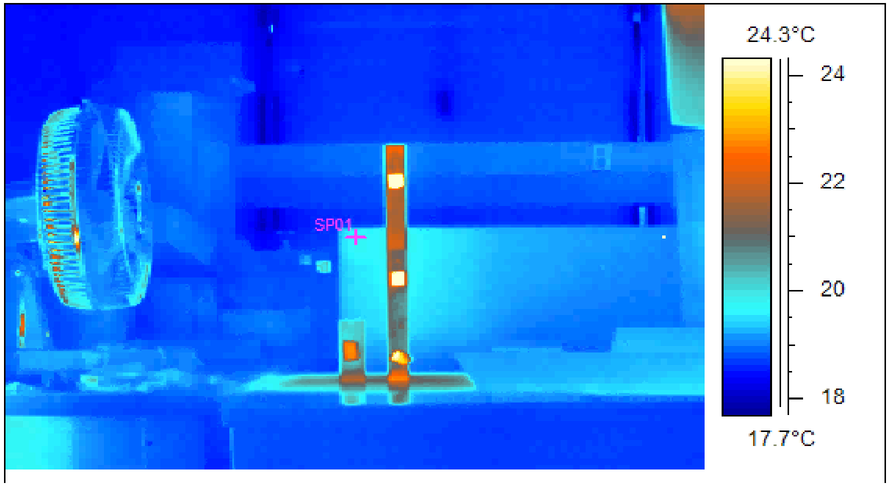


This is our holder for balls and wires. The “V” grooves have cone do not provide as much thermal conduction as gage blocks on a plate, but these are generally small gages with little thermal mass.

Currently we us fans to make things equilibrate faster and to keep the operator heat away.

Soaking Time Experiments

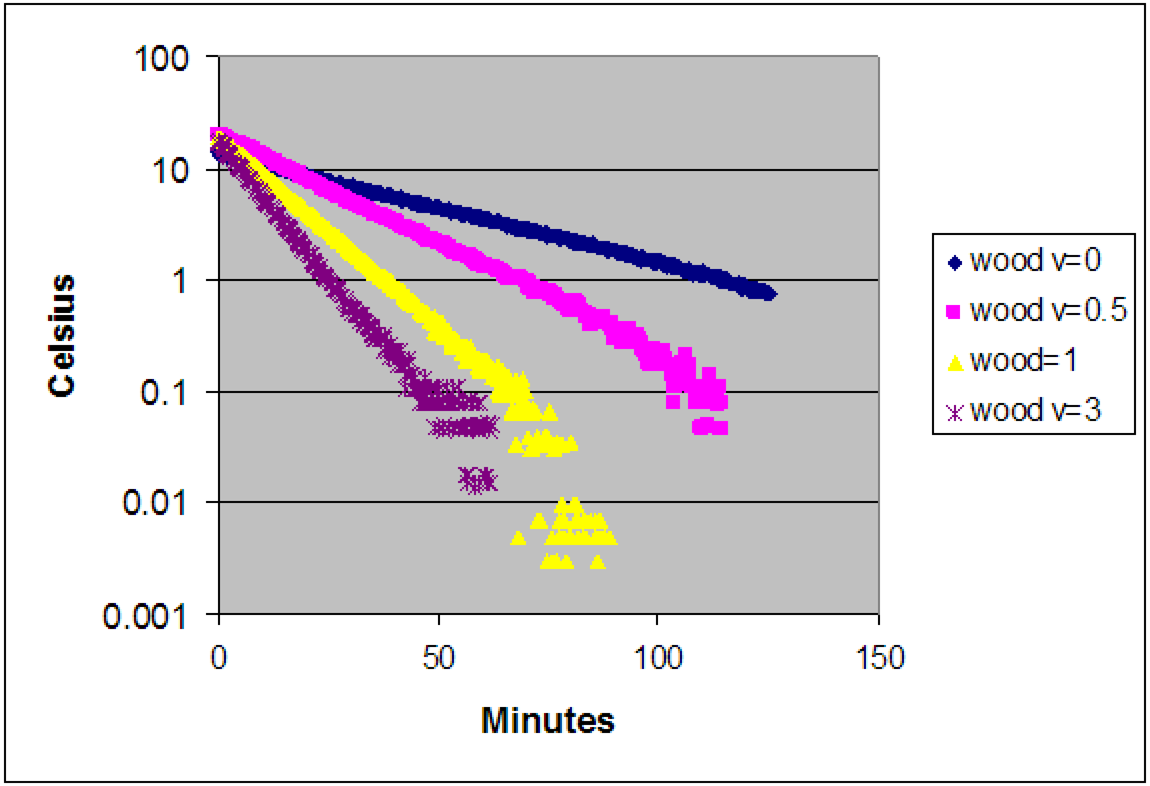




Each of the 500 mm gage blocks have three strips of tape as the thermometry target. The fan can be seen in the background and the anemometer extends horizontally from the right side of the picture.

The white board is insulated to keep the heat sources on the table from being seen by the infrared camera.

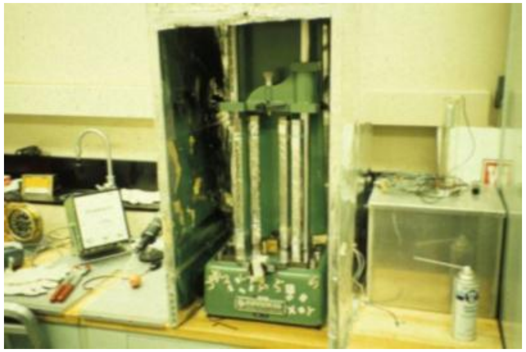
Results



This logarithmic plot shows that the exponential decal model works very well, and the addition of the fan has a dramatic effect.

Measuring Long Gage Blocks

The blocks were wrapped in Mylar, the comparator put in a insulated box with face shield, and the operator wore a cape, big gloves, and worked quickly.



Results

The soaking times for 500 mm gage blocks, even in still air is much lower than general commercial practice.

	1/10 Time	
Air Speed m/s	Wood	Steel
0.0	102	73
0.5	50	41
1.0	30	30
2.0	28	25
3.0	20	22

Digression on Similarity

Comparison of Steel to Light (wavelengths)

$\Delta L/L = (12\ \text{ppm/°C} + 1\ \text{ppm/°C})\ \Delta T = \boxed{13\ \text{ppm/°C}}\ \Delta T$

Comparison of Steel to Chrome Carbide

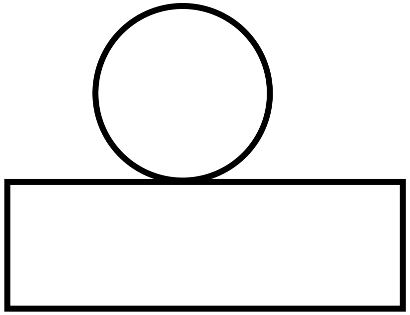
$\Delta L/L = (12\ \text{ppm/°C} - 8\ \text{ppm/°C})\ \Delta T = \boxed{4\ \text{ppm/°C}}\ \Delta T$

Comparison of Steel to Steel

$\Delta L/L = \boxed{0.5\ \text{ppm/°C}}\ \Delta T$

Comparison measurements are easier, faster, and require much less environmental control. We do very little interferometry on customer gages, and in general avoid intrinsic measurements of any kind.

Mechanical Deformation



Diamond Stylus Deformations

Force N (oz)	Steel Deformation nm (µin)	CrC Deformation nm (µin)
0.25	70	54
1.0	177	137
4.0	445	345

example: We use a steel master to measure a chrome carbide block.

Deformation for steel (0.25 N bottom, 1.0 N top) = 70 + 177 = 247 nm

Deformation for CrC (0.25 N bottom, 1.0 N top) = 540+ 137 = 191 nm

Bias of 56 nm if not corrected.

Generally, point contacts have large corrections, line contacts very small corrections, and plane contacts have negligible correction.

Contact and Fixturing

1. Line and flat contact has very little deformation.

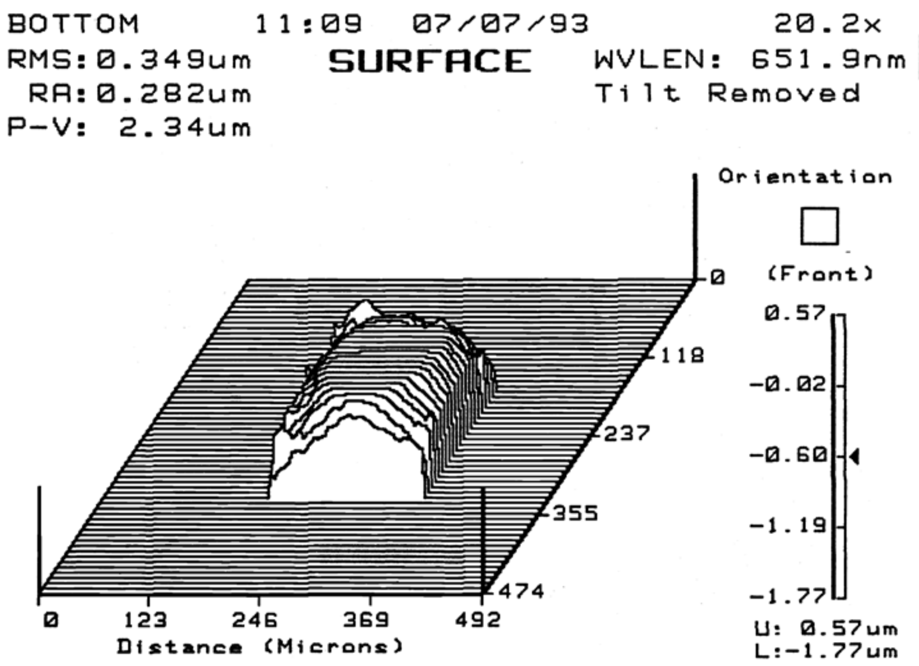
2. Point contact can have very large deformation (1 µm or larger)

3. It is fairly easy to apply the too much force to a point contact which results in a dent. The forces in wire calibration are fairly close to the elastic limit of steel.

4. If you are measuring something softer than tool steel you need to think about contact damage. Think about it twice.

5. The Engineering Metrology Toolbox has a deformation calculator. When contact deformations go much above 1 µm you might want to try a lower force.

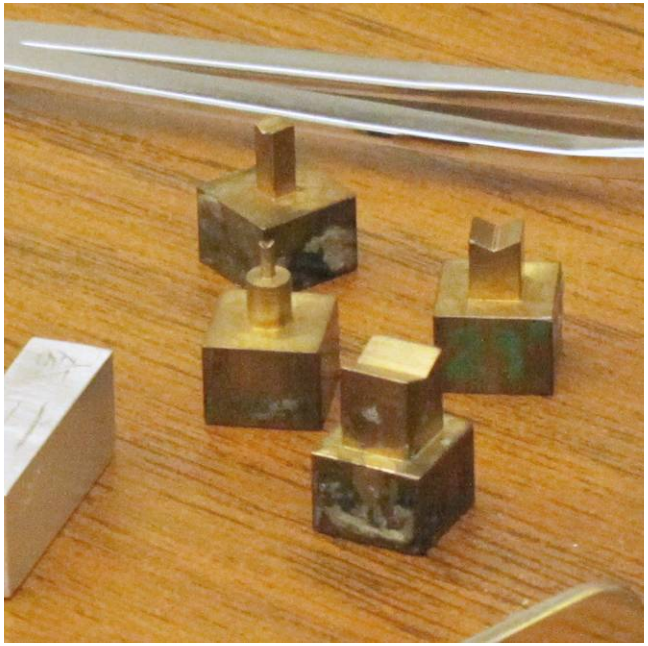
Contact Geometry

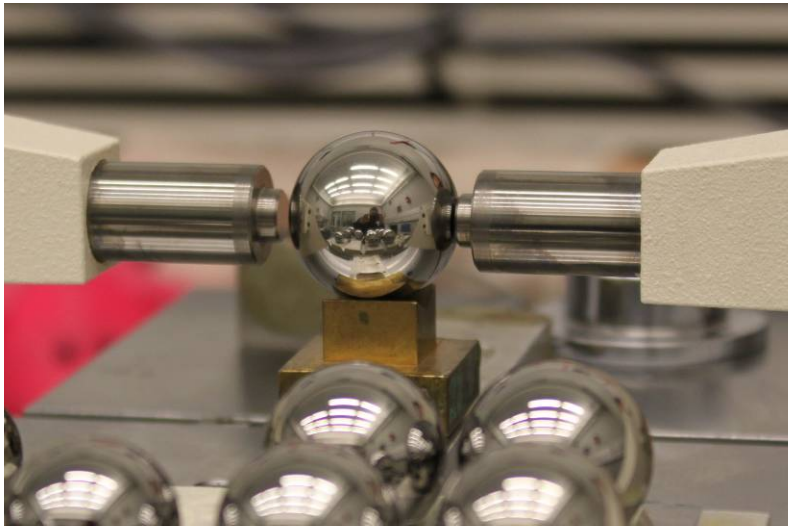


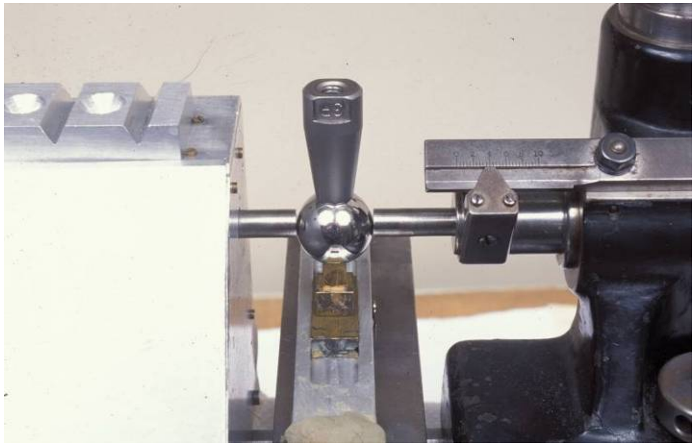
We also assume we know the geometry of the contact. This is the surface of one diamond contact on our gage block comparator. It is remarkably flat with a diameter of over 100 µm, reducing the deformation by 30 nm. This is larger than our uncertainty!

Note: The variation in the elastic modulus of diamond is 30% depending on the direction of the lattice. Since most contacts are not set to the same lattice direction a diamond contact has an intrinsic variation of up to 30%. This is large and you should avoid diamond contacts.

Ball Fixtures

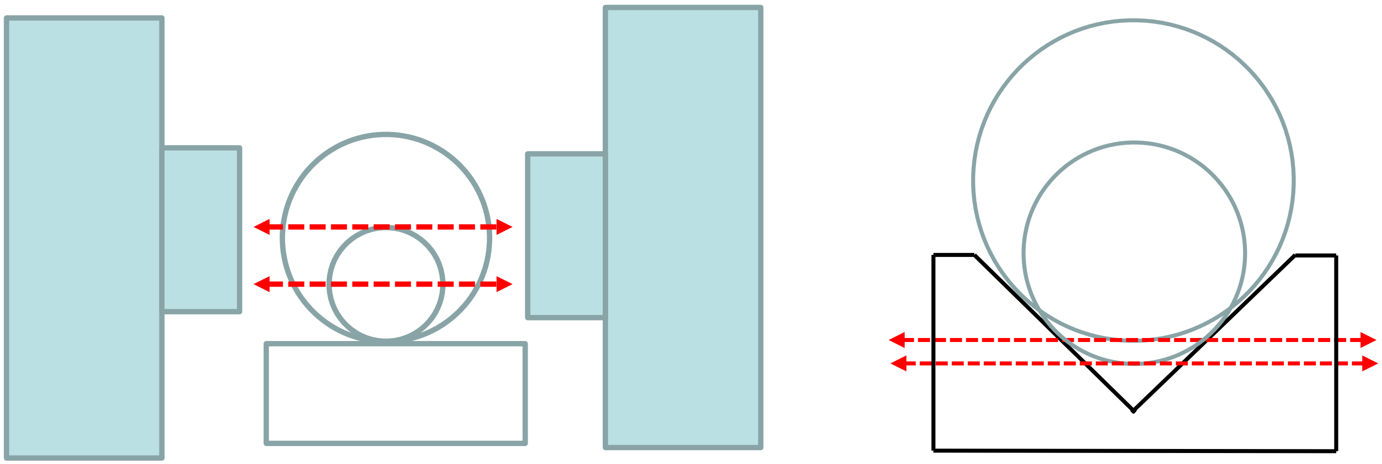






Balls need one degree of freedom so the micrometer can push them till contact. Generally this is a tiny V-block.

Fixtures



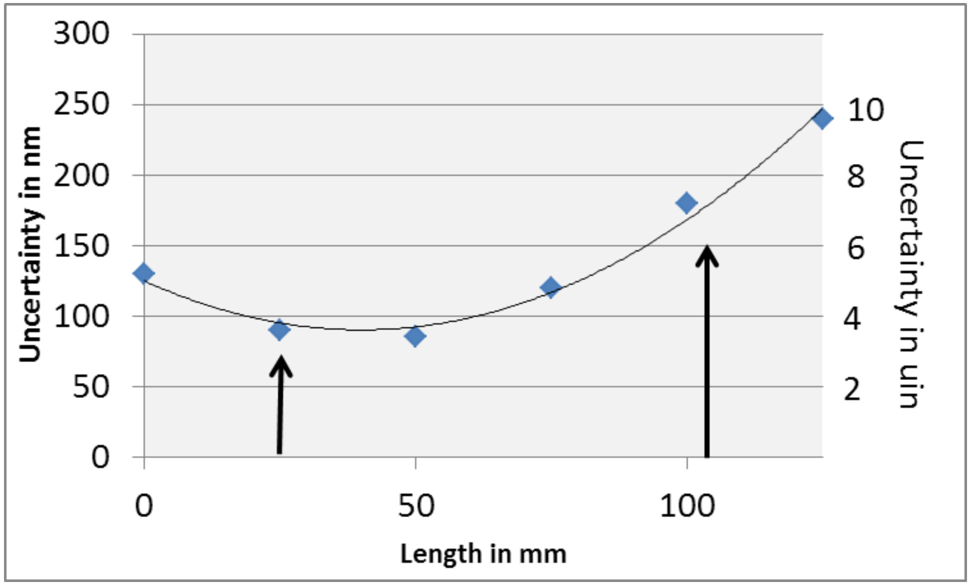
Here we see two balls held up by the same table, and the two spheres contact different places on the anvils. This adds the flatness and parallelism of the contacts to the error budget.

Uncertainty from Scale

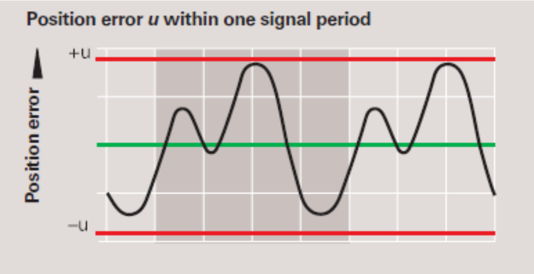
Most labs use two gages to set the scale calibration.
Assumes that the scale is linear (should be checked).
Slope variation is input to uncertainty budget.

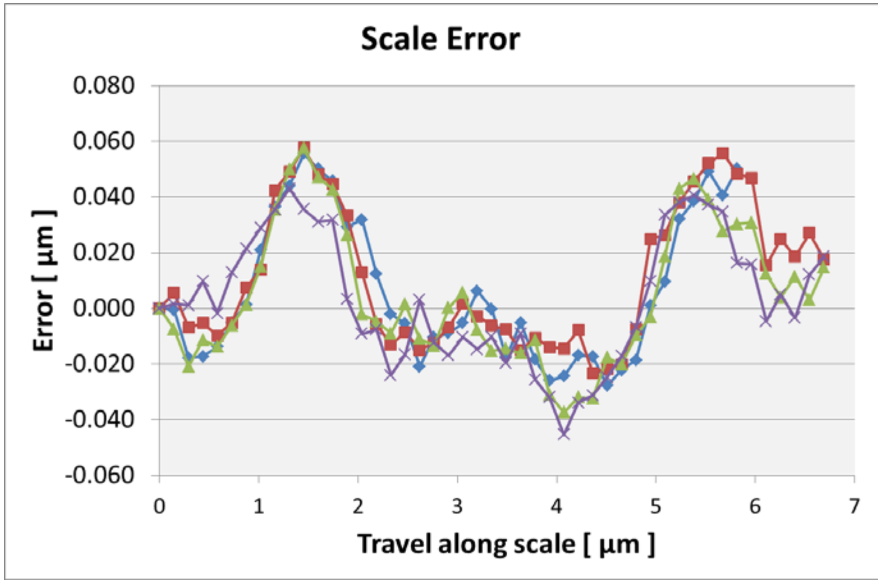
As an example, suppose we use a 25 mm and 100 mm gage blocks (1” and 4”)
We will assume that you use the calibrated value, not the nominal.

We assume the uncertainties are 75 nm 150 nm.



Encoder Error

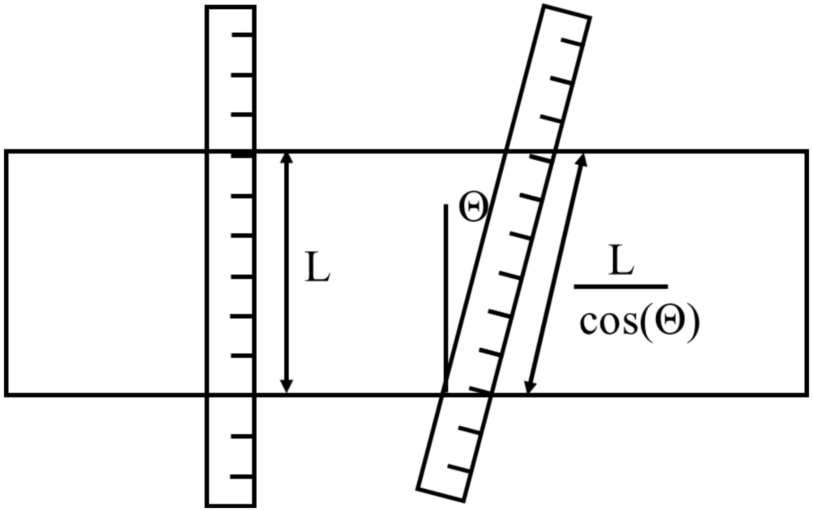




The graph on the left shows a typical response, it if from a Heidenhain Brochure, and it is about 1% of the pitch. On the right is the error measured on a measuring machine in my lab. Our machine has 4 µm pitch so the error should be about 40nm, and it is.

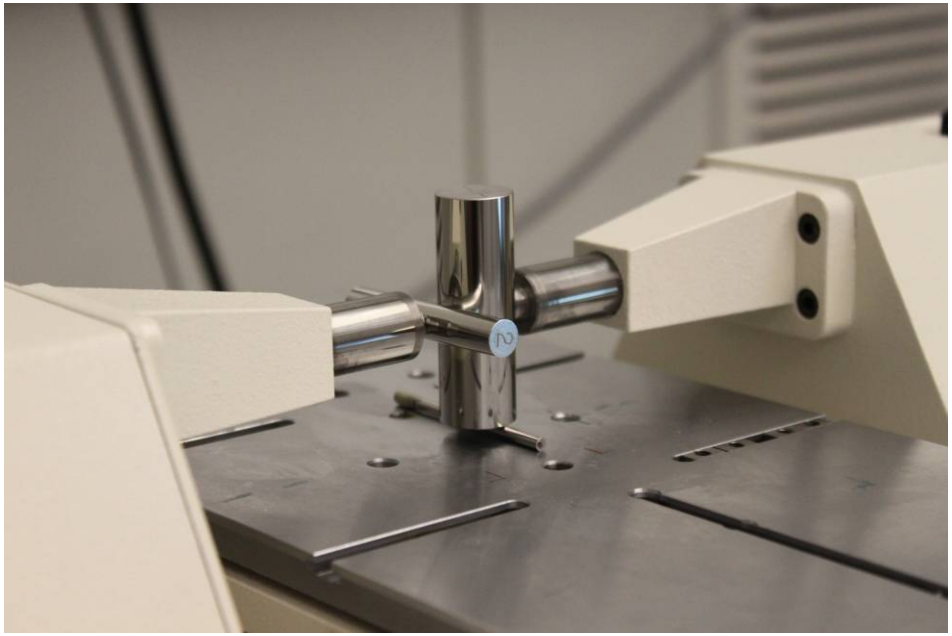
This is insidious because the error will repeat and multiple measurements will not average out the error.

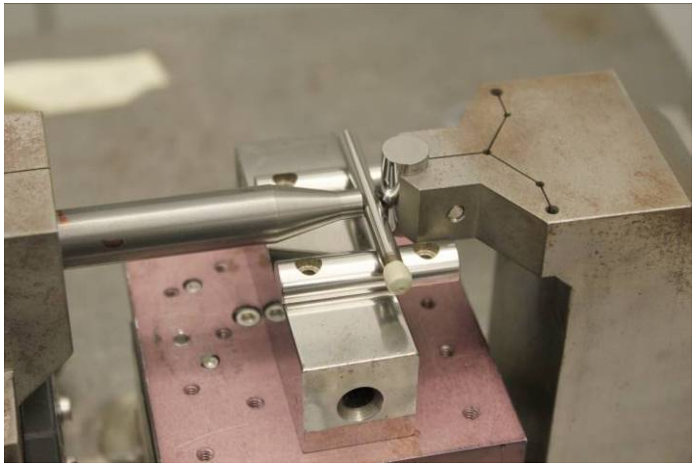
Cosine Error In Scale Measurement



An angle of 5' will produce an error of 1 ppm. This is generally not a problem with modern instruments..

Cosine Error

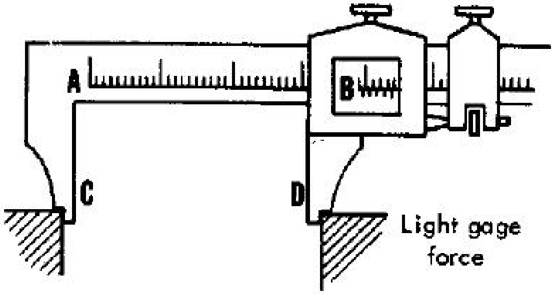




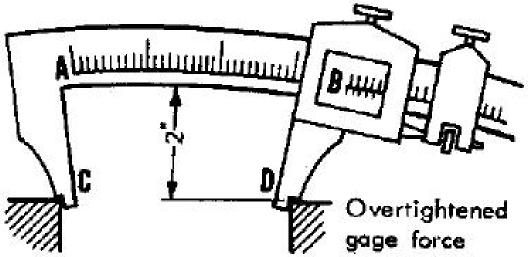
For small cylinders supported by two parallel half-rounds, the micrometer force will align the gage surface to the micrometer contact. As the cylinders get bigger, static friction becomes greater and alignment errors are common.

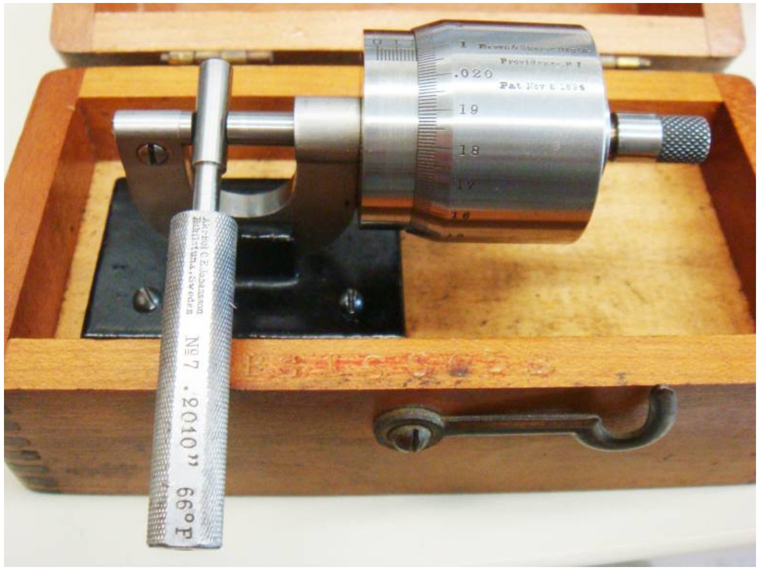
Cylinders fixtured so the axis goes up require a cylinder support so the surface can rotate into contact with the micrometer.

Abbe Error



from Busch, T., et. al., Fundamentals of Dimensional Metrology, 3rd ed.

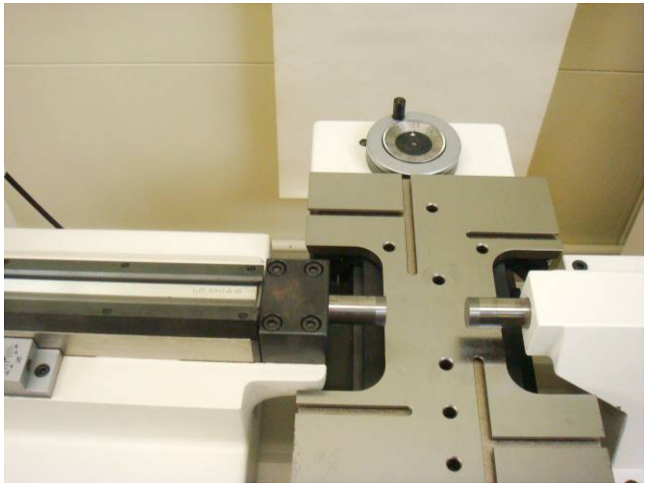




If the scale is directly on the measurement line the effects of pitch errors in the instrument are greatly reduced or eliminated. Note that a micrometer has its scale (lead screw) aligned with the center of the contacts.

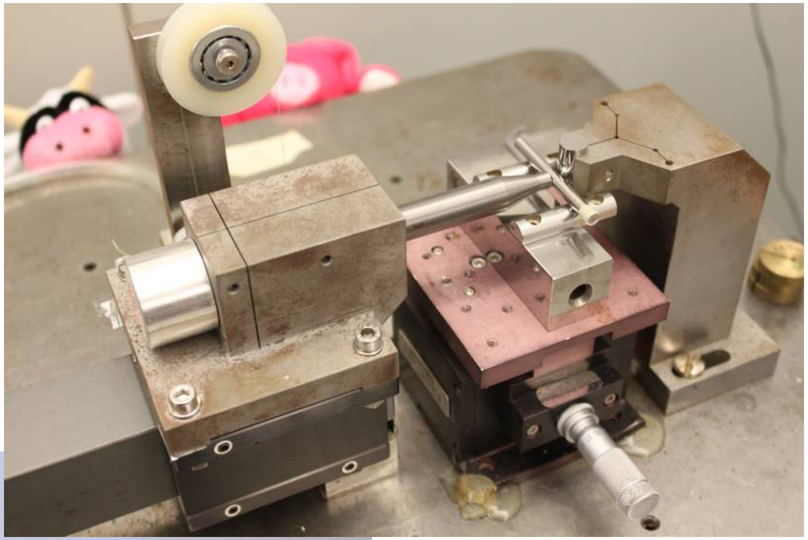
Abbe Offset

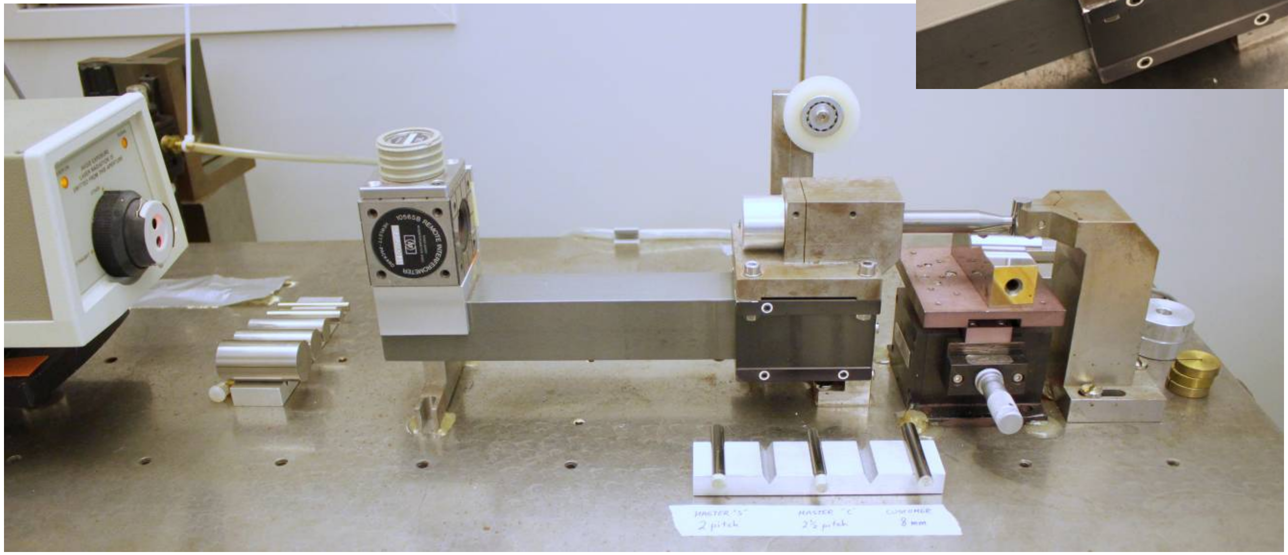
If the scale is positioned parallel to the machine motion and centered on the contacts the effects of pitch and yaw errors in the machine motion are considerably reduced.



NIST Wire Micrometer

Master wires are calibrated on this micrometer. It is quite simple. A laser interferometer provides scale, the left contact in on an air bearing, and the force is dead weight. One contact is flat tungsten carbide and the other contact is a carbide cylinder.

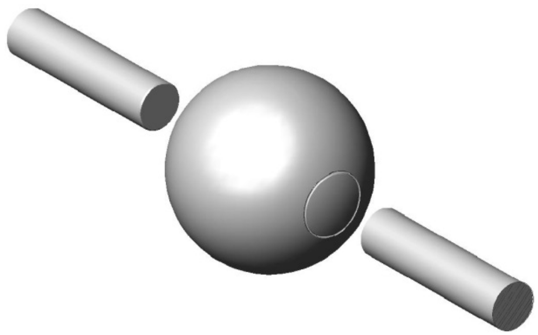


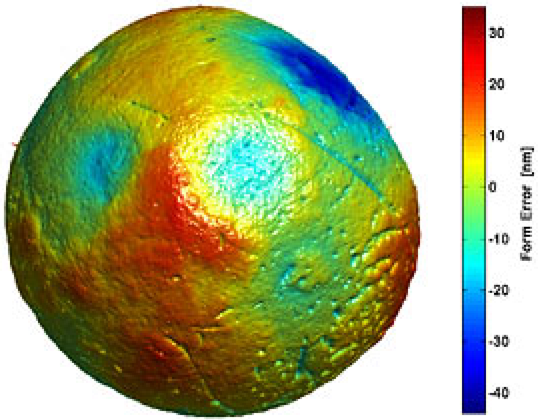


Artifact Geometry

Measurand – Detailed description of what you are to measure. In this there is a dangerous trap in using words like cylinder or sphere too loosely.

The average diameter, particular diameter, minimum material diameter, and maximum material diameter are all different because the ball is not actually a perfect sphere. No gage is completely spherical, cylindrical, or flat so the different definitions are critical.





ISO 17025-2005
5.9 Assuring the quality of test and calibration results

5.9.1 The laboratory shall have quality control procedures for monitoring the validity of tests and calibrations undertaken. The resulting data shall be recorded in such a way that trends are detectable and, where practicable, statistical techniques shall be applied to the reviewing of the results. This monitoring shall be planned and reviewed and may include, but not be limited to, the following:

5.9.2 Quality control data shall be analysed and, where they are found to be outside pre-defined criteria, planned action shall be taken to correct the problem and to prevent incorrect results from being reported.

I point out that the frequency of taking control data will set the number of previous calibrations that must be examined in your corrective action when the system is found out of control.

Check Standard

- A tool to continuously monitor the measuring process
- If the check standard is in control then the process is assumed to be in control
- Measures the long term variability of the process
- Measurement algorithm continuously tested

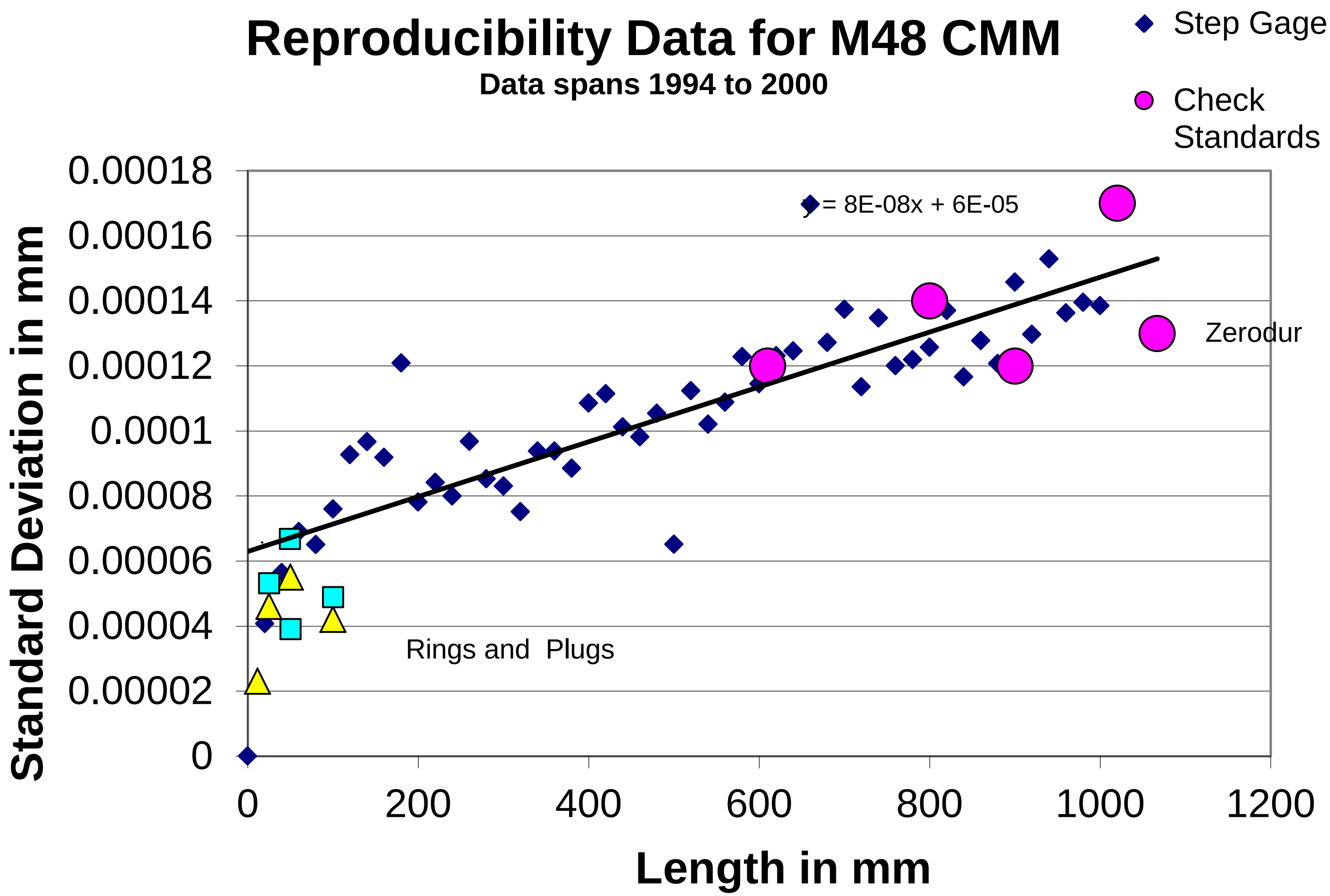
GUM

3.4 Practical considerations

3.4.1 If all of the quantities on which the result of a measurement depends are varied, its uncertainty can be evaluated by statistical means. However, because this is rarely possible in practice due to limited time and resources, the uncertainty of a measurement result is usually evaluated using a mathematical model of the measurement and the law of propagation of uncertainty.

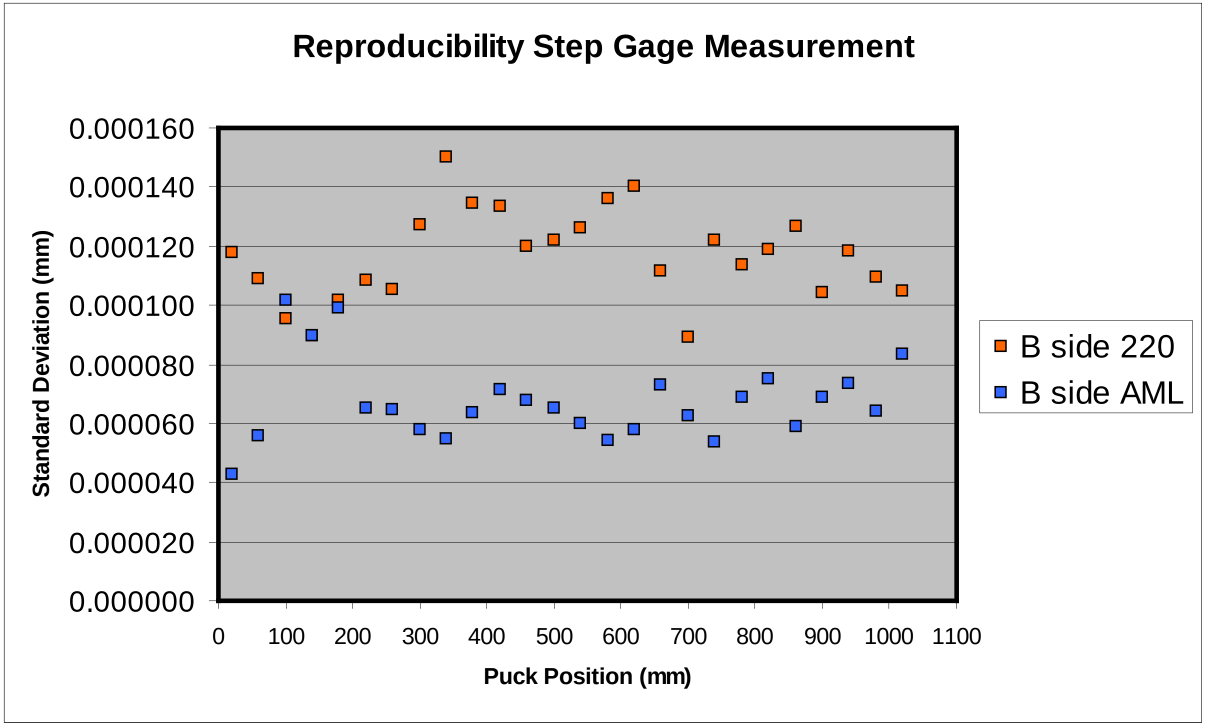
Check Standard Coverage for Gage Block Comparison Calibration

Source	Sampled in short term	Sampled in long term	customer block
Reference Master Block Length		3-5 year cycle	
Master block geometry		room/operator/instrument	
customer block geometry			X - although most have history
mechanical deformation - probe	X		
mechanical deformation - force	X		
mechanical deformation - elastic modulus			usually well matched, TC isn't
Instrument Geometry		room/operator/instrument	
Instrument Calibration	X		
Repeatability	X		
Drift Corrections	X	room/operator/instrument	
temperature calibration		each year	
tempeature readings	X		
thermal variations		room/operator/instrument	
CTE - master blocks	only two sources		
CTE - customer blocks			x



Reproducibility Data for M48 CMM
Data spans 1994 to 2000
Step Gage
Check Standards
y = 8E-08x + 6E-05
Zerodur
Rings and Plugs
Standard Deviation in mm
0.00018
0.00016
0.00014
0.00012
0.0001
0.00008
0.00006
0.00004
0.00002
0
0
200
400
600
800
1000
1200
Length in mm

Check Standards Show Performance Changes



This shows the history of our 1020 KOBA run on the same machine, the Moore M48. The top data is the old ±0.1 °C laboratory. The bottom data is from the AML with its ±0.01 °C laboratory. The difference is dramatic, lowering our uncertainty by 50%.

End

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Do not hesitate to send me an email.