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Dimensional Review of Scales for Forensic Photography

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Abstract

Scales for forensic photography provide a geometrical reference in the photographic documentation of evidence. A common scale used by investigators is a plastic, L-shaped ruler that allows for a dimensional reference in the photographic documentation of evidence or a crime scene. The ABFO No. 2 Standard Reference Scale has received recognition by the forensic science community as a reliable and accurate reference scale; however, we have surveyed commercially available scales and found a lack of consistency in manufacturing processes and, consequently a lack of strict adherence to the standard. This study seeks to evaluate the quality of commercially available photo scales, document manufacturing processes, and suggest pathways for establishing standards for forensic photo scales that will serve as a means for ensuring accuracy and user confidence.

Table of Contents

I. Introduction

Scales for forensic photography (photo scales) provide a geometrical reference in the photographic documentation of evidence. The presence of such scales in an image allows investigators to reconstruct the dimensional context of a scene and provides a means to reproduce one-to-one photographs of physical evidence. In some cases, information extracted from the reconstruction of a scene provides evidence in court. The National Academy of Science (NAS) published a report, in which it highlights inadequacies in the current state of forensic science.[1] In the report, the NAS emphasizes in part the need for the forensics community to adopt stronger methodologies and more exacting standards. Consistent with the report, crime scene investigators and analysts have expressed concern over the accuracy of forensic photo scales. As a result, the Dimensional Metrology Group (DMG) at the National Institute of Standards and Technology (NIST), in cooperation with the NIST Law Enforcement Standards Office (OLES) and the National Institute for Justice (NIJ), were tasked to investigate and report on the current state of forensic photo scale accuracy.

The American Board of Forensic Odontology (ABFO) published specifications for their ABFO No. 2 standard reference scale, hereinafter called ABFO No. 2.[2] While the specification has received positive recognition by the forensic science community, a review of commercially available photo scales shows a lack of consistency in quality and accuracy. As a result, it has become common practice for some investigators and pathologists to store the scales together with the photograph evidence after they have been used.

a) ISO 17025 accreditation of forensic laboratories

In response to the NAS report, there has been a renewed interest by forensic laboratories to adopt ISO 17025 practices for evaluating the competence and accuracy

[1] Strengthening Forensic Science in the United States: A Path Forward, The National Academies Press
[2] Hyzer, W. G. and Krauss, T. C., "The Bite Mark Standard Reference Scale – ABFO No. 2," Journal of Forensic Sciences, JFSCA, Vol. 33, No. 2, March 1988, pp. 498-506.

of tests performed.[3] As forensic laboratories become more familiar with rigorous metrological practices found in calibration laboratories, more tests will be included in a laboratory's scope of accreditation. The extraction of meaningful dimensional measurements from photographic reconstruction of a scene or documentation of evidence items will ultimately be included in this scope.

b) The ABFO No. 2 Standard Reference Scale

William Hyzer, an engineer, and Dr. Thomas Krauss, a Diplomate of the American Board of Forensic Odontology (ABFO), published a technical document in 1988 detailing the specifications for their newly developed ABFO No.2.[2] The ABFO No. 2 is a photomacrographic ruler designed to optimize the ability to reconstruct a bite mark, skin trauma, a scene or object from an image (Figure 1a). The ruler is L-shaped with length graduations on each of the perpendicular legs. In a photograph, the length scales can be used to project a virtual grid (Figure 1b). The grid propagates the length scales along the two-dimensional plane defined by the ruler. Using photogrammetric methods, any feature located on this virtual plane can be measured dimensionally. The ruler features three circles of equal diameter that are used to help ensure perpendicularity of the camera with respect to the orientation of the ruler's virtual plane.

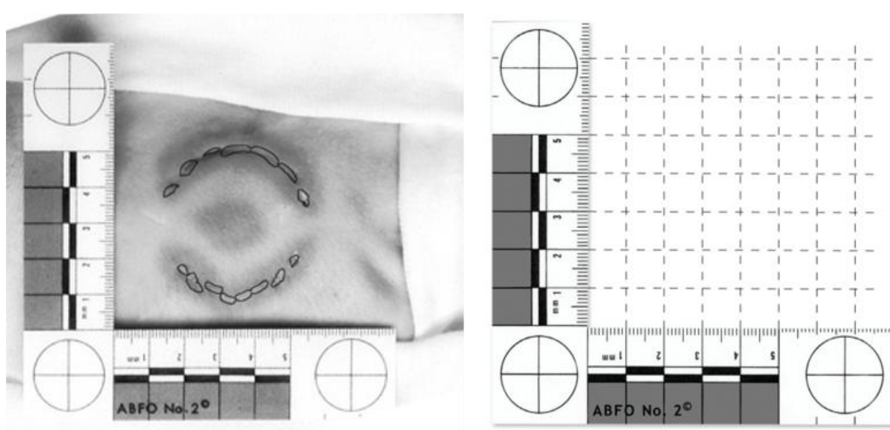


Figure 1: (a) The ABFO No. 2 standard reference scale was designed for the documentation of bite marks. (b) The length graduations can be used to project a virtual grid, which propagates the length scale to the two-dimensional plane defined by the ruler.

[3] ASCLD/LAB – *International* Program Overview 2010 Edition

Hyzer and Krauss defined a set of specifications for the design of the ABFO No. 2.[4] The specifications dictate the shape, size, position and chromatic attributes of printed features. For this study, we are investigating those specifications of the ABFO No.2 that affect the quantitative (metric) analysis of photographs.[5] These are:

1. *"The overall accuracy of scale ABFO No. 2 is ± 0.1 mm or ± 1% for the major centimetre graduations*."
2. *"The internal and external diameters of the three circles are 19.75 and 23.00 mm, respectively."* [6]
3. *"The error in placement of the three circles is within 0.25% of the nominal 80-mm separation between their centers."*
4. *"The legs are mutually perpendicular to ± 2 min of arc."* [7]

Specifications 2, 3, and 4 are depicted in Figure 2 below.

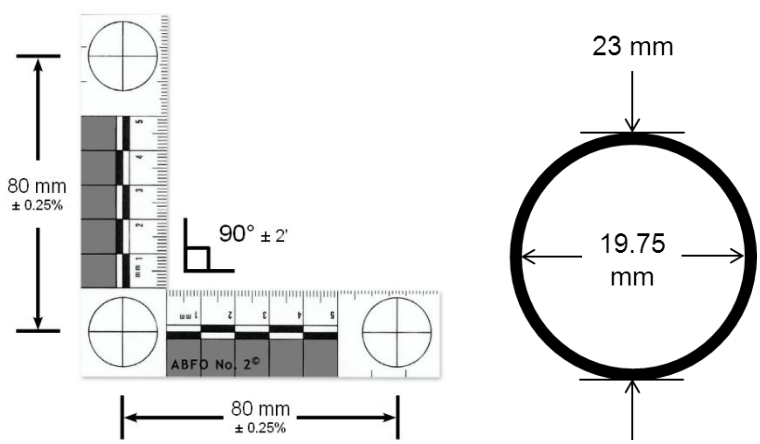


Figure 2: ABFO No. 2 specifications dictate the accuracy of the length scale, the perpendicularity of the rulers, the distance between the centers of the circles, and the internal and external diameters of the circles.

[4] Hyzer, W. G. and Krauss, T. C., "The Bite Mark Standard Reference Scale – ABFO No. 2," Journal of Forensic Sciences, JFSCA, Vol. 33, No. 2, March 1988, pp. 498-506.
[5] See Discussion section Note 1 on other features not observed in this study.
[6] See Discussion section Note 2 on conflicting specifications regarding diameters.
[7] Min of arc is also known as arcminute. 1 arcminute = 1/60 degrees.

The ABFO No. 2 was originally developed for documentation of patterned injuries thought to be bite marks; however, its design and subsequent products have been adopted for laboratory and crime scene photography in general.

c) *Concerns over accuracy*

The task of producing the ABFO No. 2 was initially granted to one manufacturer. However, a review of commercially available photo scales showed a proliferation of rulers similar in design to the original ABFO No. 2 (Figure 3). In some cases, rulers were advertised as ‘ABFO No. 2 Photomacrographic Scale,’ without the printed ‘ABFO No. 2’ label on the rulers themselves.

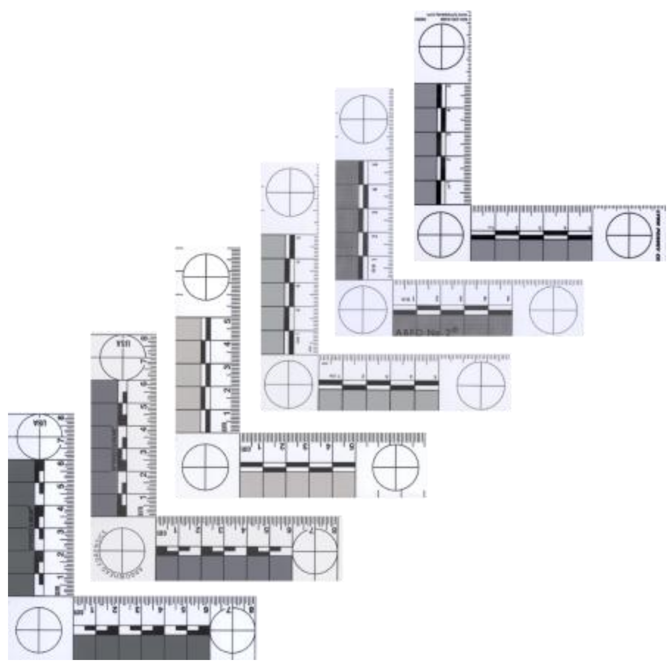


Figure 3: A review of commercially available photo scales showed a proliferation of rulers similar in design to the ABFO No. 2.

The Dimensional Metrology Group (DMG) sought to evaluate the conformance of commercially-available photo scales to the ABFO No. 2 specifications. While the photo scales in the study were chosen for their similarity to the ABFO No. 2 design, it should be noted that not all were advertised as ‘ABFO No. 2.’

II. Methods

The DMG measured dimensional features from a sample of commercially available photo scales, using as criteria the ABFO No. 2 specifications. Five rulers were purchased from each of four vendors. The following features were inspected on each ruler: (a) the accuracy of the horizontal and vertical length scale graduations, (b) the perpendicularity of the legs, (c) the inner and outer diameters of the circles, and (d) the center-to-center distance between circles. Each feature was measured five times and the average value is reported.

Measurements were made on the rulers over several years and on two vision measurement machines. The rulers were purchased in 2007 and were subsequently measured under a Mitutoyo UMAP vision measurement system. The UMAP is equipped with a vision probe capable of edge detection and focusing for coordinate mapping with accuracies of a few micrometers (Figure 4). The rulers were held flat with putty on the extremities (Figure 5) to avoid errors as a result of bending. The DMG used the UMAP to measure features (a) – (c).

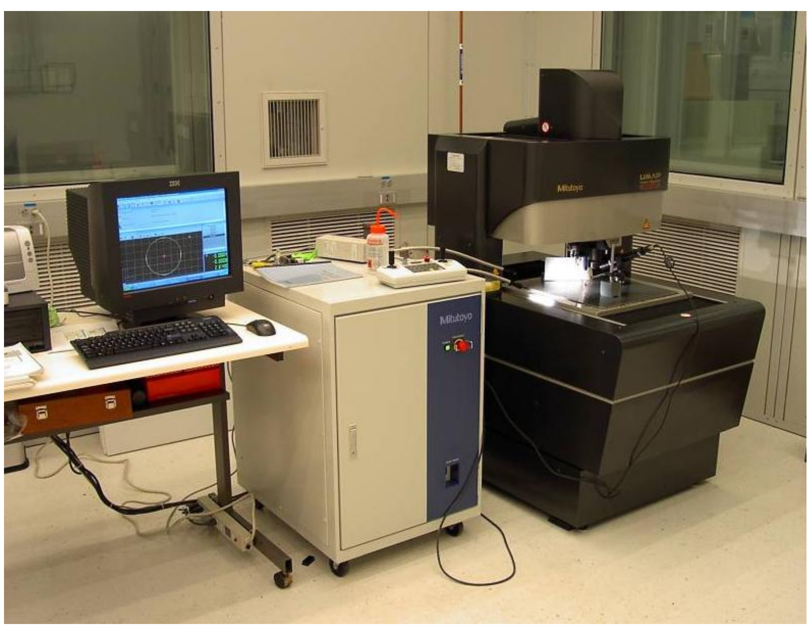


Figure 4: The UMAP vision measurement system is equipped with a vision probe capable of edge detection and focusing for coordinate mapping with accuracies of a few micrometers.

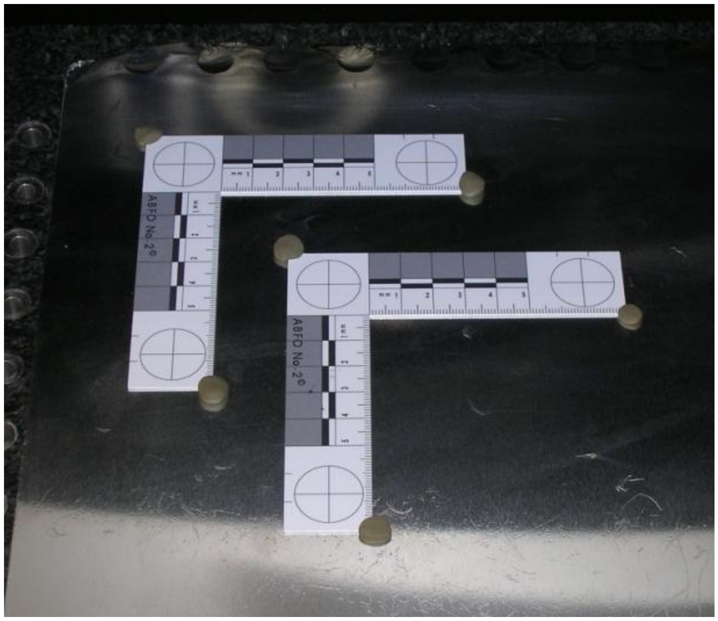


Figure 5: Putty was used on the extremities of the rulers to avoid errors from bending.

The UMAP's performance was checked using a two-dimensional grid plate that was calibrated on an M48 Coordinate Measurement Machine. The reference values from the M48 have an uncertainty of 464 nm (0.000464 mm). Thus, we confirmed the UMAP's specified uncertainty as documented by the vendor (Equation 1).

$$U\ \ X,Y\ : 0.7 + \frac{2L}{1000}\mu m;$$

Equation 1: Vendor's stated uncertainty for measurements in X and Y plane. (UMAP)

In 2008, the DMG acquired a Nikon VMR-6555 vision measurement machine (Figure 6) and completed the measurement scheme by measuring feature (d), the center-to-center distance between circles. The rulers were held flat by a vacuum chuck placed directly beneath the rulers (Figure 7).

Figure 6: The Nikon VMR-6555 was purchased in 2008 and was used for all subsequent measurements in this study.

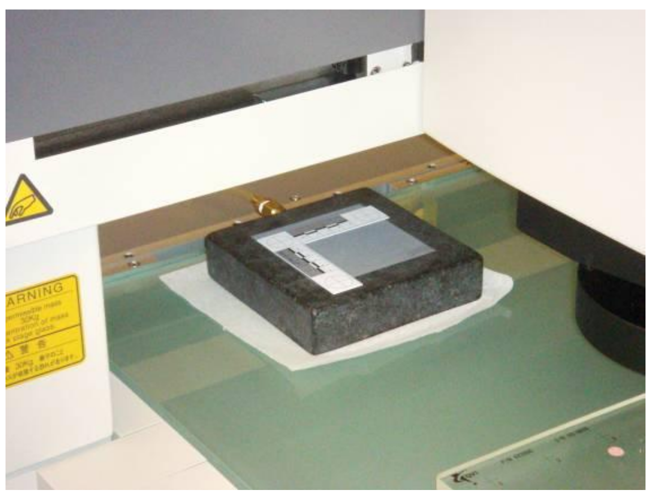


Figure 7: A vacuum chuck was placed directly beneath the rulers to hold them flat.

The system's performance was checked with the same two-dimensional grid plate calibrated to an uncertainty of 464 nm (0.000464 mm). Its specified uncertainty was also confirmed (Equation 2).

$$U\ \ X,Y\ : 1.5 + \frac{2.5L}{1000}\ \mu m;$$

Equation 2: Vendor’s stated uncertainty for measurements in X and Y plane. (VMR)

It should be noted that the measurement uncertainty is a function of the size of the measurand. In this case, the smallest displacement measured was 10 mm, while the largest displacement didn’t exceed 85 mm. Thus, the uncertainty range contributed by each measurement system is given below (Equation 3).

$$U\ \ X,Y\ : 0.72 - 0.87\ \mu m\ \ \ UMAP\ \ ,$$
$$U\ \ X,Y\ : 1.53 - 1.71\ \mu m\ \ \ VMR\ \ ;$$

Equation 3: Measurement uncertainty for measurement range covered in this study.

The error in the measurement systems is almost two orders of magnitude smaller than the tolerance values given in the ABFO No. 2 specifications. The largest source of error would actually be the print quality of features on rulers. Figure 8 gives an example of the variation in graduation print quality between vendors.[8] We can, therefore, consider any difference in the performance of the systems to be negligible.

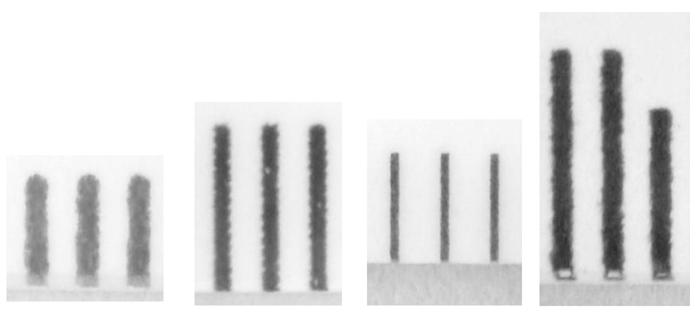


Figure 8: The print quality of features, such as the length graduations seen above, contributes the largest error in the measurements.

To understand the behavior of photo scales over time, we measured the same rulers in 2011, four years after purchase. All features were re-measured on the Nikon

[8] Please see Discussion section, Note 3 for more examples of print quality among rulers.

vision system using the same measurement scheme. The new results are presented and compared to previous data.

The DMG investigated the primary sources of forensic photo scales in the United States and found that the production is limited to only a few manufacturers. Site visits were made to these manufacturers in order to learn how they produce forensic photo scales and how they control the quality of their production. The DMG's findings are discussed.

Once the production and distribution of forensic photo scales was better understood, an extensive surveillance of a new, larger sample of rulers was performed. The Nikon VMR-6555 vision measurement system was used for this round of testing. The testing scheme for each feature is consistent with previous tests. However, this time the rulers were not held flat so as to allow us to quantify the effect of bending on the quality of the length scale.

III. Results

a) Initial testing

Length Scales

The accuracy of the scale is determined by the error in position of the length graduations with respect to 'zero.' The measured distance between the zero graduation and each subsequent graduation is compared to the nominal distance, and the error is extracted. For example, if the position of the 2 cm graduation is a distance of 2.05 cm from the 0 (zero) cm graduation, then its error is +0.05 cm. We define the position of a graduation as the intersection of its midline and the inner edge of the ruler (Figure 9). The specification states that the accuracy of the scale is "*± 0.1 mm or ± 1% for the major centimetre graduations*." We understand that to mean that the allowed error between adjacent millimeter graduations is ± 0.1 mm, while the cumulative error at each centimeter graduation shall not exceed ± 1% from its nominal value. By investigating the error in position of centimeter graduations should give a reasonable indication of the relative behavior between millimeter graduations. Thus, we measure the error in position for the first five centimeter graduations. Both the vertical and the horizontal scales were tested on each ruler (Figure 10).

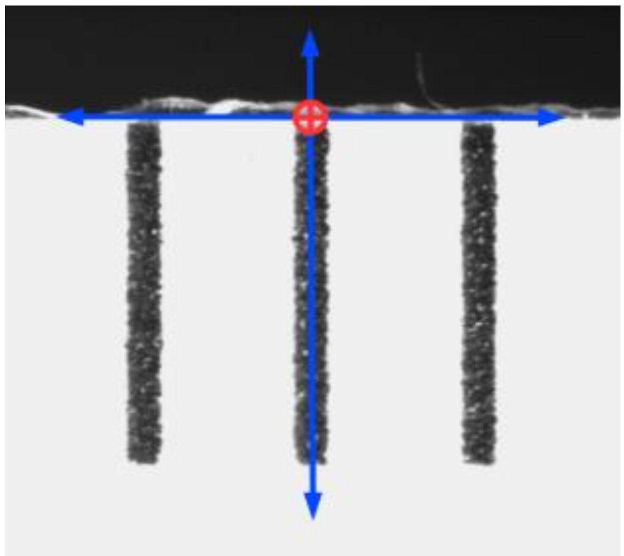


Figure 9: The position of a graduation is defined as the intersection of the graduation's midline and the inner edge of the ruler. Note the concentric crosshairs. The intersection of the crosshairs denotes the extracted position.

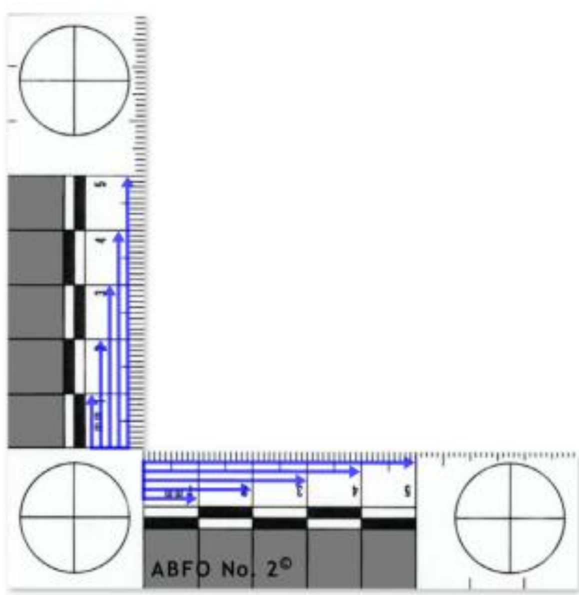


Figure 10: The test measured the error in position of the first five centimeter graduations. Both the vertical and horizontal scales were tested.

The results are shown below (Figure 11). Each vendor is reported separately. The error at each graduation is plotted against the graduation's nominal value. We plotted the individual data points – ten for each graduation. We also plotted the mean values, shown as line plots.

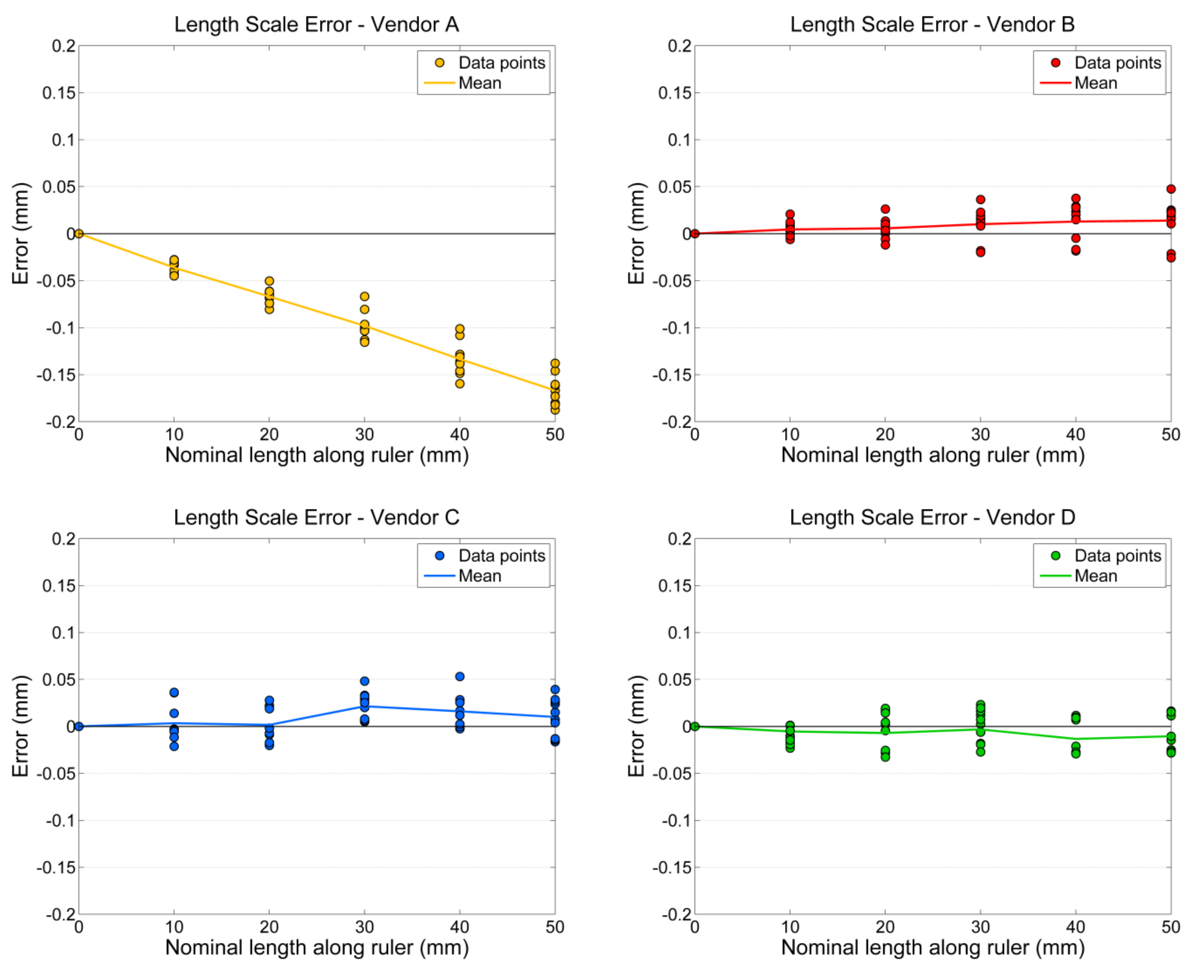


Figure 11: The error in position for each centimeter graduation is plotted against its nominal value. The mean error between each centimeter graduation is connected by a solid line. Each vendor is reported separately.

We recall from the ABFO No. 2 specifications that the allowed error is ± 1% for each centimeter graduation. This means ± 0.1 mm at the 1 cm graduation, ± 0.2 mm at the 2 cm graduation, ± 0.3 mm at the 3 cm graduation, ± 0.4 mm at the 4 cm graduation, and ± 0.5 mm at the 5 cm graduation. All four vendors stayed well within the allowed error over the range tested. It should also be noted that, apart from vendor A, the error in length scales stayed within 0.1 mm throughout the tested range.

Internal and external diameters of circles

The internal and external diameters of the circles were measured using circle-fitting algorithms provided by the measurement system. For internal diameter, the inside edge of the circle was traced (by edge detection) at various segments around its entire circumference. The software fits a circle to the measured position data of the inside edge, providing the user with a calculated diameter. The same applies to the external diameter, in which case the outside edge is traced. Each ruler has three circles. Measurements were performed on all circles and all rulers. The average internal and external diameters are presented separately for each vendor. The standard deviation and its percentage value with respect to average (variability) are also presented. (Tables 1 and 2)

Internal Diameter

Vendor	Average Internal Diameter (mm)	Standard Deviation (mm)	Variability (%)
A	19.748	0.009	0.044
B	19.590	0.029	0.148
C	19.534	0.034	0.173
D	18.206	0.016	0.088

Table 1: Measurements on internal diameter were made on each of three circles for every ruler. The average internal diameter is reported for each vendor, along with the standard deviation and variability as a percentage value from average.

We recall that the ABFO No. 2 specification for internal diameter is given to be 19.75 mm. However, it must be noted that the specification does not provide tolerance values. Thus, it is difficult to judge the conformance of vendors. Vendor A is closest to specification, also exhibiting the lowest variability among its rulers. The standard deviation and variability is an indicator of the consistency in the manufacturing process.

External Diameter

Vendor	Average External Diameter (mm)	Standard Deviation (mm)	Variability (%)
A	20.124	0.007	0.037
B	20.396	0.030	0.145
C	20.379	0.029	0.141
D	19.176	0.015	0.076

Table 2: Measurements on external diameter were made on each of three circles for every ruler. The average external diameter is reported for each vendor, along with the standard deviation and variability as a percentage value from average.

The specification for external diameter is given to be 23.00 mm.[9] The average values for external diameter indicate that none of the vendors were close to this specification. However, it must be noted that the variability is relatively low within each vendor, thus demonstrating a relatively consistent manufacturing process. Vendor A, again, exhibits the lowest variability among its rulers.

Center-to-center distance between circles

The measurements of center-to-center distance between circles (and all subsequent measurements in this study) were performed on the Nikon VMR-6555. The first step is to define the position of a circle's center. The center of a circle can be defined as either (1) the intersecting point of the two concentric crosshairs, or (2) by fitting a circle to the internal or external edges and extracting the calculated center (Figure 12). In the first method, we first find the midline of each crosshair. Then, we take the point of intersection of the two midlines as the center of the circle. Whereas, in the second method, the circle-fitting function provides the user with the point coordinates for the circle's center. Once we established point coordinates for each of the three circles, we can calculate the distances by using the Pythagorean Theorem (Equation 4). We will perform measurements using both methods and compare the results.

[9] See Discussion section on conflicting specifications

$$distance = \sqrt{(\Delta x)^2 + (\Delta y)^2};$$

Equation 4: When the point coordinates are known, the distance can be calculated using the Pythagorean Theorem. Δx and Δy are the displacement in x and y coordinates between circle centers.

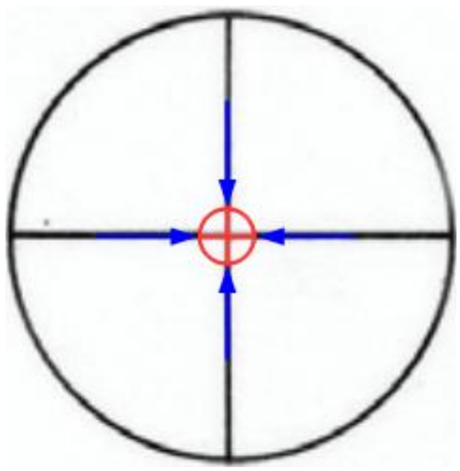


Figure 12: The centers are measured by two methods. The first method assumes the center of the circle is given by the intersection of the concentric crosshairs. The second method uses a circle-fitting function on the circumference of the circle to extract its center.

Each ruler has two center-to-center segments (Figure 13). Since the specification is the same for both the horizontal ($d_{1\text{-}2}$) and the vertical ($d_{1\text{-}3}$) segments, we don't distinguish the two in our results. For each vendor, the average of all distance measurements is presented. The standard deviation and its percentage value with respect to average (variability) are also presented (Table 3).

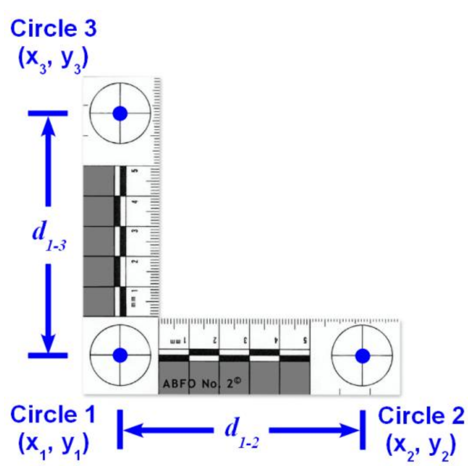


Figure 13: There are two center-to-center segments on each ruler, $d_{1\text{-}2}$ and $d_{1\text{-}3}$. Both are measured and results are not distinguished.

Vendor	Crosshairs Average (mm)	Standard Deviation (mm)	Variability (%)	Circle-fitting Average (mm)	Standard Deviation (mm)	Variability (%)
A	79.749	0.024	0.031	79.745	0.022	0.028
B	80.024	0.024	0.030	80.027	0.025	0.031
C	85.099	0.081	0.095	N/A	N/A	N/A
D	77.763	0.077	0.099	77.767	0.062	0.079

Table 3: Measurements of center-to-center distance were made using two methods. Each ruler had two center-to-center segments. The average over five rulers for each vendor is reported, along with the standard deviation and variability as a percentage value from average.

We recall that the ABFO No. 2 specification for distance between the centers of the circles is 80 mm ± 0.25% (or ± 0.2 mm). Therefore, any values below 79.8 mm and above 80.2 mm are considered not in conformance. The average values from the 'crosshair' and 'circle-fitting' method differ by no more than 0.004 mm (4 μm). This is negligible considering that it is in the same order of magnitude as the repeatability of the measurement system. We could not extract circle-fitting data from vendor C since the circumference of the circles had printed obstructions (Figure 14). Hence, we will use the results from the 'crosshairs' method.

Figure 14: Circle-fitting was not performed on vendor C rulers since part of the circumference was obstructed by other printed features.

The results indicate that only vendor B satisfies the ABFO No. 2 specification. However, it should be noted that, despite the discrepancy in center-to-center distance between vendors, the variability within each vendor is extremely low (less than 0.1%). As previously mentioned, this indicates a consistent manufacturing process.

Perpendicularity of legs

The original intention to evaluate perpendicularity of legs was to trace the inner edges of the ruler, fit a line to each edge, and extract the angle between the fit lines. However, we found the inner edges of the rulers to be of consistently low quality. The edges were not always straight and abrasions were frequent (Figure 15).

Figure 15: Inner edges were not always straight and abrasions were frequent, making them inadequate for measuring perpendicularity. The above is an example of small imperfections caused by the cutting of rulers in the manufacturing process.

Therefore, we could not rely on them to measure the angle between the legs. We chose to use the length segments connecting the centers of the circles instead. This technique is not optimal as it is not entirely consistent with the definition of perpendicularity in the specification. Nonetheless, we found it to be a reasonable alternative to using the inner edges of the legs.

We used the coordinate data for the intersection of the crosshairs to determine the distance for the three center-to-center length segments. The values were then used in conjunction with the law of cosines to extract the angle, θ (Figure 16).

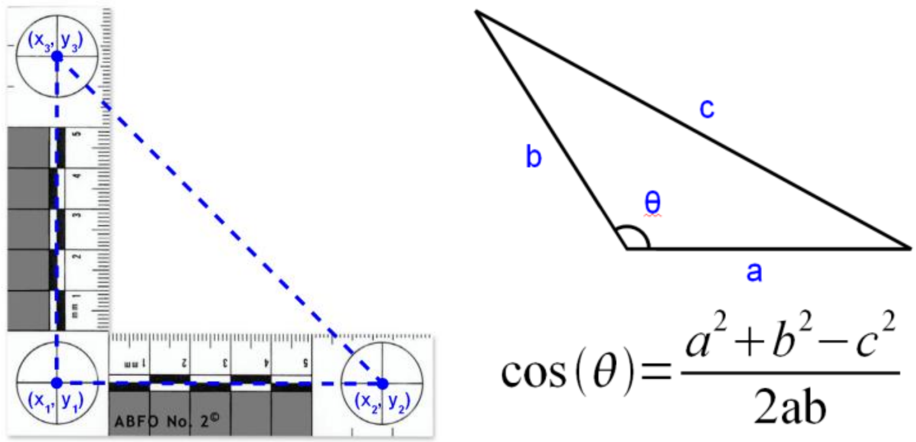


Figure 16: The center-to-center segments are used in conjunction with the cosine law to determine the angle between the legs. The crosshair intersection data was used in the length calculations.

The following plot (Figure 17) shows the error in perpendicularity for each photo scale. Individual rulers are plotted against their error (in arcminutes) from 90°. Figure 17 describes the physical significance of error in angle, with “+” and “-“ directionality.

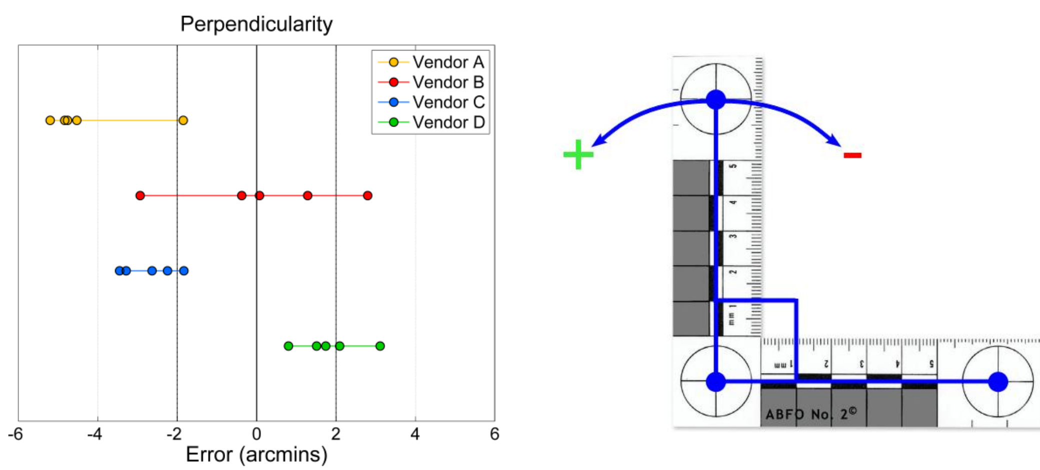


Figure 17: The perpendicularity for each ruler is plotted as its angle’s error from 90°. The sign before the error in angle follows the counter-clockwise angle convention, in which an increasing angle moves in the counter-clockwise direction.

The ABFO No. 2 tolerance for perpendicularity is ± 2 arcminutes (One arcminute is 1/60 of a degree). We notice that each vendor had rulers that fell outside the specified tolerance. Vendors A and C each show four rulers exceeding -2 arcminutes, while one ruler fell just within tolerance. On the other hand, vendors B and D each show three rulers falling within tolerance, and two exceeding it.

The method of using the center-to-center length segments as the legs and the cosine law had its shortcomings. Small errors in the length measurement of the segments would yield large errors in the estimation of angle. We look at the propagation of error from length measurement to estimation of angle. The law of cosines is rewritten:

$$\cos\theta = \frac{a^2 + b^2 - c^2}{2ab}$$

$$So, \qquad \theta = \cos^{-1}\left(\frac{a^2 + b^2 - c^2}{2ab}\right);$$

We can then use the formula for error propagation to calculate the error in θ due to errors in a, b, and c:

$$Thus, \qquad \sigma_\theta = \sqrt{\left(\frac{\partial\theta}{\partial a}\right)^2 (\sigma_a)^2 + \left(\frac{\partial\theta}{\partial b}\right)^2 (\sigma_b)^2 + \left(\frac{\partial\theta}{\partial c}\right)^2 (\sigma_c)^2};$$

We set the length segments, a, b, and c, to a default 80 mm, 80 mm, 113.14 mm, respectively. At the same time, we set their errors, σ_a, σ_b, and σ_c, to 0.01 mm. This is a reasonable error in length measurement given the print quality of the rulers (Figure 18).

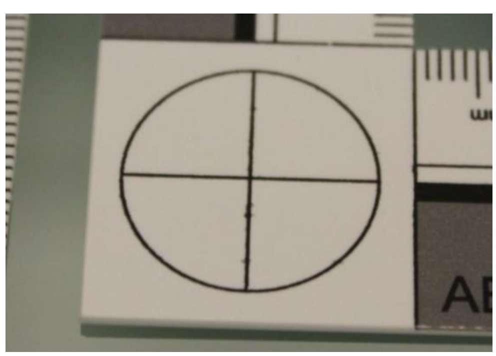


Figure 18: The error in print quality of the rulers, as shown in this image, produce errors in the determination of the crosshair intersection. This error will then propagate to the calculation of angle when testing a ruler's perpendicularity.

We find that, given these values, the error in angle calculation comes to

$$\sigma_\theta = 0.74\ arcminutes;$$

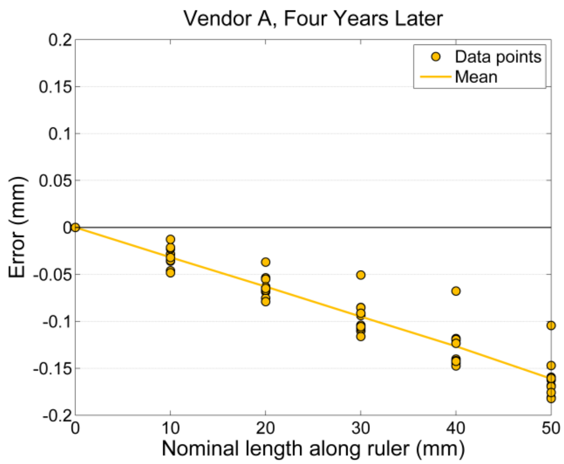
Considering that the specified angle tolerance in the ABFO No. 2 technical document is ± 2 arcmins, the error associated with our method of calculating the angle is substantial. However, the error in the alternate method of using the internal edges of the ruler would have been significantly higher, given the lack of straightness and imperfections in the edges.

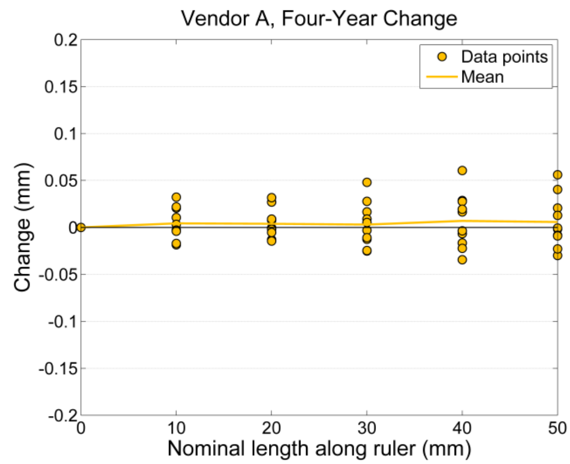
b) Four-year revisit and measurement

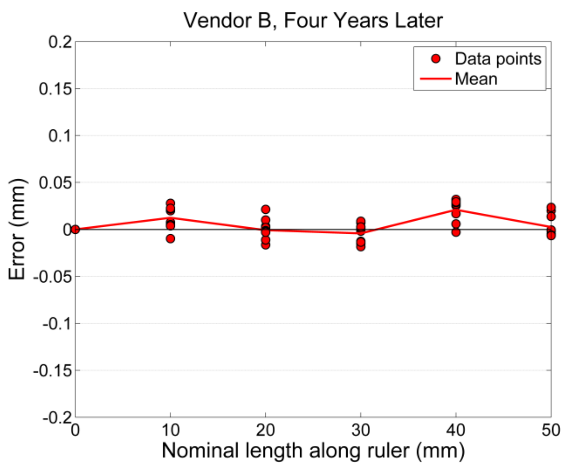
After several years, we noticed the rulers had developed a grayish yellow stain throughout their surfaces. This is not unexpected, as plastic is not considered a stable material. However, it led us to wonder if the rulers undergo dimensional changes over time. To better understand the behavior of the rulers over a long period of time, we retested the same rulers four years after purchase. The rulers were measured using the Nikon VMR-6555 vision measurement machine. All features except for circle diameters were studied.

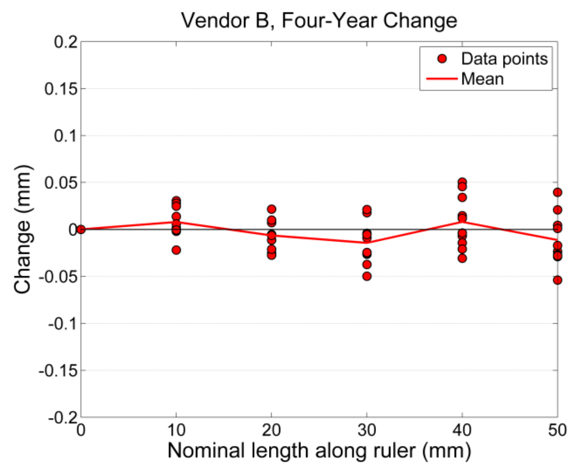
Length Scale

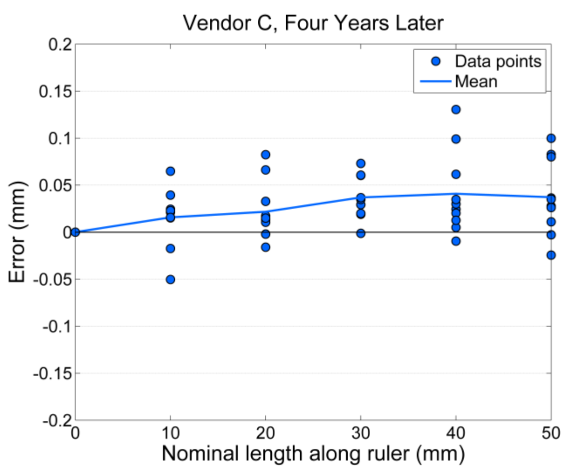
The new data is plotted separately for each vendor (Figure 19). The change is also plotted. Negative change indicates shrinking of the scale, while positive change indicates a growing scale.

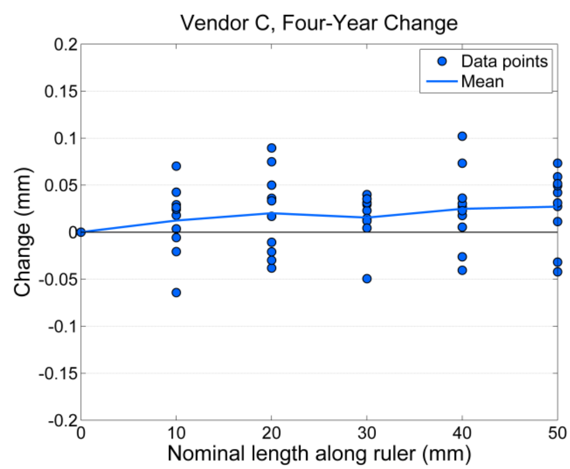

Vendor A, Four Years Later
Data points
Mean
Error (mm)
Nominal length along ruler (mm)


Vendor A, Four-Year Change
Data points
Mean
Change (mm)
Nominal length along ruler (mm)


Vendor B, Four Years Later
Data points
Mean
Error (mm)
Nominal length along ruler (mm)


Vendor B, Four-Year Change
Data points
Mean
Change (mm)
Nominal length along ruler (mm)


Vendor C, Four Years Later
Data points
Mean
Error (mm)
Nominal length along ruler (mm)


Vendor C, Four-Year Change
Data points
Mean
Change (mm)
Nominal length along ruler (mm)

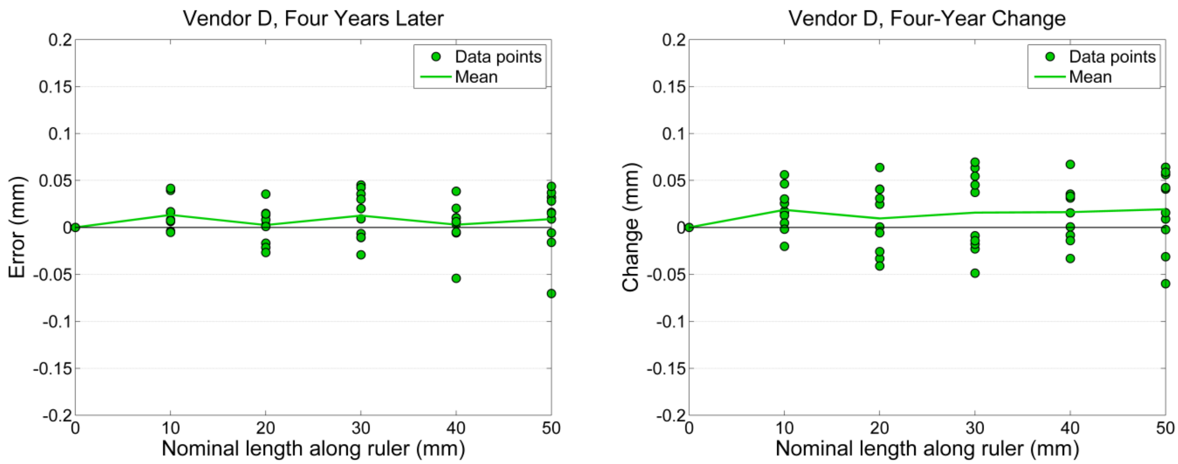


Figure 19: The length scales were measured again four years after their first testing. The new data is presented, along with the four-year change.

We notice that most change in length scale stays within ± 0.05 mm, with some instances exceeding it. Despite the change, the new position data show that the rulers still satisfy the ± 1% tolerance.

Center-to-center distance between circles

Previously, we proved that the difference between using the 'crosshairs' method and using the circle-fitting method is negligible. Therefore, we define the center of the circles to be the intersection of the crosshairs. The results of the new center-to-center distance measurements are shown in Table 4 below.

Vendor	Crosshairs Average (mm)	Average Change (mm)	Largest Change (mm)
A	79.746	-0.003	-0.005
B	80.017	-0.007	-0.016
C	85.087	-0.011	-0.055
D	77.759	-0.004	0.021

Table 4: Only the crosshair intersection method was used in the four-year retesting of center-to-center distance. The new average values are presented for each vendor. The average four-year change and the largest four-year change are also presented.

We look to the ± 0.2 mm tolerance as criteria for judging the behavior of the rulers over time. The average change in distance is at least one order of magnitude smaller than the specified tolerance. Despite the distances being off from specification, they were stable over four years.

Perpendicularity of legs

The same method was applied as previously noted. The new coordinate data for the intersection of crosshairs are used to calculate the distance between centers of circles. Once we have the distance of each length segment, we use the law of cosines to determine the angle. The new results are presented with the resulting change over four years (Figure 20).

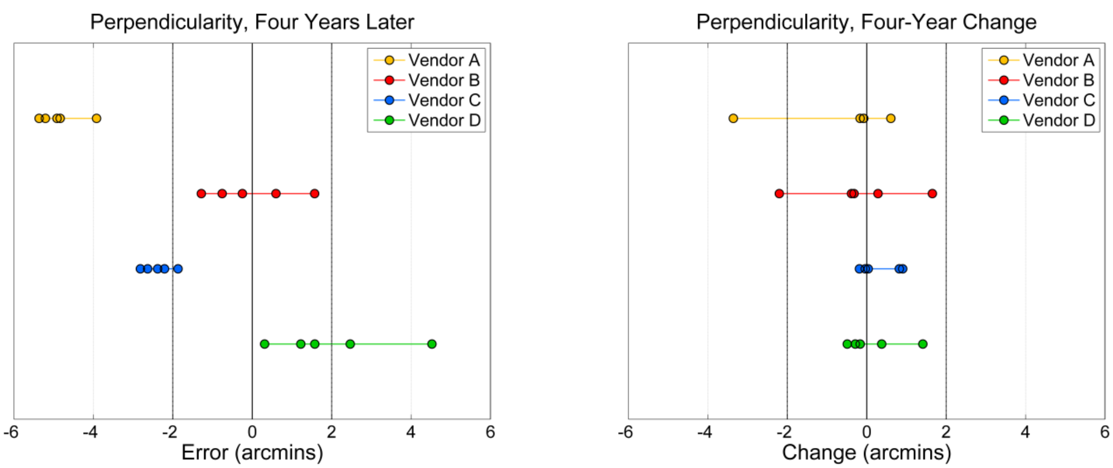


Figure 20: The new perpendicularity data is presented together with the four-year change.

After four years, the data show that there is considerable change in the angle. However, it should be noted that angle is very sensitive to small changes in length of segments. The error calculation is discussed previously in the article.

c) *Manufacturer visits*

Site visits of the manufacturers revealed manufacturing processes and methods of quality control. Depending on the material of the ruler, there are various methods of impressing features. Ink-based digital printing is suitable for thinner, usually paper-based, rulers. Silk screen printing is used for hard plastic rulers, such as the ABFO No. 2. Etching, on the other hand, is often used for steel rulers.

A common technique for quality control is to check the printed scales with a 'certified' steel ruler. The steel ruler is placed flush against the printed ruler's edge so that the positions of the graduations can be compared. The units being compared should be consistent (i.e. English with English or metric with metric). The 'zero' graduation of the photo scale is lined up with the zero graduation of the steel ruler. In cases that the 'zero' of the steel ruler is the edge of the ruler itself (Figure 21), it is suggested to line up the zero graduation of the photo scale with the '1' graduation of the steel ruler.

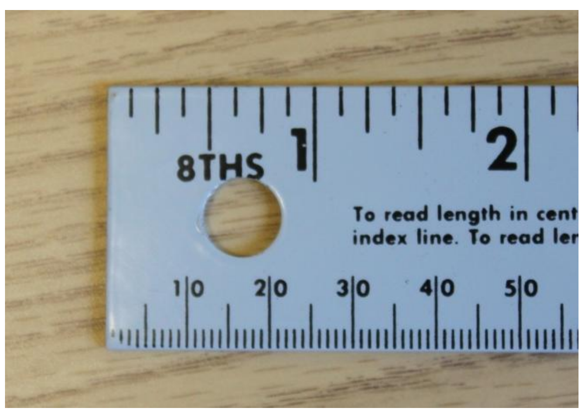


Figure 21: A common method for checking the accuracy of a plastic ruler's length scale is to compare it to the scale of a steel ruler. Sometimes, the 'zero' of the steel ruler's scale is defined to be the ruler's edge. In this case, it is suggested that the next graduation (of equal unit) be used as the 'zero.'

An eyepiece can help in the comparison by providing magnification (Figure 22). Care should be taken to reduce parallax caused by the viewing angle, with or without an eyepiece. It should be noted that manufacturers did not mention checking any other feature other than from the length scale.

Figure 22: An eyepiece can help in comparing two length scales placed flush against each other. Care has to be taken to avoid parallax error caused by oblique viewing angles.

When discussing quality control, manufacturers mentioned the use of ‘certified’ steel rulers. Often, a ‘certified’ ruler is understood to mean a ruler calibrated by a laboratory whose length measurements are traceable to a National Metrology Institute (NIST in the United States). At the moment, there are no standard procedures for the testing of forensic photo scales subsequent to manufacture and sale. While a calibrated ruler establishes a certain level of measurement confidence, it is not necessary for checking plastic rulers. Coincidentally, our group previously performed a study of the accuracy of three differently-priced steel rulers using the Nikon machine to make measurements. The results show that, while the more expensive steel rulers had minimal errors, the least expensive steel ruler’s errors were still small when compared to tolerance values for plastic rulers. In this study, the least expensive ruler was off by a little more than 0.1 mm over its entire length of 300 mm, or 0.033% from nominal, which is almost two orders of magnitude smaller than the ABFO No. 2 specification. The data is shown below (Figure 23).

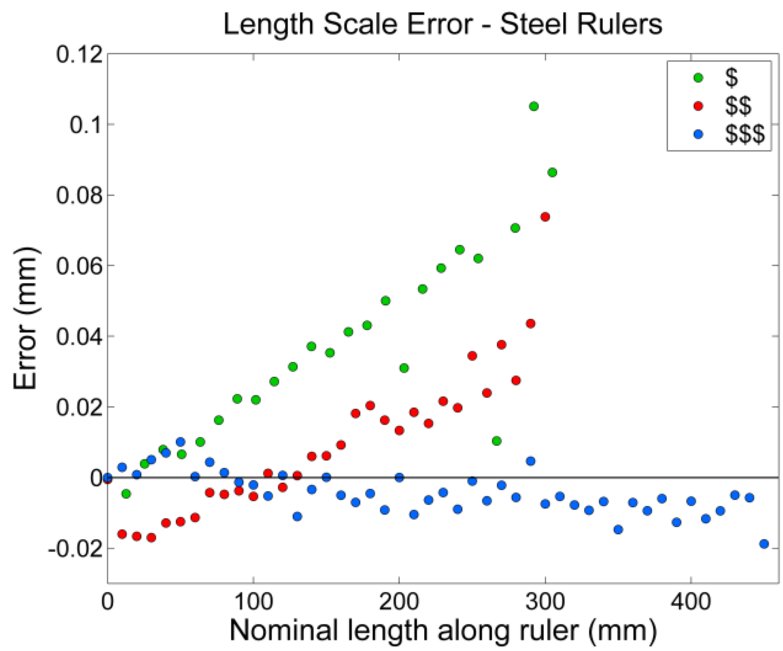


Figure 23: A study of length scales on steel rulers shows that, while the more expensive rulers had minimal errors, the errors on the least expensive were still much smaller than the errors seen on plastic rulers.

Therefore, while the use of certified steel rulers is good practice, it might not be absolutely necessary for the purpose of verifying that photo scales meet the ABFO No. 2 specifications.

Manufacturers typically have a documented procedure for deciding whether or not the printed scale is acceptable. If rulers are printed in large quantities, it is typical for the vendor to check a ruler at the beginning of the printing process, one in the middle, and one at the end. When a ruler is checked and found to be outside the manufacturer's tolerance, the printing is stopped. All rulers printed before the failed check, but after the last successful check, are rejected. Appropriate adjustments are then made to the setup and printing is resumed. When asked about tolerance, manufacturers quoted their own values, without mention of ABFO No. 2 specifications. Also, instead of quoting length-dependent tolerance values, manufacturers quoted tolerances over the entire length of the scale.

One manufacturer stated that their tolerance is +/- one half of the smallest graduation over the entire length of scale. For forensic photo scales, the smallest graduation is a millimeter, which means that at the 5 cm graduation, the allowed tolerance would be 0.5 mm, or 1%. This is consistent with ABFO No. 2 specification. A second manufacturer stated that anything outside of “dead on” was to be considered unfit for sale. A study on human hyperacuity found that a person can discern one tenth of a graduation with the bare eye.[10] We can assume that any discrepancy less than a tenth of a millimeter (0.1 mm) would be considered “dead on” by this manufacturer.

d) Surveillance testing

While visiting the manufacturers, we learned about the general distribution of forensic photo scales in the United States. In December of 2011, we performed a comprehensive surveillance test of photo scales distributed by the manufacturers we visited (Figure 24). We tested five photo scales from each of 10 vendors. The vendors are labeled A – J. We tested the rulers for all features except for internal and external diameter of the circles.

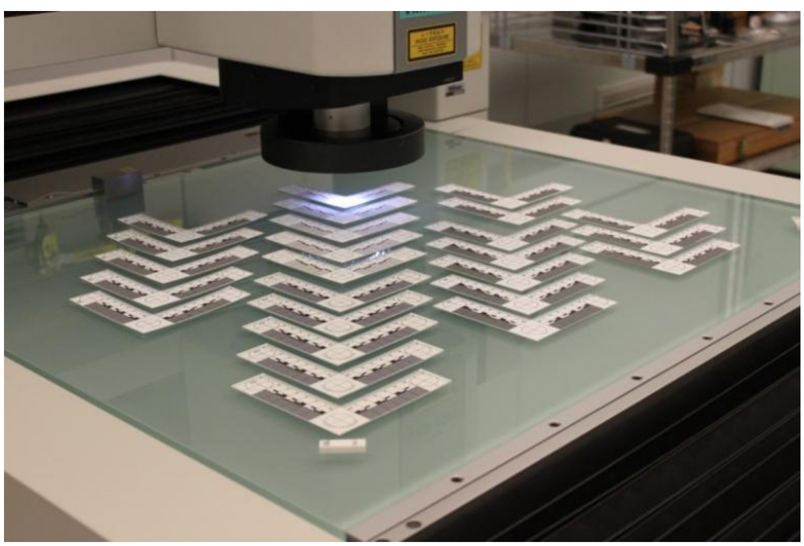
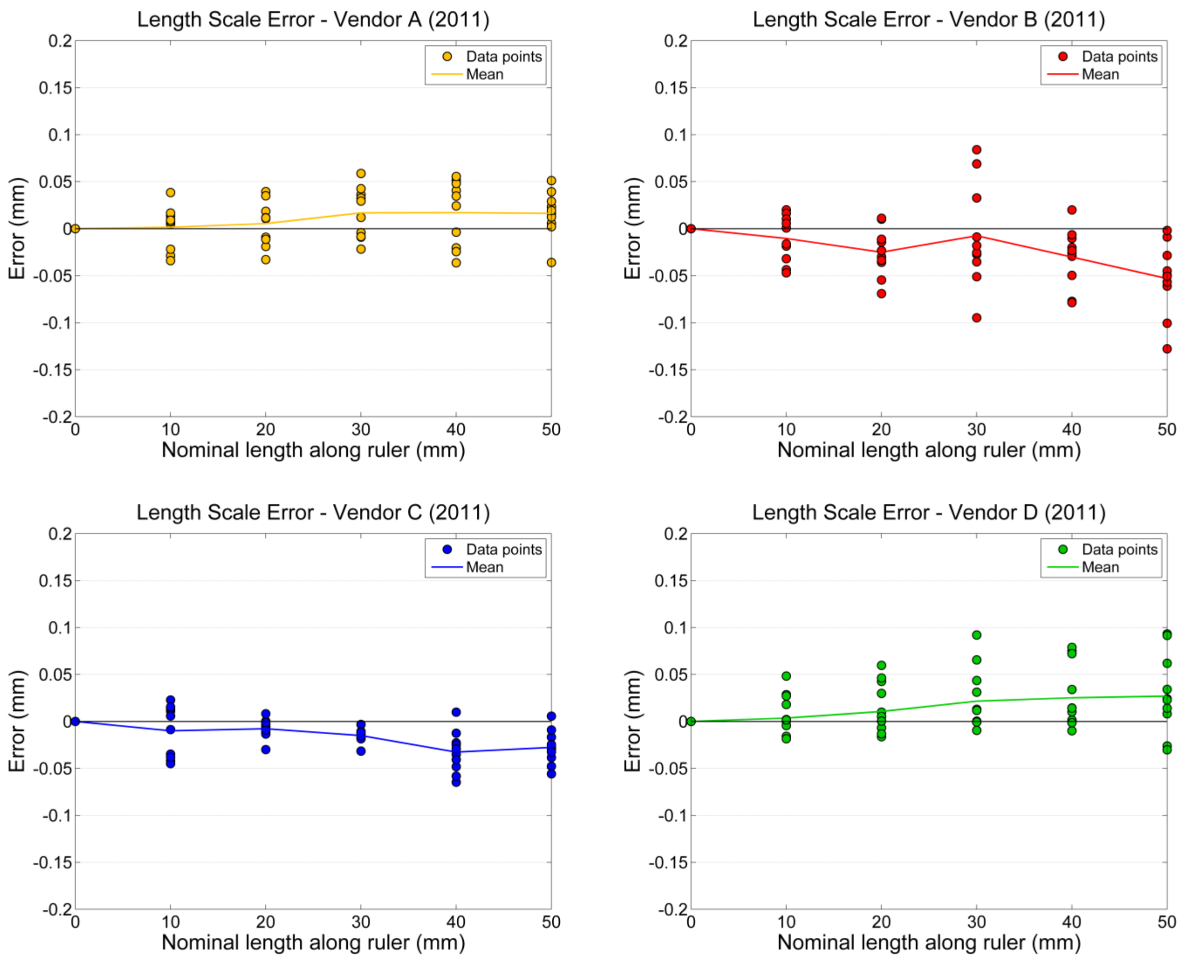


Figure 24: In December of 2011, the DMG performed a comprehensive surveillance test of photo scales. Five rulers from each of ten vendors were tested. All measurements were made on the Nikon VMR-6555 vision measurement system.

[10] Tomita, Y. and Honda, S., “Experimental evaluation of instrument scale readings obtained by eye interpolation of fractional interval values,” Measurement, Vol. 13, Issue No. 2, April 1994, pp. 147-151.

Length Scale

The results for length scale are presented for each vendor separately. Both the horizontal and the vertical length scale data are plotted (Figure 25).



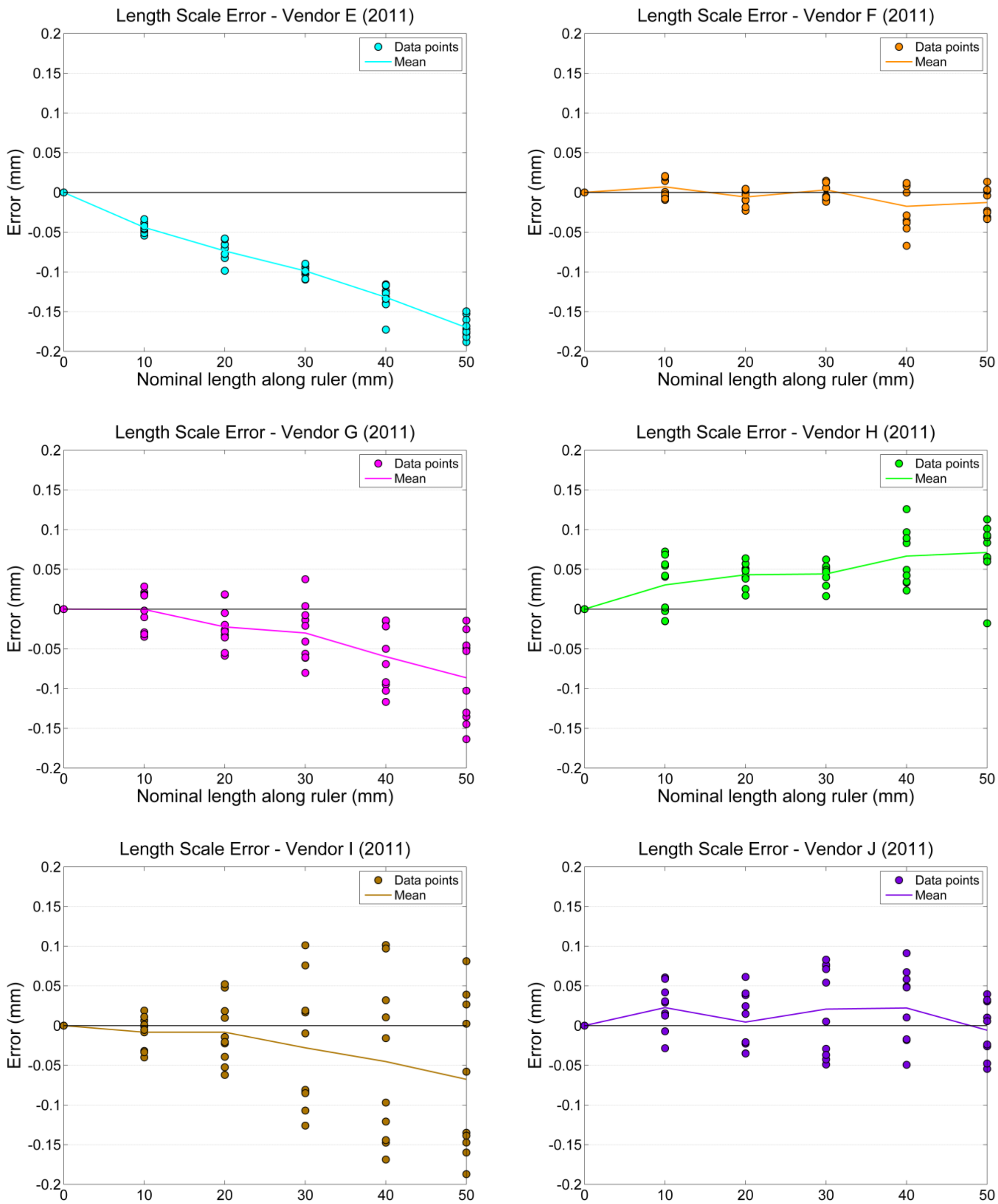


Figure 25: The error in position for each centimeter graduation is plotted against its nominal value. The mean error between each centimeter graduation is connected by a solid line. Each vendor is reported separately.

The results show that, much like in the previous study, all rulers satisfy the *"± 1% for the major centimetre graduations*" tolerance set by the ABFO No. 2 technical note.

Center-to-center distance between circles

For the center-to-center distance, we used only the intersection of the crosshairs to denote the center of the circle. The data is presented in Table 5 below.

Vendor	Crosshairs Average (mm)	Standard Deviation (mm)	Variability (%)
A	79.743	0.043	0.053
B	79.641	0.039	0.049
C	77.721	0.046	0.059
D	80.084	0.054	0.068
E	79.738	0.012	0.016
F	84.999	0.165	0.194
G	84.924	0.063	0.075
H	85.179	0.046	0.055
I	84.942	0.233	0.275
J	82.527	0.028	0.034

Table 5: Only the crosshair intersection method was used in the surveillance testing of center-to-center distance. The average over five rulers for each vendor is reported, along with the standard deviation and variability as a percentage value from average.

Perpendicularity of legs

The law of cosines was used on the three length segments. We note the error in angle calculation due to errors in measurement of distance as previously discussed. Vendors A – J are displayed from top to bottom (Figure 26), with vendor A being at the top (yellow) and vendor J at the bottom (purple).

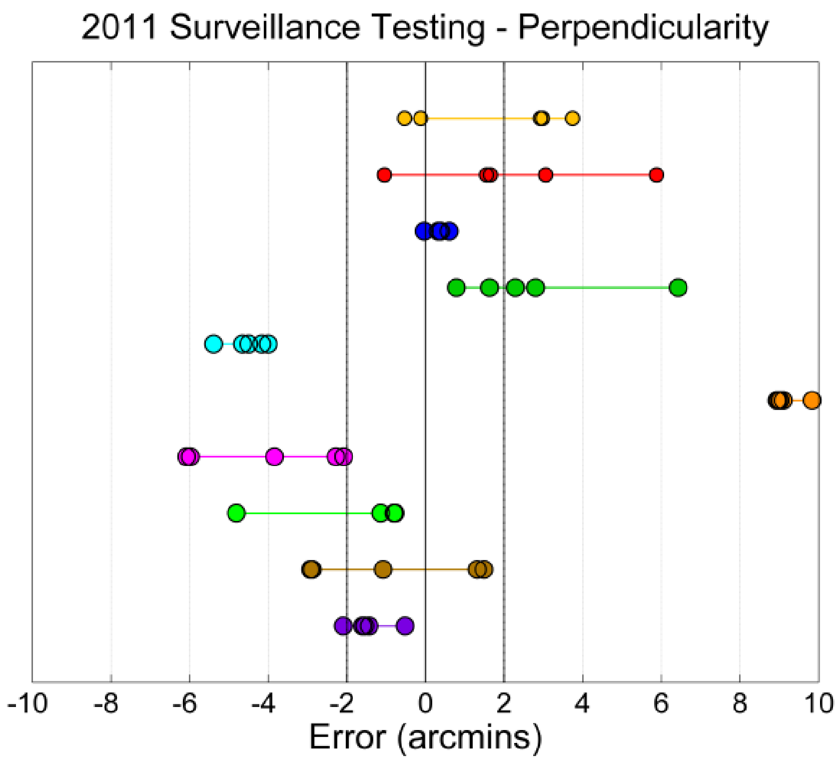


Figure 26: The perpendicularity for each ruler is plotted as its angle's error from 90°. Vendors A – J are displayed from top to bottom, with vendor A being at the top (yellow) and vendor J at the bottom (purple)

Bending

Upon receipt of the new rulers, we noticed that many of them had varying degrees of bending (Figure 27).

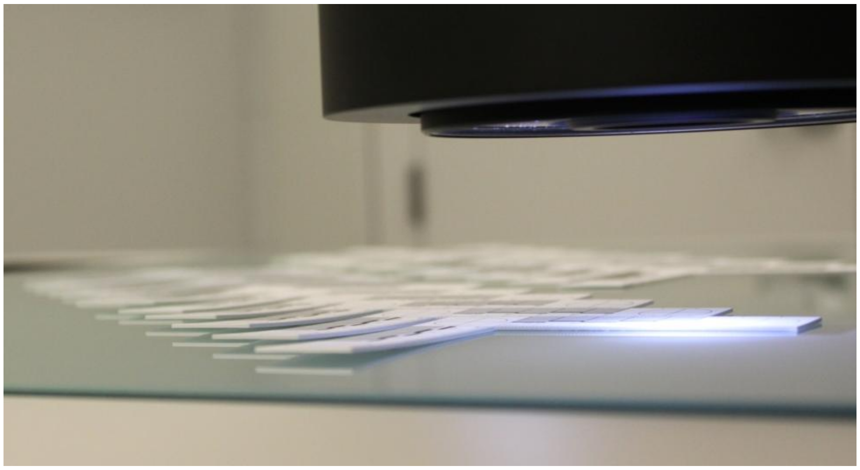


Figure 27: Rulers had varying degrees of bending out of the packaging. The DMG studied the effect of bending on the length scale.

The point-to-point distance algorithm used in measuring length scale doesn't take into account change in height. There was concern that, as a result of the change in height, our measurements were not representative of the actual distance between features. To evaluate bending, we measured height at the center of each circle. The Nikon vision measurement machine measures along the z axis (Figure 28) by shining a laser onto the surface and changing the position of the lens until the laser is in focus. Displacement in z is determined by the displacement in the focusing lens.

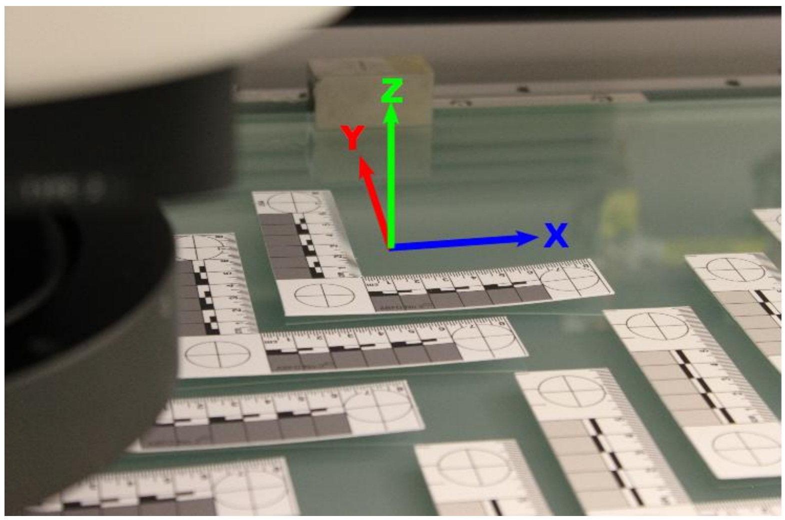


Figure 28: The Nikon VMR-6555 vision measurement system measures features in the x-y plane using edge detection. To gather information in the z-axis, the system uses contrast-based focusing. If the feature doesn't provide contrast information, the system can use a laser spot to provide a target for focusing.

By knowing the change in height, we can correct the length measurement to what it would be if the ruler were flat. As we measured the rulers, we took height information at each circle center. Then, for simplicity, we approximate the bending to a straight line, and use the slope of each center-to-center segment to determine the angle of bending. Figure 29 below shows a profile view of the ruler with exaggerated dimensions for clarity.

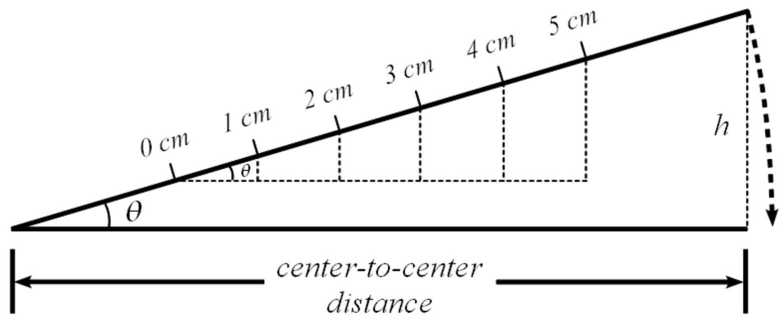


Figure 29: The bending was approximated to be straight, allowing the DMG to calculate the angle of bending, θ, from the change in height over the center-to-center distance between circles. The angle θ is then used to calculate the correction to the measured position of the graduations with respect to the 'zero' graduation.

The solid diagonal line is the bent ruler, while the horizontal solid line below is the ruler as the measurement system sees it. The system doesn't take into account change in height, so it assumes a flat object. The difference in height between one center of the circle to the next is given by h. The angle of bending, θ, can be solved using Equation 5 below.

$$\tan\theta = \frac{h}{center - to - center\ distance};$$

Equation 5: The angle of bending, θ, for a ruler is solved using the center-to-center distance and the height difference along that distance as measured on the vision system. The equation assumes that the bending is linear.

We measured the height difference between each center-to-center segment on all rulers. The results are presented in Figure 30 below with center-to-center distance on the x-axis and the corresponding height difference on the y-axis.

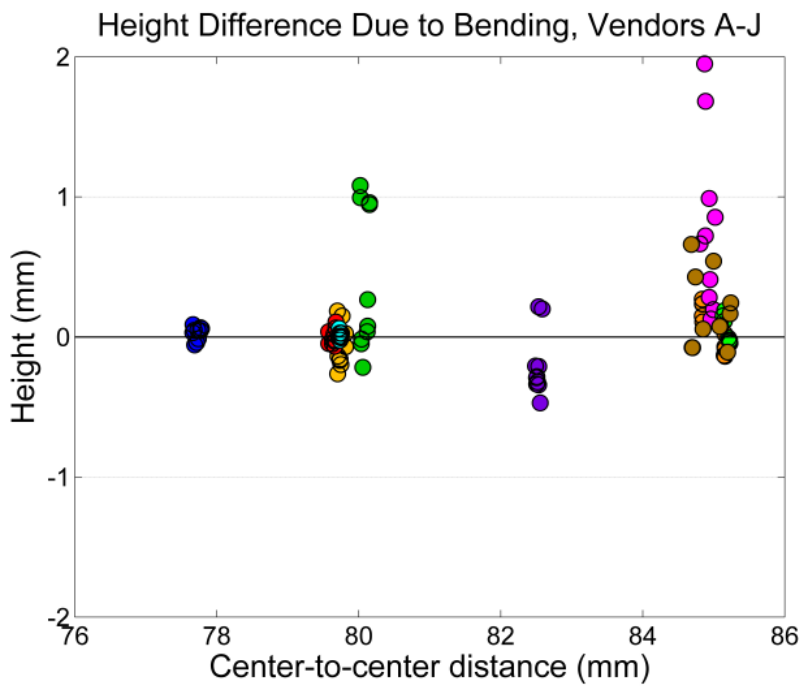
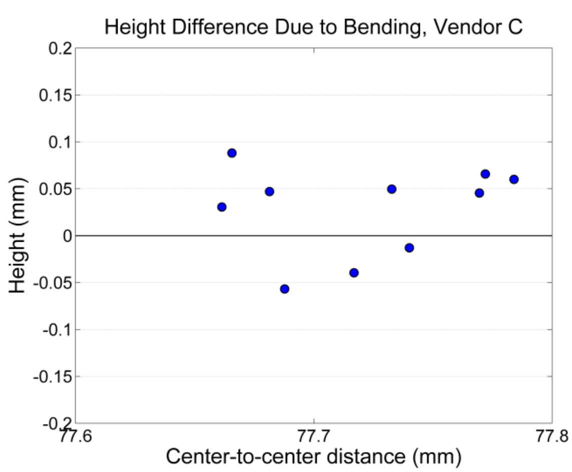
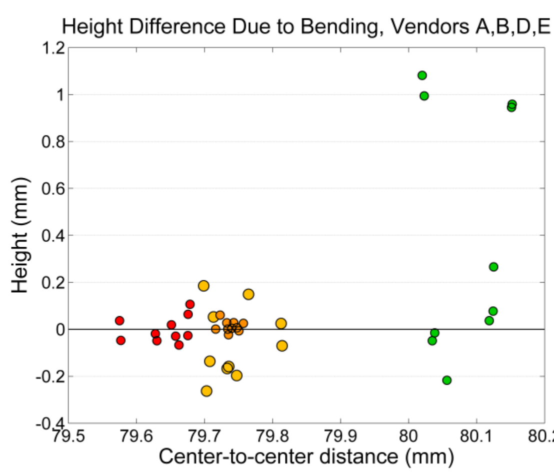


Figure 30: Measured height difference due to bending over the center-to-center distance between circles.

The bending varies significantly among vendors. To remove confusion, we plot each cluster of data points separately (Figure 31). Please note that each graph has different scales for both the x- and y-axes.





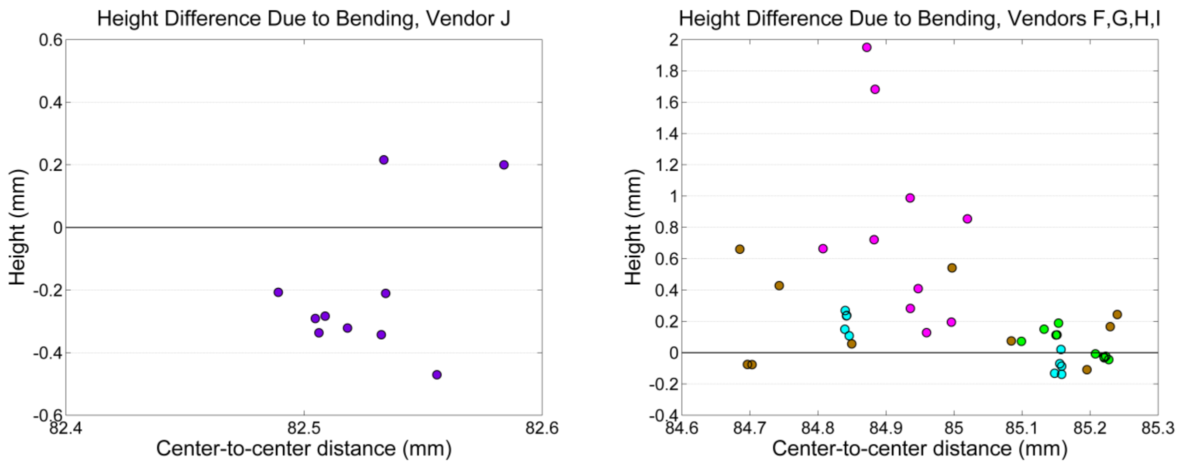


Figure 31: Clustered data points for height difference are isolated to provide more detail. It should be noted that the plots present varying x- and y- scales.

We notice that the largest bending occurs at nearly 2mm height difference over an 84.9 mm center-to-center length segment. To determine the impact of bending to the length scale, we calculate θ for each ruler. Since the bending is approximated to be linear and the length scale is located along the center-to-center length segment, the angle between graduations is also θ.

So, to calculate the corrected length scale distance between zero and any subsequent centimeter graduation, we will use the following trigonometric relation:

$$\cos\theta = \frac{d_{x,measured}}{d_{x,corrected}};$$

where $d_{x,measured}$ is the length between zero and the x graduation in question as measured by the vision machine, $d_{x,corrected}$ is the corrected length for that segment, and θ is the angle of bending. The geometrical representation of this trigonometric relation is given in Figure 32.

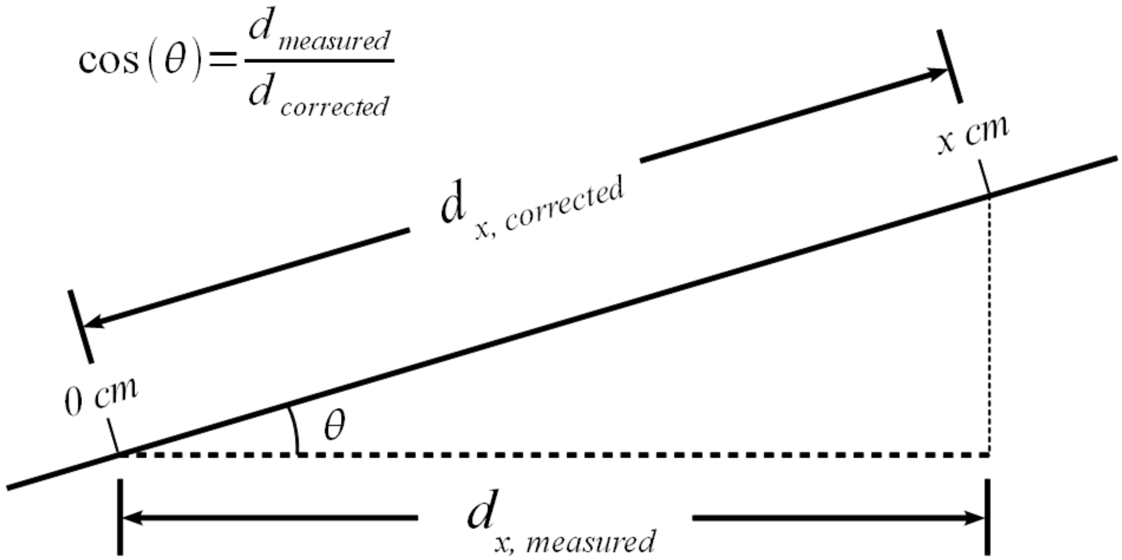


Figure 32: The corrected distance between zero and the x graduation, $d_{x,corrected}$, can be determined using the above trigonometric relation, given the measured distance, $d_{x,measured}$, and the angle of bending, θ.

Since $\cos(\theta)$ is an even function (symmetric about $\theta = 0$), negative values of θ have the same effect on length scale correction as positive values of θ. This allows us to work with absolute values of θ.

Below we present the largest measured bending for each vendor (Table 6). Since the correction is linear along the scale of the ruler, we present the correction to the length scale as a value per centimeter. We also present the correction at the 5 cm graduation as it will be the largest correction.

Vendor	Largest θ (degrees)	Correction per cm (mm)	Correction at 5 cm (mm)	Correction at 5 cm (µm)
A	0.189	5.436×10^{-5}	2.718×10^{-4}	0.272
B	0.077	8.965×10^{-6}	4.482×10^{-5}	0.045
C	0.065	6.419×10^{-6}	3.209×10^{-5}	0.032
D	0.774	9.131×10^{-4}	4.565×10^{-3}	4.565
E	0.044	2.886×10^{-6}	1.443×10^{-5}	0.014
F	0.182	5.034×10^{-5}	2.517×10^{-4}	0.252
G	1.316	2.631×10^{-3}	1.315×10^{-2}	13.153
H	0.127	2.457×10^{-5}	1.228×10^{-4}	0.123
I	0.447	3.037×10^{-4}	1.518×10^{-3}	1.518
J	0.327	1.623×10^{-4}	8.116×10^{-4}	0.816

Table 6: For each vendor, the largest angle of bending is reported, along with its corresponding length scale correction. Due to the linear approximation of bending, the correction is also linear along the length scale. Thus, the correction at the 5 cm graduation is presented since it will be the largest correction along the ruler.

One of the rulers from vendor G exhibited the largest bending at 1.316 degrees (°), which resulted in a maximum correction at the 5 cm graduation of 13.153 µm. We note that this is almost 38 times smaller than the specified length scale tolerance (0.5 mm at the 5 cm graduation). Therefore, when considering the errors from feature print quality, the error from the ruler's bending is negligible.

IV. Conclusions

The results from each test show that all vendors satisfied the length scale specification as written in the ABFO No. 2 technical note. [11] The measurements of internal and external circle diameters and center-to-center distance demonstrated a lack of adherence to specifications. However, it should be noted that results for each vendor were consistent. The testing for perpendicularity of the two legs showed that more than half of the rulers tested were off from the ABFO No. 2 specification. [12] Furthermore, there was little consistency between rulers of the same vendor. The four-year revisit showed minimal changes in length scale, internal and external circle diameters, and center-to-center distance. Perpendicularity, on the other hand, showed significant change. The surveillance testing at the end of 2011 provided results similar to those produced previously. Also, the effect of bending on length scale was found to be negligible.

a) Current industry standards

NIST publishes Handbook 44[13] that establishes “specifications, tolerances, and other technical requirements… for official promulgation in and use by the states in exercising their control of commercial weighing and measuring apparatus.” The specifications indicate the minimum accuracy needed to make measurements for buying and selling products. A large portion of the document deals with weighing devices as weight measurements are dominant in commerce. There are also specifications for accuracy of gasoline pumps, taxi odometers, and, more relevantly, instruments to measure length. Section 5.52 defines the minimum accuracy for length measurements by rule or tape.

Under Section 5.52 *Linear Measures*, part T.1. *For Measures Except Metal Tapes:*

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[11] ± 1% (for each centimeter graduation)

[12] 90° ± 2 arcminutes

[13] National Institute of Standards and Technology Handbook 44, 2012 Edition, “Specifications, Tolerances and Other Technical Requirements for Weighing and Measuring Devices”, as adopted by the 96th National Conference on Weights and Measures 2011

“Maintenance tolerances in excess and in deficiency for measures except metal tapes shall be as shown in Table 1: Maintenance Tolerances, in Excess and in Deficiency, for Linear Measures Except Metal Tapes. Acceptance tolerances shall be one-half the maintenance tolerances.”

Table 1. Maintenance Tolerances, in Excess and in Deficiency, for Linear Measures Except Metal Tapes	
Nominal Interval from Zero	**Tolerance**
feet	**inch**
½ or less	1/64
1	1/32
2	1/16
3	3/32
4	1/8
5	5/32
6	3/16

Table 7: “Table 1” from NIST Handbook 44, Section 5.52, Part T.1 provides minimum accuracy requirements for length measurements by rule or tape. The first row is highlighted as it covers the length range of length scales in this study. Note that acceptance tolerances are given to be one half the maintenance tolerances.

It should be noted that, in many standards and specifications, including NIST Handbook 44, it is common to have two tolerances: acceptance and maintenance. The maintenance tolerance is larger and reflects the general assumption that rulers can wear, which can cause slight length changes. This is most often caused by damage to the scale marking lines.

We look to the tolerance for rulers with a nominal length of ½ feet or less, which is 1/64 inch. Since this value reflects the maintenance tolerance, we will take half of it to be the acceptance tolerance, or 1/128 inch. We compare this tolerance with the ABFO No. 2 tolerance in Table 8 below. The values are presented as a percentage of nominal length.

Acceptance Tolerances NIST Handbook 44 and ABFO No. 2	
Specification	**Acceptance Tolerance (%)**
NIST Handbook 44	0.13
ABFO No. 2	1.00

Table 8: The ABFO No. 2 acceptance tolerance is compared to that from Handbook 44. Tolerance values are presented as percentages of nominal length.

We see that the ABFO No. 2 tolerance is considerably higher (by a factor of 7) than that of the ordinary ruler used in 'legal for trade' as established by Handbook 44. However, we also note that most of the rulers tested in this study maintained their error from nominal to within 0.2% (0.1 mm) at the 5 centimeter graduation. The worst case exhibited an error within 0.4% (0.2 mm) over the same nominal distance.

Another industry standard is one set forth by the International Organization of Legal Metrology. The OIML R 35 – 1 '*Material measures of length for general use'* is one of several "international recommendations which are model regulations that establish the metrological characteristics required of certain measuring instruments and which specify methods and equipment for checking their conformity."[14]

Under Section II - *Metrological Requirements,* Part 4.2 *Maximum permissible error on initial verification, under rated operating conditions:*

" 4.2.1 The maximum permissible error on initial verification, positive or negative,

a) for the nominal length, and
b) for any other distance between any two non-consecutive scale marks,

is expressed by the formula:

$$a + bL \ mm,$$

where: L is the value of the length in question, rounded up to the nearest whole

[14] OIML (International Organization of Legal Metrology) R-35-1, *Material Measures of Length for General Use*, Edition 2007 (E)

number of metres, a and b are coefficients the values of which are given, for each accuracy class, in Table 1."

Accuracy class	*a*	*b*
I	0.1	0.1
II	0.3	0.2
III	0.6	0.4

Table 9: "Table 1" from OIML R 35 - 1, Section II, Part 4.2 provides coefficient values for the calculation of maximum permissible error under several accuracy classes. The coefficients are used in the formula $a + bL \ \ mm$, where L is in meters, for any two non-consecutive graduations (or "scale marks").

We examined what the acceptance ("initial verification") tolerances would be under OIML R 35 - 1 for the 5 centimeter graduation (Table 10).

Acceptance Tolerances at 5 cm (OIML R 35 - 1)	
Accuracy Class	**Acceptance Tolerance (mm)**
I	0.2
II	0.5
III	1.0

Table 10: The OIML R 35 - 1 acceptance tolerances are calculated at the 5 cm graduation for each accuracy class.

We compared the acceptance tolerances at 5 cm with the ABFO No. 2 tolerance. The values are presented as a percentage of nominal length (Table 11).

Acceptance Tolerances at 5 cm OIML R 35 – 1 and ABFO No. 2	
Specification	**Acceptance Tolerance (%)**
Accuracy I	0.4
Accuracy II	1.0
Accuracy III	2.0
ABFO No. 2	1.0

Table 11: The ABFO No. 2 acceptance tolerance is compared to tolerances at 5 cm for each accuracy class in OIML R 35 -1. Tolerance values are presented as a percentage of nominal length.

The ABFO No. 2 tolerance is equivalent to the OIML R 35 - 1 accuracy class II tolerance. However, remember that most of the rulers tested maintained their error from nominal to within 0.1 mm (0.2%) at the 5 centimeter graduation, while the worst exhibited an error within 0.2 mm (0.4%) over the same nominal distance.

b) Suggestions for a forensic photo scale standard

The required accuracy of a ruler depends on the needs of its users, in this case the forensic examiner, and the practical ability of the rulers to be calibrated. Our knowledge of the first question is not great enough to make useful suggestions, but we do have adequate information for the second requirement, the practical uncertainty involved with ruler calibration and use.

The unaided human eye can generally resolve a misalignment between a master scale and a test scale of 0.1 mm or better.[15] We observed that the least expensive of machinist rules that we tested had length scale errors of less than 0.1 mm for nominal length graduations up to approximately 300 mm. We revisit the data for the accuracy of length scales on steel rulers (Figure 34).

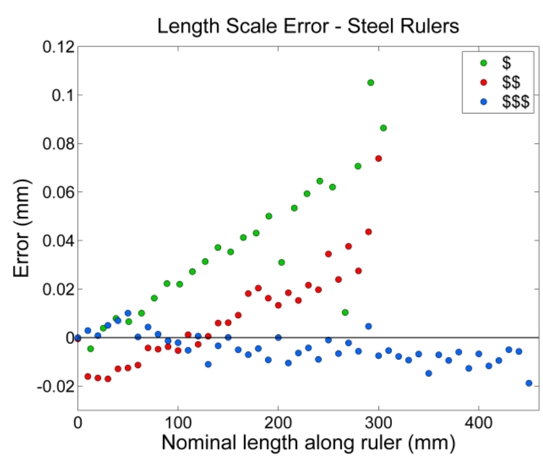

Figure 34: This graph shows the errors of the markings for three different steel rulers of different quality that shows a more expensive ruler is, in fact, likely to be more accurate.

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[15] Tomita, Y. and Honda, S., "Experimental evaluation of instrument scale readings obtained by eye interpolation of fractional interval values," Measurement, Vol. 13, Issue No. 2, April 1994, pp. 147-151.

It is clear that having a master rule with the marks within 0.1 mm of their nominal position is a reasonable requirement. There are also a number of accredited laboratories that can calibrate these master rules to the required accuracy.

Plastic scales, however, cannot be expected to hold this accuracy in actual use. While the samples we measured showed reasonable stability over time, the thermal expansion coefficient is large enough to cause errors of 0.1 mm for a 100 mm scale over typical outdoor temperatures (0° C to 40° C).

From these factors and our ruler measurements, it appears that a reasonable expectation would be that at 20° C any two marks should be within the following tolerance of the nominal distance:

$$Tolerance = \ 0.1 + 0.2L \ \ mm, where\ L\ is\ the\ nominal\ distance\ in\ meters$$

The second issue is the availability of accredited calibration labs. A survey of labs that calibrate rulers is given in the next graph, which shows the length dependent part of the uncertainty. The tolerances from different Standards are shown below (Figure 34).

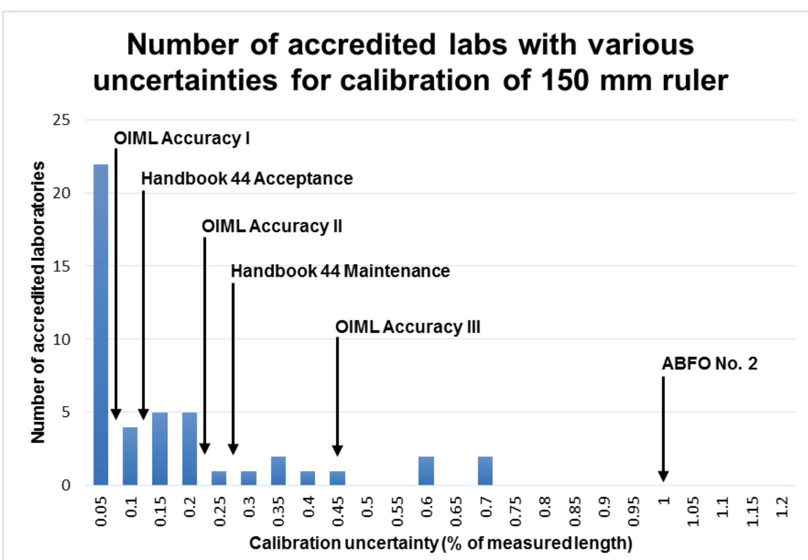


Figure 34: This histogram shows the number of accredited laboratories in the US with various levels of uncertainty for calibration of 150 mm (~ ½ foot) length scales. We overlay the tolerances from NIST Handbook 44, OIML R 35 – 1, and ABFO No. 2.

This shows that there are commercial alternatives to NIST for calibration, which would have large savings in time and cost. It also shows that the tolerances from a current standard could be used to simplify a standard for forensic photography scales.

The bulk of a new standard could be used to better define the materials allowed for scales, criteria for the dimensions and legibility of markings, and optimizing targets for photography.

V. Notes

Note 1: The ABFO No. 2 technical note also provides specifications for width of legs and reflectance values of grayscale feature. These features were not considered for this study as they were deemed not quantitatively significant.

Note 2: The ABFO No. 2 technical note gives two conflicting specifications regarding the external diameter of the circles:

In the third page of the technical note *The Bite Mark Standard Reference Scale – ABFO No. 2*, under the section titled *Scale Development*, it reads:

> "Three circles, each 20 mm in diameter, are included on the scale."

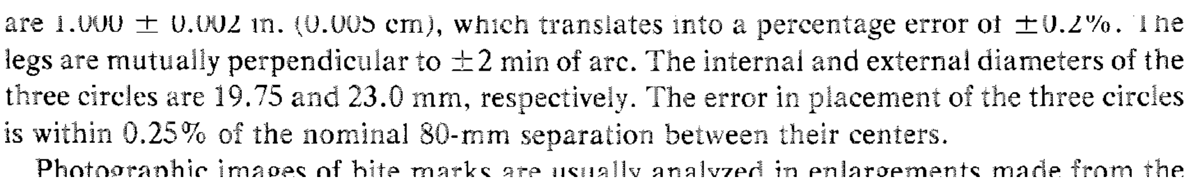
The excerpt is shown below as a cut from the digital file.

legs of the scale are 1 in. (2.54 cm) in width. The 80-mm length of the inner edges of both legs is considered adequate for use in all but unusually large bite marks. Three circles, each 20 mm in diameter, are included on the scale. These are considered large enough for precise work under practical conditions of use for purposes of image rectification and measurement.

While, on the fifth page of the technical note, under the section titled *Analytical Considerations and Techniques*, it reads:

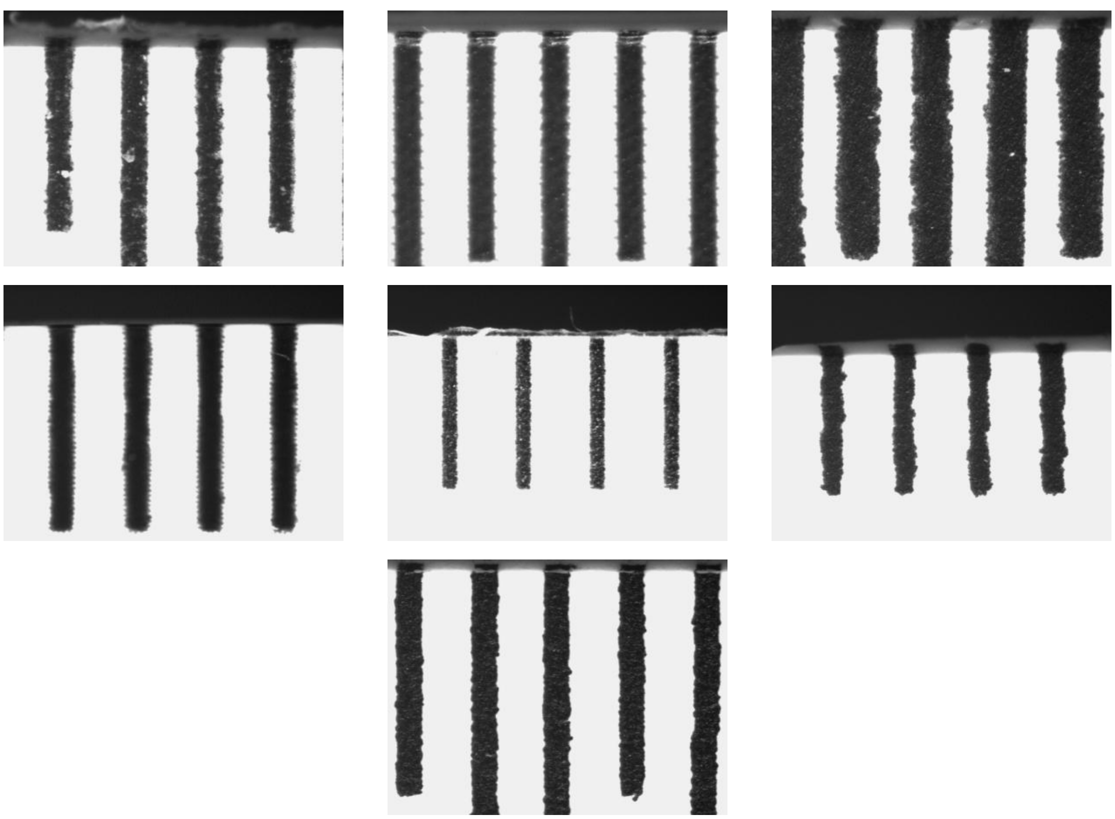
“The internal and external diameters of the three circles are 19.75 and 23.0 mm, respectively.”

The excerpt is shown below as a cut from the digital file.


are 1.000 ± 0.002 in. (0.005 cm), which translates into a percentage error of ±0.2%. The legs are mutually perpendicular to ±2 min of arc. The internal and external diameters of the three circles are 19.75 and 23.0 mm, respectively. The error in placement of the three circles is within 0.25% of the nominal 80-mm separation between their centers.

Photographic images of bite marks are usually analyzed in enlargements made from the

Note 3: More examples of the variation in print quality among rulers.



Disclaimer:

Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.