# Evaluation of resolution and periodic errors of a flatbed scanner used for digitizing spectroscopic photographic plates

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**We evaluated the use of a commercial flatbed scanner for digitizing photographic plates used for spectroscopy. The scanner has a bed size of 420 mm by 310 mm and a pixel size of about 0.0106 mm. Our tests show that the closest line pairs that can be resolved with the scanner are 0.024 mm apart, only slightly larger than the Nyquist resolution of 0.021 mm expected by the 0.0106 mm pixel size. We measured periodic errors in the scanner using both a calibrated length scale and a photographic plate. We find no noticeable periodic errors in the direction parallel to the linear detector in the scanner, but errors with an amplitude of 0.03 mm to 0.05 mm in the direction perpendicular to the detector. We conclude that large periodic errors in measurements of spectroscopic plates using flatbed scanners can be eliminated by scanning the plates with the dispersion direction parallel to the linear detector by placing the plate along the short side of the scanner.**



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## 1. INTRODUCTION

There is a vast collection of photographic plates at atomic and molecular spectroscopy laboratories around the world, with the National Institute of Standards and Technology (NIST) housing thousands. These plates are spread around the world, they are not easily accessible and many of them have not been fully utilized. For example, spectra are frequently taken at several different conditions in order to identify which spectral lines are from a particular ionization stage, but only spectra containing the ionization stage of interest are analyzed. Subsequent work on other ionization stages could make use of the same plates using the spectra taken at other conditions if the plates were made available in digital form. Digitally-available data would also make it possible to reproduce results of a published report, which is not otherwise achievable without access to the photographic plates and a measuring machine.

Similar problems also exist at many astronomical institutions with large collections of wide field astronomical plates. In some cases, like that of the Harvard Astronomical Plate Collection, these collections number hundreds of thousands of plates. In order to digitize them in a timely manner, a significant effort has been dedicated to the construction of a custom scanner. The DASCH project is an effort to scan the Harvard Plate Collection in order to preserve them and enable them to be used to investigate temporal variations in astronomical objects over the last 100 years [1]. While it would be desirable to construct a similar scanner for digitizing spectroscopic plates, this is beyond the capabilities and budget of many the spectroscopy laboratories around the world with significant collections of plates.

The requirements for scanners for spectroscopic plates are somewhat different to those for wide field astronomical plates and typical uses of commercial scanners. Commercial scanners require high resolution for digitization of large format films and a color scan rather than the monochromatic scan required by scientific plates. The absolute position and photometric accuracy is less important. The dimensional accuracy of commercial scanners was investigated by Jones et al. [2] using a precision glass scale. They found that the position accuracy depended on the scan direction, with periodic variations of about 1 % in the direction perpendicular to the scan head. In digitizing

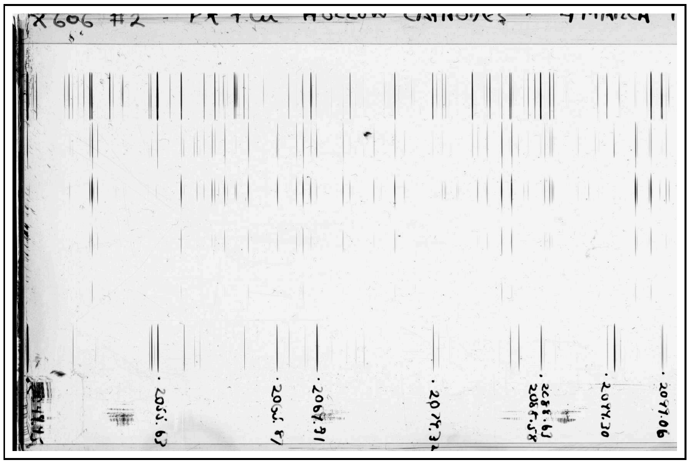

**Fig. 1.** Section of a spectroscopic plate taken with the NIST normal incidence spectrograph, showing two tracks of a Cu/Pt/Ne hollow cathode lamp (top), three tracks of a Pt/Ne hollow cathode lamp (middle), and one of a Cu/He hollow cathode lamp.

wide field astronomical plates, an uncertainty in the position of a few $\mu$m is essential for astrometric measurements. Good two-dimensional photometric accuracy is important for measurements of variable stars over the 100+ year timescale available for the photographic plates. Spectroscopy has the intermediate requirement that an uncertainty in the position of the order of 0.001 mm is required in the dispersion direction, but a larger uncertainty is acceptable perpendicular to the dispersion direction. The spectroscopic plates used most commonly at NIST have a high vacuum ultraviolet sensitivity and low dynamic range, and therefore are not usable for accurate photometric measurements.

### A. Previous methods for analysis of spectroscopic plates

The majority of the photographic plates housed at NIST are 50 mm wide and 457 mm long and contain several tracks of the spectra taken at different conditions or wavelength regions. An example is shown in Fig. 1.

The main objective in analyzing such a plate is to measure the position and approximate density of the spectral lines and to calibrate the position using known wavelength standards. Until recently this was done using a rotating prism comparator (see [3], where a full description can be found). In this instrument, the image of a section of the spectrum is displayed on a screen and is also sent through a slit to a photomultiplier attached to an oscilloscope. A rotating prism in front of the slit sweeps the image of the spectrum along the slit, so that the oscilloscope displays a trace of a small section of the spectrum together with its mirror image. The angle of the slit is adjusted to be parallel to the images of the spectral lines by observing the trace on the oscilloscope. The width and height can also be adjusted to optimize the resolution and the signal. The plate is moved using a precision lead screw until the scan of a spectral line and its mirror image coincide. The position of the plate is then recorded with a rotary encoder attached to the lead screw. Since this process is somewhat time-consuming, it is usual to measure only the spectra of most interest and as a result there are many spectra recorded on archival plates that have never been analyzed in this way. In addition, no permanent digital record of the plate is produced, only the measurements of the positions of the spectral lines.

Wavelength calibration of the spectra may be done either using intrinsic standards or wavelength standards from the spectrum of a well-known calibration source on an adjacent track. From there, a correction polynomial is calculated using the standards and that polynomial is then applied to the uncalibrated spectrum. If the standards were on an adjacent track a small shift or linear correction is also needed to account for any lateral displacement or tilt in the plate as it was moved vertically between tracks in the spectrograph. Since the polynomial is being used to obtain the dispersion of the spectrum, long-range errors in the measurement of the position of a spectral line on the plate are unimportant as they simply become one of the terms in the polynomial. Short-range periodic errors, however, would prevent an accurate dispersion from being obtained as they cannot be approximated by a polynomial. The comparator that is used at NIST has periodic errors of less than 0.001 mm and any scanner used to replace it would either need a similar accuracy, or be able to acheive such accuracy in software.

### B. Requirements for digitizing spectroscopic plates

The ideal scanner for digitizing photographic plates would have a sufficient size to cover the whole plate, a resolution sufficient to resolve the smallest features on the plate in at least one scan axis, and no significant periodic errors in the scanning mechanism. The plates range in size from 50 mm (2 in) to 102 mm (4 in) in width and 254 mm (10 in) to 457 mm (18 in) in length, with the majority being 50 mm by 457 mm. The minimum linewidth on these plates is determined by the slit size used with the spectrographs and could be as low as 0.01 mm for the NIST normal incidence spectrograph (NIVS). However, the majority of the plates were taken with 0.02 mm or larger slits. Therefore, the images on the plates are usually at least 0.02 mm wide. This implies that any potential scanner would require a pixel size of less than 0.007 mm in at least one dimension in order for the position to be determined accurately. In the other dimension the pixel size could be larger and by using many pixels along the length of the spectral line it would be possible to make more detailed analysis of line intensity variations across the slit image. With these specifications, an ideal scanner would be able to record plates up to 460 mm long and 100 mm wide with a resolution of 0.007 mm or smaller. There should be no periodic errors greater than about 0.001 mm in the scanning mechanism that could distort the wavelength scale. Unfortunately, no such scanner is currently commercially available.

A typical commercial flatbed scanner used for transparencies illuminates the photographic film or plate with a light source in the lid of the scanner. A linear charged-coupling device (CCD) detector and lens system images the width of the bed, or some smaller width at higher resolution, and moves underneath the plate recording its transmission. The resulting scans of plates from this type of scanner can be expected to have different position errors, depending on the direction the plate is placed on the scanning bed. Periodic errors are commonly observed whenever a rotary motor moves an object linearly through a rotary motion to linear motion mechanism. These errors are determined by the mechanism used to map the position and velocity of the moving object - in this case, the scan head. For example, if the scan head were moved by a belt drive, periodic errors may occur at a period corresponding to the circumference of the gears in the drive.

These periodic errors have in the past been compensated for using an external scale. For example, Meftah et al [4] scanned a photographic plate together with a precision ruler with markings every 1mm. They interpolated the position between the scale markings and used it to measure the position of the lines on the photographic plate. Although they do not give an estimate of the uncertainty of this interpolation, their overall uncertainty of $5\times10^{-4}$ nm in the wavelength of an isolated spectral line would require the positions of the lines to be determined to 0.019 mm, using their dispersion of 0.026 nm/mm.

An alternate way of using the scanner can eliminate these periodic errors by placing the direction of dispersion of the spectrum parallel to the detector in the scanner. In this case, the position errors are determined by the uniformity pixels in the detection system. These errors are less likely to be periodic, are likely to be very small, and are fixed.

This paper describes our evaluation of a commercial scanner in order to determine its suitability for the digitizing of spectroscopic plates, placing the plates in both orientations on the scanner bed. This scanner used, an Epson Expression XL11000 [5], has an optical resolution of about 0.0106 mm (2400 pixels per inch), an adapter for scanning transparencies, and a scanner bed measuring 420 mm (16.5 in) long and 310 mm (12.2 in) wide. A 50 mm by 457 mm plate thus needs to be digitized in two scans. Each scan takes about 5 min for a 50 mm by 300 mm scan with the plate placed parallel to the detector, and 8 min for a 50 mm by 420 mm scan with the plate placed perpendicular to the detector. A focus system will allow plates slightly above the scanner bed to be focused, so it is possible to image the plates without them touching the scanner glass. We investigated the resolution and periodic errors in the scanning mechanism that affect the accuracy of the digitization. We find that while periodic errors are too large in the direction perpendicular to the scan head for the scans to be useful for digitizing spectroscopic plates, the periodic errors are less than 0.001 mm if the plates are placed parallel to the scan head. Although the study is done for only one scanner the findings are likely to be applicable to other high-resolution scanners.

## 2. EXPERIMENTAL METHOD

In order to evaluate the position errors in the scanner, tests were done with both a calibrated scale and an actual photographic plate taken from our plate collection. The actual scanner resolution was determined using a test target.

### A. Resolution test

The optical resolution of the scanner used was listed as 94.5 pixels per mm (2400 pixels per inch), determined by the pixel size of the detector and the optical system used to image the plate onto the detector. If this is the true resolution, the Nyquist sampling condition would thus imply that lines separated by 0.021 mm could be resolved. However, the resolution acheived in practice is frequently larger than the pixel size for commercial scanners. To determine the actual resolution of the scanner we scanned a USAF-1951 test target and examined the image. The closest line pairs that were visibly resolved on the image of the target had a separation of 0.0248 mm (group 5, element 3 on the target, corresponding to 40.3 lines/mm) in the direction parallel to the sensor, and 0.0221 mm (group 5, element 4 on the target, corresponding to 45.3 lines/mm) in the direction perpendicular to the sensor. We compared this to a measurement of the same target with the rotating prism comparator described in section A, using typical settings used in the measurement of photographic plates of spectra with narrow lines. The closest line pairs that were resolvable with the comparator had a separation of 0.0156 mm (group 6, element 1, corresponding to 64 lines/mm). We conclude that while the resolution of the scanner is slightly poorer than the rotating prism comparator, it is still sufficient to resolve the majority of the close line pairs recorded on spectroscopic plates.

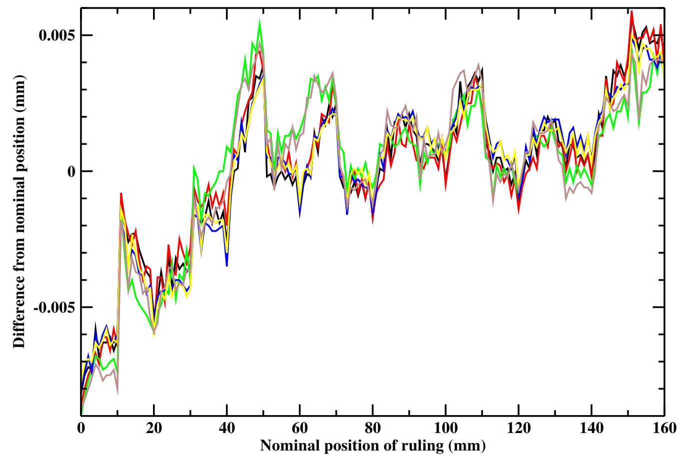


**Fig. 2.** Calibration of the scale used for investigating the accuracy of the commercial scanner. Six scans of the scale were taken at different positions along the markings using a coordinate measuring machine calibrated with an external laser displacement system.

### B. Scanner tests with calibrated scale

The calibrated scale was 160 mm long with markings every 1 mm. Each marking had a width of about 0.07 mm and length of about 3.5 mm. The scale was calibrated by Dr T. Doiron (NIST Dimensional Metrology Group) at 6 different positions across the length of the markings with a video sensor coordinate measuring machine calibrated with an external laser displacement system. This calibration is shown in Fig.2. The calibration shows both a long-range error of up to 0.008 mm that can be approximated by a polynomial, and a shorter range error of about 0.003 mm with a period of about 20 mm. To confirm that this shorter range error was in the scale rather than the measurement we measured the scale on the rotating prism comparator described in section A. Figure 3 shows the difference between the measurement by the comparator and the mean of the 6 values from the coordinate measuring machine. A linear trend is seen in the difference between the two measurements. This could possibly be due to a difference in temperature between the two measurements resulting in a change in length of either the scale or the leadscrew. This type of error is not significant in the measurement of an actual photographic plate, as a polynomial would be fitted to wavelength standards across the photographic plate in order to obtain a final calibration. When the linear trend seen in the plot is subtracted from the difference, no periodic error is seen and the standard deviation is 0.001 mm. We conclude that the calibrated scale can be used to determine the accuracy of the commercial scanner with an uncertainty of 0.001 mm and that the rotating prism comparator has a similar uncertainty.

The scale was aligned on the scanner bed in two directions as shown in Fig. 4: parallel to the short side and CCD detector ('vertically' hereafter) and parallel to the long side ('hori-

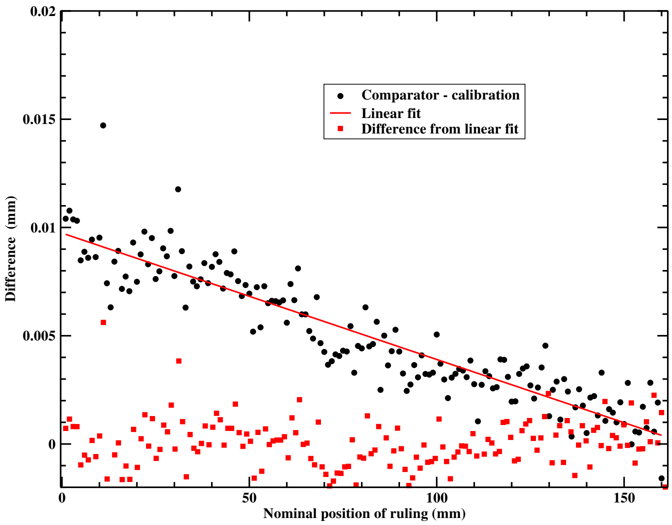


**Fig. 3.** Calibration of the scale used for investigating the accuracy of the commercial scanner.

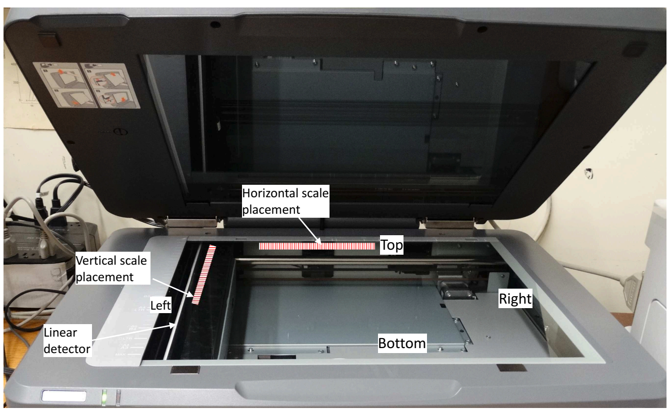


**Fig. 4.** Photo of scanner bed showing placement of scale in vertical and horizontal positions.

zontally' hereafter, perpendicular to the CCD detector). A custom guide ensured the scale was placed reproducibly parallel to each side. This guide ensured that a small section of the glass along the edge of the bed was exposed to allow the scanner to measure the intensity of the light source. A preview scan then allows for a section of the bed including the scale to be selected and focused. The section scanned included the full size of the scale for both the horizontal and vertical placement. The scan of the scale is saved in tagged image file format (TIFF). This image is integrated along the full height of the markings in order to obtain a plot of the integrated transmission of the scale at each position along its length. The positions of the markings are found using the program Xgremlin [6], which we frequently use for analysis of our grating spectra. The results are compared to the mean of the six measurements of the positions obtained from the NIST coordinate measuring machine.

Figure 5 shows the results from two scans with the calibrated scale placed vertically on the left side of the scanner bed, one with the scale pushed to the top of the bed and the other with the scale pushed to the bottom of the bed. The top panel shows that the difference across the scanner bed is smooth and can be fitted with a 5th order polynomial, similar to the polynomial

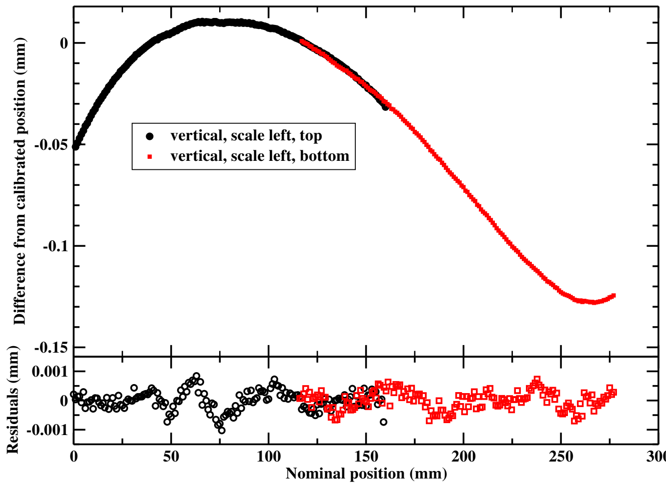


**Fig. 5.** Results for 2 scans of the calibrated scale placed vertically, with the scale pushed to the top of the bed (black circles) and with the scale pushed to the bottom of the bed (red squares). The top panel shows the difference between the scanned position of the markings and the calibration. The bottom panel shows the residuals for each scan after fitting a 5th order polynomial to the differences in the top panel.

that would be used to calibrate a photographic plate measured with our rotating prism comparator. The residuals after fitting this polynomial are in the bottom panel and have a standard deviation of 0.0003 mm. Similar results were obtained with repeated measurements at different horizontal positions on the scanner bed.

Figure 6 shows the results for six scans of the calibrated scale, this time placed horizontally on the scanner bed. The top panel shows three scans with the scale placed at different positions against the top of the bed, and the bottom panel shows similar scans with the scale placed against the bottom of the scanner bed. There is a clear periodic error in the scanned position, with a period of about 50 mm and an amplitude of between 0.03 mm and 0.05 mm. It appears to correspond to the pulley in the belt drive system used to move the detector system, visible in Fig 4. just below the word 'Top'. Comparison of the scans taken at the top of the bed and the bottom of the bed shows that the shape of this periodic error is reproducible, suggesting it would be possible to reduce it by scanning a calibrated scale along with a photographic plate of interest. However, the size of the periodic error means that it would be difficult to obtain a similar accuracy in the positions using this method to that obtained by placing the plate vertically on the scanner bed.

### C. Scanner tests with photographic plate

The next test used the photographic plate from the NIST archives (exposure x606, plate 2, taken on 7th March, 1983) shown in Fig. 1. This plate was used in the NIST atlas of the spectrum of a platinum/neon reference lamp and full details of the experiment are given in [7]. It was selected as it has three tracks of the same spectral region of a platinum-neon hollow cathode lamp taken with different lengths of exposure. The third and fourth tracks from the top of Fig. 1 contain a sufficiently common number of sharp lines of moderate exposure to test the scanner. A custom holder was made to hold the plate vertically and slightly above the bed of the scanner, so that it did not touch either the scanner glass or the lid. This enabled

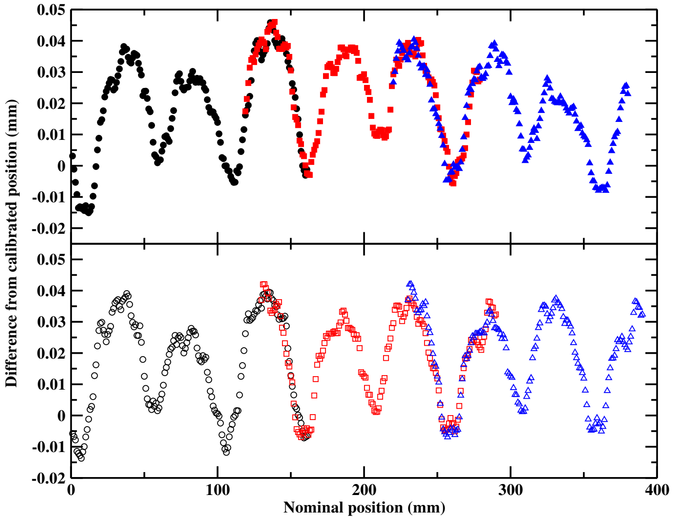


**Fig. 6.** Top panel: Difference between the scanned positions of the marking and the calibrated positions for three scans of the calibrated scale placed at different positions along the top the scanner bed, aligned parallel to the long side of the bed (horizontally). Bottom panel: As top panel, but with the scale along the bottom of the scanner bed.

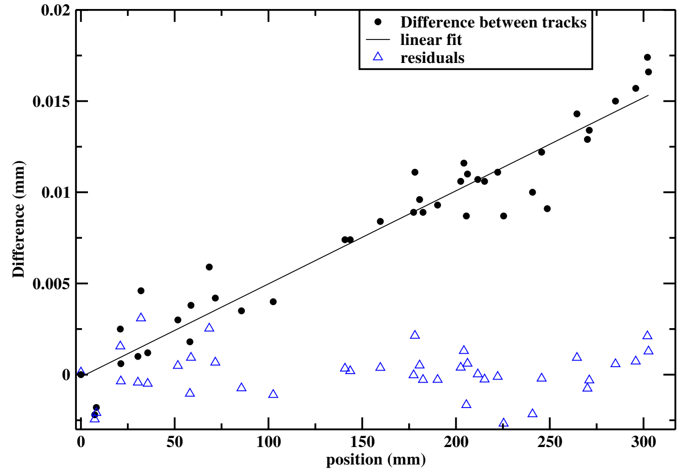


**Fig. 7.** Comparison of positions of the same spectral lines on two adjacent spectra of a sealed platinum-neon hollow cathode lamp run at 20 mA.

it to be scanned across the full width of the scanner bed. The image was processed in the same way as the image of the calibrated scale.

Figure 7 shows a comparison of the positions of spectral lines from these tracks. There is a linear dependence on the difference between the positions on the two tracks as a function of the position. This difference is present on the photographic plate and is caused by a slight tilt in the plate holder when it is moved from one position to the other. When this linear dependence is removed, the residuals have a standard deviation of 0.0014 mm. This is similar to the uncertainty obtained in scanning the plate with a comparator.

The final test was to confirm that it is possible to calibrate a spectrum using known wavelengths standards. Figure 8 shows the calibration of the spectrum of a Pt/Ne lamp on the 3rd track from the top in Fig. 1, scanned with the plate placed vertically on the scanner bed. A linear dispersion was applied in order to obtain an approximate wavelength scale that was used to identify the spectral lines. The top panel shows the difference between the wavelengths from this linear scale and the wavelengths from the NIST platinum atlas [7]. The deviation from a linear dispersion here includes both errors from the scanner and from the spectrograph. These differences were then fitted with an 8th order polynomial in order to obtain the final dispersion curve, similar to the polynomial used to calibrate spectra measured using the comparator described in section A. The residuals from this fit are shown in the lower panel of Fig. 8 and have a standard deviation of $10^{-4}$ nm, similar to the uncertainties obtained for a comparable measurement made using the comparator. This confirms that it is possible to obtain accurate wavelengths from the scanner if the plate is placed vertically on the scanner bed.

## 3. DISCUSSION

The similarity of the measured errors in the scanned positions between the top and the bottom panel of Fig. 6 suggests that it should in principle be possible to correct for the periodic error in scans with the plate placed horizontally. This is similar to the technique used by Meftah et al. [4]. Subtracting the two plots in Fig 6 gives errors with a standard deviation of 0.004 mm, over an order of magnitude greater than the errors shown in Fig 5. With fewer reference points available from a typical atomic spectrum this uncertainty is likely to increase.

The main deficiency of the scanner we used is the size of scanner bed, which is unable to digitize the full size of the 457 mm long plates that are the majority of our archive when the plates are placed vertically. Two scans of the plate are thus needed to cover digitize the whole plate, with an overlap of about 160 mm. For most of our spectra there are sufficient wavelength standards to ensure an adequate calibration but this may be a limitation if the scanner used has a smaller bed that cannot scan the plates with a large overlap. By utilizing the full length of the scanner of 418 mm, it would be possible to scan up to 8 of our 50 mm by 457 mm plates at once. Each scan would then take about 45 min and result in a file roughly 2 Gb in size using our scanner.

By scanning the photographic plate rather than measuring the line positions using a comparator it is possible to perform a more sophisticated analysis of the spectrum. In our tests, we integrated the spectrum over the full height of the image on the plate. If the spectral lines are slightly tilted with respect to the pixels this would result in a small broadening of the lines and loss of resolution. This would be reduced by integrating over several smaller sections of the image and aligning the images separately. Some of the light sources used to produce spectra for our plates produce spectral lines that vary in intensity along the image. For the case of our sliding spark source this variation can give valuable information about the ionization of the atom emitting the line. A scan of the plate preserves this information for use in spectral analysis, where it can be used to distinguish all the lines emitted from a specific ionization.

## 4. CONCLUSIONS

Our measurements show that the large periodic errors in previous measurements of spectroscopic plates using flatbed scanners can be eliminated by scanning the plates with the dispersion direction parallel to the linear detector by placing the plate

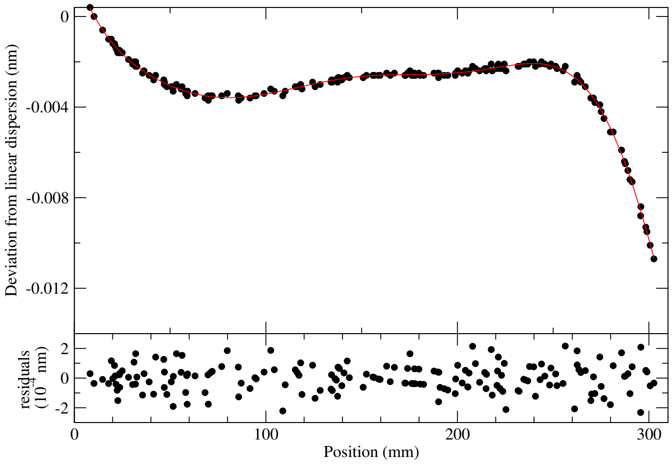


**Fig. 8.** Calibration of one of the spectra on the same plate as Fig. 7 using platinum wavelength standards. The top panel shows the wavelength difference between a linear dispersion and the standards (points), with the red line an 8th order polynomial fit to the difference. The bottom panel shows the residuals after subtracting this polynomial from the data.

along the short side of the scanner. Periodic errors in this direction are less than 0.001 mm, but approach 0.05 mm in the direction perpendicular to the detector, where the plate is imaged by moving the detector underneath the scanner bed. The measured resolution of the scanner is similar to that obtained from the rotating prism comparator that we currently use to measure photographic plates.

Although no currently-available commercial scanner meets all the requirements for digitizing plates, commercial scanners provide an inexpensive and convenient solution for preserving almost all of the key scientific information on the plate. In order to use them for digitizing spectroscopic plates, we recommend that the actual resolution of the scanner is first measured with a resolution test chart, both parallel to and perpendicular to the scanner head. We also recommend that a calibrated scale is scanned in both orientations to ensure that any periodic errors are either negligible or can be adequately corrected.

## ACKNOWLEDGMENTS

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