Investigation of a Multivariate Correction Method for HVI Fibrogram Measurements

Md Abu Sayeed 1,*, Brendan R Kelly 1,2, Christopher Turner 1◊ and Eric F Hequet 1◊

Abstract: Cotton fiber length parameters are used across the cotton industry to select elite germplasm, purchase cotton bales and manage mill throughput. The High Volume Instrument (HVI) provides the most commonly used fiber length parameters, upper half mean length (UHML) and uniformity index (UI). UI is the ratio of mean length (ML) to the UHML expressed as a percentage. These length parameters, UHML and ML, are generated following the fibrograph principle and are highly correlated with two span lengths on the fibrogram curve. These two length parameters represent a small part of the fibrogram and do not characterize the total within-sample variation. In previous studies, we found that fiber length variation captured by the whole fibrogram improves the prediction of yarn quality. However, HVIs are currently calibrated for UHML and UI. In this study, we investigated a correction method using a set of 461 commercial samples to correct the whole fibrogram curve across HVIs and validated the method using an independent set of 932 commercial samples. The correction procedure lowers the Euclidian distance between fibrograms as much as 35%, bringing the fibrogram measurements into agreement across multiple HVIs. This indicates that the whole fibrogram could be used to improve HVI fiber length measurements across the cotton industry.

Keywords: High Volume Instrument (HVI); fiber length distribution; fibrogram; multivariate correction; cotton fiber length; fiber quality measurements

1. Introduction

Every cotton bale produced in the United States is tested for several fiber quality parameters such as micronaire, upper half mean length (UHML), uniformity index (UI), fiber strength, color, and trash in order to determine their best use. These measurements are used throughout the cotton industry for different purposes, such as identifying bales for purchase, determining the proper settings on spinning equipment, and evaluating germplasm in research [1–4]. Mathematical correction techniques are used to provide consistent fiber quality measurement across the cotton industry [5]. For example, many laboratories participate in the Commercial Standardization of Instrument Testing of Cotton (CSITC) round test to make sure cotton fiber quality measurements are comparable across the industry. Any new measurement technique requires developing a correction procedure to be adopted by the industry.

The cotton industry uses cotton fiber length parameters as potential indicators of end-product quality. Breeders focus on improving fiber quality using fiber length and other fiber quality parameters to select superior breeding lines [6–8]. Screening a breeding nursery based on these parameters allows a breeder to develop germplasm with the potential for improved spinning performance [8,9]. Textile mills use fiber length and other fiber quality parameters to select cotton bales that enable them to spin their targeted yarn quality [10].

The importance of fiber length extends beyond the longest fibers in the sample. Within-sample variation in fiber length impacts the quality of the spun yarn [8,11–13].
Excessive short fiber content causes work stoppages and slows mill throughput [6,14–16]. Therefore, measuring the within-sample variation in fiber length is essential for selecting elite breeding lines as well as for mills managing throughput and yarn quality.

High Volume Instrument (HVI) fiber length measurements are based on the fibrograph principle [17], where an HVI comb prepares a fiber beard by catching a sample of fibers randomly along their lengths (Figure 1A,B). After removing extraneous matter and loose fibers through brushing (Figure 1C), the fiber beard is scanned over a red-light beam (Figure 1D) while a sensor positioned above the beard measures the amount of light attenuated by the beard [17–20]. The starting point of the scan is 3.81 mm (0.15 inches) from the edge of the comb [21,22] and determines the total population of fibers to be scanned. The amount of light is maximally attenuated at the starting point, the base of the beard, so the measurement at the start of the scan is normalized to 100%. While the fiber beard is scanned over the light towards the tip of the beard, fewer and fewer fibers are available to be examined. Eventually, the scan reaches a point where no fiber remains to be scanned and no light is blocked, resulting in 0% attenuated light [19,20,23]. Changes in the percentage of light attenuated by the fiber beard from 100% to 0% are recorded by the HVI and used to generate a light attenuation vs. displacement curve called the fibrogram (Figure 2). In this representation, the amount of attenuated light is meant to estimate the percentage of the number of fibers at each point in the beard. The HVI reports two fiber length parameters, UHML and UI, calculated from this curve [17,18]; however, the fibrogram itself is not reported as a standard output of the instrument.

![Figure 1. HVI fiber length measurement method. (A) Samples in the fibrosampler. (B) HVI combs prepare fiber beards by catching samples of fibers randomly along their lengths. (C) Brushing to remove loose fibers and extraneous matter. (D) Scanning the fiber beard over a red-light beam.](image-url)
The fibrogram holds valuable information about the within-sample variation in fiber length that is not currently reported but is needed by the industry [15,23–25]. In addition, the two length parameters presently reported by the HVI do not characterize the total within-sample variation in fiber length captured by other measurement techniques, such as the Advanced Fiber Information System (AFIS) [6,12]. In a previous publication, we demonstrated that the current HVI fiber length parameters are not independent and share 95% of their variation [23]. A principal component analysis of the whole fibrogram curve demonstrated that at least three principal components are required to explain approximately 99% of the total fiber length variation captured by the fibrogram [23]. We also demonstrated that the whole fibrogram could explain yarn quality better than current HVI length parameters and is comparable to the AFIS length distribution by number. This research was performed solely on one HVI at the Texas Tech University (TTU) Fiber and Biopolymer Research Institute (FBRI).

The total fiber length variation captured by the whole fibrogram curve could be very useful for the entire cotton industry. It could be used to identify new fiber length parameters as more than one type of fiber length variation could be characterized [23]. Because these measurements are based on HVI fibrograms and do not require any additional testing, they could provide cotton breeders important fiber length information from the same instrument they are already using—the HVI. Using the fiber length information captured by the whole fibrogram curve, breeders could develop germplasm with improved within-sample variation in fiber length. In addition, short fibers could cause problems with production efficiency and yarn quality in spinning mills [14–16]. Thus, spinning mills could use the information captured by the whole fibrogram, which includes shorter fibers, to optimize their machine setup and mill management throughput. However, the whole fibrogram is not corrected. Therefore, a procedure is needed to correct the fibrogram allowing comparison among fibrograms.

In order to compare this HVI measurement industry-wide, it is important to develop a correction procedure to bring the fibrogram measurements among HVIs to a similar level. There are many different measurements that can be extracted from the fibrogram [18] which could relate to both long and short fibers within the sample. Our goal is not to correct these

![Figure 2. A fibrogram generated by the High Volume Instrument (HVI).](image-url)
individual measurements (or other potential measurements based on the fibrogram) but rather the whole fibrogram. Therefore, in this research, we propose a method for correcting fibrograms so that they are consistent and comparable across multiple HVIs. Furthermore, we validate this protocol on a larger set of independent samples.

2. Materials and Methods

2.1. Establishing the Fibrogram Correction Method

A set of 461 samples from commercial bales covering a wide range of fiber quality characteristics was selected with the goal of identifying samples exhibiting a wide range in fibrogram shape characteristics needed for establishing a correction protocol. Each commercial sample contains at least 100 g of lint. The UHML for this sample set ranges from 23.9 mm to 31.5 mm, and the UI ranges from 77.1% to 85.2% (Table 1). Micronaire, strength, elongation, Rd, and +b also show a wide range of variation. All the samples used in this experiment were conditioned for at least 48 h at 21 ± 1 °C and 65 ± 2% RH prior to HVI testing.

Table 1. Range of HVI fiber quality parameters for the reference set of samples.

| Fiber Quality      | Min  | Ave  | Max  |
|--------------------|------|------|------|
| Mic (no unit)      | 3.24 | 4.67 | 5.44 |
| Strength (g/tex)   | 23.4 | 29.5 | 38.8 |
| Elongation (%)     | 4.30 | 6.69 | 10.20|
| UHML (mm)          | 23.9 | 28.5 | 31.5 |
| UI (%)             | 77.1 | 81.6 | 85.2 |
| Rd (%)             | 56.8 | 77.5 | 83.4 |
| +b (No unit)       | 6.60 | 9.33 | 13.60|

There are two primary sources of variation in this experiment: one is from the samples and the other is between instruments. The goal is to investigate the latter, i.e., whether the differences in fibrograms among HVIs could be reduced. Therefore, to minimize the variation due to the sample, a common research protocol of ten replications of the fibrogram was implemented for these samples, where the average of these 10 replications represents a single sample. This protocol was selected to follow a common HVI 4-4-10 research protocol (4 micronaire measurements, 4 color and trash measurements, and 10 length and strength measurements), which exceeds the commercial cotton classification protocol of 1-2-2 (1 micronaire, 2 color and trash, 2 length and strength).

The fibrogram curve was exported from the HVI Uster software by measuring samples using the HVI length and strength module testing mode. Fibrograms obtained through the module testing reports are vector graphic images, where each curve is represented in the vector file as 81 data points. A MATLAB script was developed to extract the 81 data points representing the fibrogram curve obtained for each replication.

These 81 data points represent values of attenuated optical light over a set of fixed, uniformly spaced lengths from 3.81 mm (0.15 inch) to 54.61 mm (2.15 inch) with a spacing of 0.635 mm (0.025 inch). However, fibrograms are more commonly analyzed by considering lengths associated with specific values of attenuated light—referred to as span lengths or percent span lengths. As such, we transposed the fibrograms from a curve that represents amount of attenuated light versus length to one that presents length versus amount of attenuated light (Figure 3). Using a MATLAB script, we used linear interpolation to calculate lengths associated with the amount of attenuated light expressed as a percentage from 1% to 99% in 1% increments. For the remainder of this work, any mention of a fibrogram is referring to this particular representation.
2.2. Defining Reference Fibrogram Measurements and Correction Domain

There is not an established reference method for the fibrogram measurement. In lieu of a reference method, one of the three HVIs at the TTU FBRI was chosen to provide reference fibrogram measurements. That HVI is henceforth referred to as the “Reference HVI” and the other two HVIs at the FBRI were considered as “Test HVIs” for this experiment.

One way of correcting the fibrogram curve would be to use equations obtained by regression between the reference HVI and the test HVI for each point in the curve. This approach would require 99 independent correction equations and would ignore the collinear nature of the fibrogram curve. In order to facilitate the comparison of the fibrograms across different HVIs, a correction procedure is needed that respects the collinear nature of the length measurements along the fibrogram curve. Thus, the goal is to correct the curve as a whole rather than correcting individual points.

The proposed correction procedure is based on the eigen decomposition of the reference sample set. The method first transforms the fibrogram data into a linear space, where the fibrograms are represented as independent linear variables. A widely implemented method of eigen decomposition is principal component analysis (PCA). Because fewer principal components may summarize a larger set of variables, using PCA also minimizes the number of equations needed to correct the fibrogram as a curve [26].

The correction of the within-sample variation or the shape of the curve occurs in the principal component domain, which we refer to as the correction domain. We then use the loadings of the components in the correction domain to transform all other test sets from the fibrogram domain into the correction domain. PCA was only performed on this initial reference set (461 samples) to establish the correction domain.

2.3. Reference Correction Samples

Let $X_r$ be a $n \times m$ set of data denoting reference samples extracted from the Reference HVI where each column represents a fibrogram and the rows correspond to the 99 span lengths (i.e., $n = 99$). Also, let $P$ be an $n \times n$ orthonormal matrix that solves

$$Y_r = PX_r$$

(1)
such that $\frac{1}{n-1} Y_r Y_r^T$ is diagonal. The rows of $P$ are the principal components of $X_r$ rank-ordered by variance from largest to smallest, and $Y_r$ denotes the reference samples in the principal component domain, which we refer to as the correction domain. Previous research showed that at least three principal components are required to explain 99% of fiber length variation captured by the whole fibrogram curve [23]. Therefore, the first three components of $P$, denoted by $P'$, were considered to correct the fibrogram across HVIs. $P'$ is a $3 \times n$ matrix. Let $Y'_r$ be a be a $3 \times m$ matrix that represents the reference samples, $X_r$, transformed by $P'$ into the correction domain by

$$Y'_r = P'X_r$$

In order to capture the maximum possible range of fiber length variation within the reference set, two extreme samples and one median sample for each of the first three components were selected to provide a total of nine reference correction samples (i.e., $m = 9$). It is important to note that these nine correction samples were not developed following the standard protocol for the development of standard calibration/correction cotton (ASTM 2020). These are just regular commercial samples and may contain more within-sample variation than the USDA standard calibration cotton. In addition to that, they might not cover the total range of fiber length variation represented by all the commercial cotton produced in the US. However, this research aims to investigate whether it is possible to reduce the difference in the fibrogram measurement due to machine differences.

2.4. Correction Equations

Two other HVIs at the FBRI were chosen as Test HVI 1 and Test HVI 2 to establish the correction procedure. The nine samples selected as reference material were measured with each Test HVI for ten replications per sample (Figure 4). Using $P'$, the correction samples data from the Test HVIs were transformed into the correction domain by

$$Y'_i = P'X_i$$

where $X_j$ represents the fibrogram data of the reference samples tested on one of the Test HVIs, $Y'_i$ is the fibrogram data transformed into the correction domain, and the subscript $i$ indicates the Test HVI ($i = 1, 2$). Using least squares regression, we then solved the linear model

$$y'_i = a_i + \beta_i y_i + \epsilon$$

where $y'_i$ and $y_i$ represent a single fibrogram from the Reference HVI and Test HVI transformed to the correction domain, respectively, and coefficients $a_i$ and $\beta_i$ minimize the error, $\epsilon$, in a least squares sense. Here, $a_i$ is a $3 \times 1$ column vector whose values represent the corrective offset corresponding to each principal component, and $\beta_i$ is a $3 \times 3$ diagonal matrix with the diagonal elements representing the corrective slope for each component. Equation (4) is solved for each Test HVI producing two sets of coefficients: $a_1$ and $\beta_1$ corresponding to Test HVI 1 and $a_2$ and $\beta_2$ corresponding to Test HVI 2.

With these coefficients, given a sample fibrogram $x$ (an $n \times 1$ vector) that has been tested on Test HVI $i$, we can calculate a corrected fibrogram, $x_c$, according to

$$x_c = P^T(a'_i + \beta'_iPx)$$

In Equation (5), it is important to note that the full set of principal components, $P$, is used to transform $x$. As such, $a'_i$ is an $n \times 1$ column vector whose first three elements correspond to $a_i$ and the rest are zeros. Likewise, $\beta'_i$ is an $n \times n$ diagonal matrix where the first three diagonal elements correspond to the diagonal elements of $\beta_i$ and the remaining diagonal elements are all one. Essentially what Equation (5) does is transform $x$ into the $n$-dimensional correction domain, apply a linear transformation to only the first three dimensions using coefficients in $a'_i$ and $\beta'_i$, and then transform it back into the original fibrogram space by using the inverse of $P$, i.e., $P^T$ (because $P$ is orthogonal).
2.5. Applying Correction Equations

The selection of nine samples as reference materials left us with a set of 452 samples on which the correction procedure was investigated. After establishing the correction coefficients ($\alpha_1$, $\beta_1$, $\alpha_2$, and $\beta_2$) with the nine reference samples, the set of 452 commercial samples was tested on both the Reference HVI and the Test HVIs using the same testing protocol. The correction Equation (5) was applied to each of the fibrograms obtained from the Test HVIs to produce a set of corrected fibrograms for each of the 452 samples for each Test HVI (Figure 5).

Euclidean distances (ED) of fibrograms between the Reference HVI and Test HVIs before and after correction were calculated as

$$ ED = \sum_{j=1}^{99} \sqrt{(x_j - z_j)^2}, $$

where $x_j$ is the $j$th span length from the Reference HVI fibrogram and $z_j$ is the $j$th span length from the Test HVI fibrogram. Comparing the distances of the Test HVI fibrograms before and after correction to the Reference HVI fibrograms for the same sample provides a measure of efficacy of the correction procedure.
2.6. Validation of the Correction Procedure

Finally, we validated the proposed correction procedure using an independent set of 932 commercial samples. After proper conditioning, samples were measured using the same protocol—10 replications of the fibrogram on the Reference HVI and the Test HVIs. Fibrograms from each HVI were averaged to produce a single fibrogram per sample and instrument. Using the same correction coefficients as before, we then applied the correction Equation (5) to all of the averaged fibrograms from the Test HVIs.

2.7. Reducing the Number of Samples Required for Fibrogram Correction

While the selection of nine reference samples that provide a high, middle, and low value in each of the three components in the correction space is reasonable for a proof of concept, it is impractical when implemented in a laboratory setting. The USDA Agricultural Marketing Service (USDA-AMS) currently develops only two standard calibration cottons following a very robust protocol [27]. Curation of seven additional reference samples following that same protocol may require more time and effort than is practically feasible. Therefore, it is of interest to determine the minimum number of reference samples required to perform the correction procedure effectively.

To that end, the proposed correction procedure was evaluated using sets of two, three, and six samples and compared with the results obtained by using nine reference samples. Each new set of reference samples was selected to cover the maximum possible range of
each component. For each new reference set, the entire correction procedure (including generating new correction coefficients) was carried out using 461 commercial samples—the same set used to define the correction domain and applied on the set of 452 commercial samples. The correction procedure was then validated using the 932 validation samples with each reference set. To evaluate the effectiveness of each minimal set of reference samples, we analyzed the distances between fibrograms for each sample using Equation (6) before and after correction and, then compared the results to the original correction procedure using nine reference cottons.

3. Results and Discussion

3.1. Establishing the Correction Procedure

The reference samples were chosen to exhibit a wide range in multivariate fiber length variation as characterized by the fibrogram measurement. Collectively, the samples form a single cluster in the correction domain as shown in Figures 6 and 7. The correction samples selected from this set to establish a fibrogram correction protocol cover a similar range of each component in the correction domain within the reference samples set. Figure 6 shows the six samples chosen to cover the range of the first two components as red and blue points, while Figure 7 shows the three samples in black that represent the range of values of the third component. Furthermore, these samples also capture a similar range of fiber length variation for the first three components for Test HVI 1 and Test HVI 2 (Table 2). The slopes and offsets of the linear regression between Reference HVI and Test HVIs are used as the correction factors (Table 3). In the equations, X represents the values from the Test HVI and Y represents the values from the Reference HVI.

Figure 6. Scatter plot of the first two components of fibrograms transformed in the correction domain. Red dots cover the range of fiber length variation captured by the first component, blue dots the second component, and black dots the third component.
Figure 7. Scatter plot of the first and third components of fibrograms in the correction domain. Red dots cover the range of fiber length variation captured by the first component, blue dots the second component, and black dots the third component.

Table 2. The range of fiber length variation of 452 commercial samples captured by the first three components are similar among the Reference HVI, Test HVI 1, and Test HVI 2.

| Sample ID | Component 1 | Component 2 | Component 3 |
|-----------|-------------|-------------|-------------|
|           | Ref HVI     | Test HVI 1  | Test HVI 2  |
| Min       | 3.76        | 3.73        | 3.78        |
| Ave       | 4.39        | 4.37        | 4.43        |
| Max       | 4.94        | 4.79        | 4.84        |
| Range     | 1.18        | 1.06        | 1.06        |

Table 3. Correction equations derived by simple linear regression between Test HVI 1 and the Reference HVI as well as between Test HVI 2 and the Reference HVI for the first three components.

| Component | Test HVI 1 | Test HVI 2 |
|-----------|------------|------------|
| 1         | $Y_1 = 1.011X_1 - 0.025$ | $Y_1 = 0.989X_1 - 0.008$ |
| 2         | $Y_2 = 0.855X_2 + 0.009$ | $Y_2 = 1.011X_2 - 0.017$ |
| 3         | $Y_3 = 0.762X_3 + 0.093$ | $Y_3 = 1.073X_3 + 0.026$ |

3.2. Application of the Proposed Correction Process

The proposed correction procedure was applied on 452 commercial samples to bring the fibrogram measurements from Test HVI 1 and Test HVI 2 to a similar level as the Reference HVI. The fibrograms in Figure 8 are the average of 452 samples from the Reference HVI (red) versus the uncorrected fibrograms from Test HVI 1 (blue) and Test HVI 2 (black). The average fibrogram from all samples from Test HVI 1 seems to deviate from the average fibrogram from the Reference HVI to a greater degree than the average fibrogram from Test HVI 2. After correction, the average fibrogram from Test HVI 1 and Test HVI 2 looks similar to the average Reference HVI fibrogram (Figure 9). The differences between HVIs for fibrogram measurements are mainly in the part of the curve representing the shorter fibers within the sample (Figure 8).
The proposed correction procedure was validated using 932 commercial samples. The global performance of the proposed correction equations was determined by calculating EDs of fibrograms for 452 commercial samples before and after correction as shown in Figure 10. The average ED between the Reference HVI and Test HVI 1 is 4.68 mm when the average ED after correction is 3.02 mm (Figure 10). The correction procedure significantly reduces the difference between the Reference HVI and Test HVI 1 based on 95% confidence intervals. However, the average ED between the Reference HVI and Test HVI 2 is 2.45 mm before correction when the average ED after correction is 2.47 mm, which is not significantly different based on the 95% confidence intervals. It appears that Test HVI 2 is already in good agreement with the Reference HVI and, thus, little to no correction is necessary. The difference in slope and offset of the generated equations for Test HVI 1 are numerically higher than one and zero, respectively, compared to the Test HVI 2 (Table 3). This means that Test HVI 1 requires more correction than Test HVI 2.
3.3. Validation of the Correction Procedure

The proposed correction procedure was validated using 932 commercial samples. Figure 11 shows the average EDs before and after correction for Test HVI 1 and Test HVI 2 as well as the 95% confidence intervals. The average ED between the Reference HVI and Test HVI 1 is 4.34 mm when the average ED after correction is 3.34 mm. The correction procedure significantly reduces the difference between the Reference HVI and Test HVI 1 based on 95% confidence intervals. However, as with the previous case, little or no correction was needed for Test HVI 2.

The nine reference samples were selected to represent the variation in the set of 452 commercial samples. However, the validation set contains a wider fiber length variation captured by the whole fibrogram than the original set of samples from which the reference samples were selected. Figure 12 shows the scatter plot of the first two principal components of the 452 samples (red dots) set versus the validation set of 932 samples (blue dots). It is clear from this figure that the validation set covers a wider range of fiber length variations. While the correction procedure based on the original reference samples significantly reduced the difference between the Reference HVI and Test HVI 1, it likely

Figure 9. Average fibrogram of 452 samples measured with the Reference HVI (red), corrected Test HVI 1 (blue), and corrected Test HVI 2 (black).

Figure 10. The average ED and 95% confidence interval of 452 commercial samples before and after correction.

The results show that the correction procedure could not completely eliminate the differences between the Reference HVI and Test HVIs—i.e., the EDs after correction are not zero. This could be due to several factors. One possible reason could be the natural within-sample variation in fiber length. The selected reference samples are not developed following the standard protocol to develop a calibration/correction cotton [27]. The correction/calibration cottons (USDA standards) used by the cotton industry are provided by the USDA Agricultural Marketing Service (USDA-AMS) and produced following a sophisticated protocol [27]. The samples used as references in this experiment are regular commercial samples. In addition to that, the natural within-sample variation in fiber length of the 452 samples could also be the reason for the deviation between Reference HVI fibrograms and Test HVI fibrograms after correction. Ten replications per sample are likely not enough to capture the true within-sample variability. However, the goal of the correction procedure is to correct the deviation due to the instruments. Considering all these limitations, the obtained result demonstrates that the proposed correction method brings the fibrograms to a better agreement between the Reference HVI and Test HVIs.
would be improved by using reference samples more representative of the fiber length variation found in this validation set.

**Figure 11.** The average EDs and 95% confidence interval of 932 validation samples before and after correction.

**Figure 12.** The scatter plot of principal component 1 and principal component 2 of both the reference set and the validation set indicating that the validation set possesses a wider range of variation than the 452 commercial samples.

3.4. Reducing the Number of Samples Required for Fibrogram Correction

The previous results show that the correction protocol can reduce fibrogram variation among HVIs when using three samples per component (nine samples total) to represent the total shape variation in the fibrogram. This experiment examines selecting fewer reference samples (sets of two, three, or six samples) to achieve the same effect. Also, since Test HVI 2 is shown to be in good agreement with the Reference HVI, we only include Test HVI 1 in this experiment.

The goal of selecting a reduced number of reference samples is to find samples that represent extremes in more than one of the three components in the correction domain.
As the number of samples is reduced from six to three and finally two, the total amount of variation represented by these samples in the correction domain was also reduced. Identifying fewer cottons that represented a large variation across the entire correction domain became increasingly difficult.

To analyze the results more succinctly, we examined the average of the EDs of the fibrograms both before and after correction for each of the correction samples sets, which are shown in Figure 13. The average of the EDs between the Reference HVI and Test HVI 1 before the correction was 4.68 mm. When three, six, and nine samples are used to establish the correction method, the average of EDs are not significantly different (3.02 mm, 3.04 mm, and 3.17 mm, respectively). Figure 14 shows the results of each set of reference samples applied to the validation set. Nine, six, and three samples corrected the fibrograms to a similar level.

Figure 13. The average EDs before and after correction and 95% confidence intervals based on 452 commercial samples for different sets of reference samples.

Figure 14. The average EDs before and after correction and 95% confidence intervals based on 932 validation samples for different sets of reference samples.
The average of EDs based on correction with only two reference samples is 3.70 mm for both 452 samples and 932 validation samples, which is significantly different than the average ED after correction based on three, six, and nine samples (Figures 13 and 14). On the other hand, it is also significantly different than the average ED before correction for both sets of samples meaning that two samples reduce the difference between the Reference HVI and Test HVI but not as much as nine, six, or three samples. The two samples do not cover the range of fiber length variation as much as three, six, or nine samples do. Correction with two samples may still be possible; however, it would be very difficult to select samples that can capture the necessary fiber length variation in the correction domain.

4. Conclusions

The cotton industry requires a fast and reliable method of measuring within-sample variation in cotton fiber length. Recent studies show that fiber length variation captured by the whole fibrogram curve provided by the HVI can potentially explain yarn quality better than the current HVI system and as good as the AFIS length distribution by number [23]. However, the fibrogram curve is not a corrected measurement and cannot currently be compared across different HVIs. This limits the industry-wide adoption of the whole fibrogram measurement. To remedy this, we proposed a method for correcting the whole fibrogram curve.

Our results show that the proposed fibrogram correction procedure can correct the fibrogram as a complete curve, thereby facilitating a comparison of the measurement across instruments and laboratories. This correction technique was validated on a wide array of commercial samples. Currently, only two span lengths from the whole fibrogram are used to characterize the fiber length variation, which could be corrected by this method. In addition, it would be possible to correct any additional fiber length measurement extracted using the whole fibrogram.

The correction procedure was developed using nine samples, but it was shown that it is possible to reduce the number of samples needed for correction to only three samples. In order for this to work, it is necessary to identify three samples that demonstrate a sufficient range of variation in fibrogram shapes to be used as reference points. It is important to note that the current standards are produced only for two measurements (UHML and UI). Development of standards for the whole fibrogram curve may not be easy. At least three types of fiber length variation characterized by the first three components need to be considered during the development of the standard for the whole fibrogram. Therefore, more research is needed to identify these samples or to generate samples through processing.

While this investigation is an attempt to correct the fibrogram measurement as a whole curve, it might be possible to identify a subset of span lengths (or other fiber length parameters) that adequately characterize the fiber length variation contained in the whole curve. If that is the case, then the correction procedure could be established for those specific parameters. Identifying a set of appropriate measurements based on the fibrogram requires more research.

The information held within the corrected fibrogram curve has the potential to impact many sectors of the cotton industry. Cotton breeders can use this information to identify elite germplasm with improved within-sample variation in fiber length. Facilities focused on processing cotton fiber, such as spinning mills, may be able to use this newly available information to optimize their processes.

Author Contributions: Conceptualization, M.A.S., B.R.K. and E.F.H.; methodology, M.A.S., C.T., B.R.K. and E.F.H.; validation, M.A.S., B.R.K. and E.F.H.; formal analysis, M.A.S.; investigation, M.A.S., B.R.K. and E.F.H.; data curation, M.A.S., C.T., B.R.K. and E.F.H.; writing—original draft preparation, M.A.S.; writing—review and editing, M.A.S., C.T., B.R.K. and E.F.H.; supervision, E.F.H. and B.R.K.; project administration, E.F.H.; funding acquisition, E.F.H. and B.R.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Cotton Incorporated (Grant or Project number 17-533).
Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors thank all the technicians at Fiber and Biopolymer Research Institute at Texas Tech University for their help during conditioning and testing the samples. The Authors also thank cotton incorporated for the financial supports.

Conflicts of Interest: The authors declared no potential conflict of interest with respect to the research, authorship and/or publication of this article.

References

1. Faulkner, W.B.; Hequet, E.F.; Wanjura, J.; Boman, R. Relationships of cotton fiber properties to ring-spun yarn quality on selected High Plains cottons. *Text. Res. J.* 2012, 82, 400–414. [CrossRef]

2. Mathangadeera, R.W.; Hequet, E.F.; Kelly, B.; Dever, J.K.; Kelly, C.M. Importance of cotton fiber elongation in fiber processing. *Ind. Crops Prod.* 2020, 147, 112217. [CrossRef]

3. El Mogahzy, Y.E.; Broughton, R., Jr.; Lynch, W.K. A Statistical Approach for Determining the Technological Value of Cotton Using HVI Fiber Properties. *Text. Res. J.* 1990, 60, 495–500. [CrossRef]

4. Üreyen, M.E.; Kadoglu, C. Regression Estimation of Ring Cotton Yarn Properties from HVI Fiber Properties. *Text. Res. J.* 2006, 76, 360–366. [CrossRef]

5. McCormick, K.M.; Morais, J.P.S.; Hequet, E.; Kelly, B. Development of the correction procedure for High Volume Instrument elongation measurement. *Text. Res. J.* 2019, 89, 4095–4103. [CrossRef]

6. Hinds, Z.; Kelly, B.R.; Hequet, E.F. Correction to: Stability, variation, and application of AFIS fiber length distributions. *J. Cott. Res.* 2020, 3, 10. [CrossRef]

7. Kelly, C.M.; Hequet, E.F.; Dever, J.K. Breeding for improved yarn quality: Modifying fiber length distribution. *Ind. Crops Prod.* 2013, 42, 386–396. [CrossRef]

8. Kelly, B.R.; Hequet, E.F. Breeding and genetics. *J. Cott. Sci.* 2012, 16, 1–16. [CrossRef]

9. Yang, S.; Gordon, S. Accurate prediction of cotton ring-spun yarn quality from high-volume instrument and mill processing data. *Text. Res. J.* 2017, 87, 1025–1039. [CrossRef]

10. Cai, Y.; Cui, X.; Rodgers, J.; Thibodeaux, D.; Martin, V.; Watson, M.; Pang, S.S. A comparative study of the effects of cotton fiber length parameters on modeling yarn properties. *Text. Res. J.* 2013, 83, 961–970. [CrossRef]

11. Kelly, B.R.; Hequet, E.F. Variation in the advanced fiber information system cotton fiber length-by-number distribution captured by high volume instrument fiber length parameters. *Text. Res. J.* 2018, 88, 754–765. [CrossRef]

12. Wakeham, H. Cotton Fiber Length Distribution—An Important Quality Factor. *Text. Res. J.* 1955, 25, 422–429. [CrossRef]

13. Backe, E.E. Effect of Short Fiber Content in Cotton on Plant Performance and Quality. *Text. Res. J.* 1986, 56, 112–115. [CrossRef]

14. Tallant, J.D.; Fiori, L.A.; Dorothy, C.; Tallant, J.D.; Fiori, L.A.; Dorothy, C. The Effect of the Short Fibers in a Cotton on its Processing Efficiency and Product Quality Part 1. Affecting the Short Fiber Content by the Addition of cut cotton fibers. *Text. Res. J.* 1959, 2, 687–695. [CrossRef]

15. Thibodeaux, D.; Senter, H.; Knowlton, J.L.; McAllister, D.; Cui, X. The impact of short fiber content on the quality of cotton ring spun yarn. *J. Cott. Sci.* 2008, 12, 368–377.

16. Hertel, D.K.L. A Method of Fibre-Length Analysis Using the Fibrogram. *Text. Res. J.* 1940, X, 510–525. [CrossRef]

17. Chu, Y.T.; Riley, C.R. New Interpretation of the Fibrogram. *Text. Res. J.* 1997, 67, 897–901. [CrossRef]

18. Delhom, C.D.; Kelly, B.; Martin, V. Physical Properties of Cotton Fiber and Their Measurement. In *Cotton Fiber: Physics, Chemistry and Biology*; Fang, D., Ed.; Springer: Cham, Switzerland, 2018; pp. 41–73. ISBN 978303008710. [CrossRef]

19. Kelly, B.; Abidi, N.; Ethridge, D.; Hequet, E.F. Fiber to Fabric. *Cotton* 2015, 57, 665–744.

20. Hertel, K.L.; Lawson, R. Factors Affecting Fiber Length-Scanning Measurements. *Text. Res. J.* 1964, 34, 866–880. [CrossRef]

21. Krowicki, R.S.; Thibodeaux, D.P. Holding Length: Effect on Digital Fibrograph Span Length. *Text. Res. J.* 1990, 60, 383–388. [CrossRef]

22. Sayeed, M.A.; Schumann, M.; Wanjura, J.; Kelly, B.R.; Smith, W.; Hequet, E.F. Characterizing the total within-sample variation in cotton fiber length using the High Volume Instrument fibrogram. *Text. Res. J.* 2020, 91, 175–187. [CrossRef]

23. Krowicki, R.S.; Duckett, K.E. An examination of the fibrogram. *Text. Res. J.* 1987, 57. [CrossRef]

24. Louis, G.L.; Fiori, L.A. Graphical Convresion of digital Fibrograph into Suter-Webb array data pdf. *Text. Res. J.* 1967, 37, 815–816. [CrossRef]

25. Abdi, H.; Williams, L.J. Principal component analysis. *Wiley Interdiscip. Rev. Comput. Stat.* 2010, 2, 433–459. [CrossRef]

26. ASTM Standard Practice for Establishment of Calibration Cottons for Cotton. *Astrn 2020,* i, 10–13. [CrossRef]