**Document Title:** Consecutive and Random Manufactured Semi-Automatic Pistol Breech Face and Fired Cartridge Case Evaluations

**Author(s):** Ashley Chu, Shannon McClorry, Roy Geiss, David Read, David Howitt, Michael Hill

**Document No.:** 244565

**Date Received:** January 2014

**Award Number:** 2009-DN-BX-K168

# FINAL REPORT

# CONSECUTIVE AND RANDOM MANUFACTURED SEMI- AUTOMATIC PISTOL BREECH FACE AND FIRED CARTRIDGE CASE EVALUATIONS.

## Award Number 2009-DN-BX-K168

Ashley Chu, Shannon McClorry, Roy Geiss, David
Read, David Howitt and Michael Hill
Forensic Science Program, 1909 Galileo Ct. Suite B
University of California, Davis, California 95618

## ABSTRACT

This report describes our work on the evaluation of the impression markings on cartridge cases fired from semi-automatic pistols to determine to what extent these markings can be used to individualize a firearm and whether they can be quantified in terms the possibility that it occurred by random chance. We have been able to demonstrate that the size of the individual regions of corresponding topography on the breech faces of cartridge cases fired from the same slides were consistently larger than those that were consecutively manufactured and that there are other aspects to the matching that are not reflected by cross correlation analysis. The conclusions that can be drawn from this work are that the differences between the cross-correlation coefficients from matching and non-matching cartridge cases can not only be increased by focusing on particular sized regions of correspondence but that other approaches such as pattern recognition can also be effectively used to supplement the cross correlation techniques. Thus by modifying the algorithms that determine the similarities it should be possible to increase the number of cartridge cases that can be added to a database before it will be overwhelmed by false positives.

# TABLE OF CONTENTS

## EXECUTIVE SUMMARY

The subjective approach to tool-mark identification and the failure of cross correlation algorithms to support a national database for firearms examination raise valid concerns [1-4] that we have investigated for the specific case of identifying cartridge cases fired from semi-automatic pistols. This effort has focused on the ways in which confocal microscopy can be used to reproduce the topography associated with the impression evidence on a cartridge case as well as the ways in which random changes to the surfaces should be anticipated to develop a better understanding of the criteria that can be used to distinguish to a match. The goals of this work were to quantitatively evaluate the topographies of matching cartridge in terms of their deviations from random behavior and to determine whether improvements could be made to the viability of a National database. Various approaches to the comparisons were undertaken and numerical probabilities to the individual correspondences, associated with the one-to-one matching of a breech face, were determined by comparing experimental topographies to those created by random computer modeling because, unlike the one-dimensional case for bullets [5], the two-dimensional problem did not easily lend itself to an analytical approach.

Although it is clear that correlations can be made, which has been shown by the work done by the National Institute of Standards and Technology [1], as a part of the National Academy of Sciences evaluation of firearms databases, their study concluded that although the breech face was the most valuable source of impression evidence they also concluded that the cross correlation coefficients, determined from the relationships between known matching and known non-matching breech faces, were not sufficiently different from each other that one could feasibly construct a database large enough to serve as a nationwide repository for searchable data. Thus we felt there was a need to understand the relationships that distinguish these correlation coefficients from the types of assessments that are actually used for evidence comparison and whether there are alternative ways to distinguish matches that could be used in conjunction with the cross correlation techniques to broaden the distinction between matches and non-matches.

The original intent of this proposal was to use confocal microscopy to reproducibly determine the topography of the impression markings on cartridge cases fired from consecutively manufactured semi-automatic pistols in order to evaluate the consequences of random markings and sub class characteristics of the features that constitute a match. Two sets of 10 slides were evaluated and although sub-class features could be distinguished on the breech faces of one of the sets of slides using an optical microscope these particular aspects of the impressions did not seem to be reflected in the topographies that were ultimately derived from the fired cartridge cases using confocal microscopy. Indeed it was found that both sets of slides could be regarded as providing random breech face markings for confocal analysis.

In addition to the direct comparison of the breech faces and the fired castings from the breech faces, the impressions transferred to the cartridge cases discharged from different stages of the sequential firings were also analyzed. This was done for both sets of consecutively manufactured slides to distinguish the consistency with which the breechface topography transfers as well as to determine alternative possibilities to match the individual primer faces including Cross Correlation methods, Pattern Matching and Morphological Component Analysis. In this way we were hoping to develop an alternative to the subjective methods currently being used by examiners to individualize a firearm in much the same way as the Consecutively Matching Striae approach has enabled examiners to quantify the distinctions between the random striations on fired bullets.

The analysis of the cartridge cases involved two specific set of consecutively manufactured slides, one set having a machined surface and the other a sandblasted one, the idea being that the former would provide a set with sub-class contributions to the impressions while the other would not. This actually turned out not to be the case, because it was in fact the sand blasted breech faces that showed the signs of sub class characteristics in the optical microscope.

Confirmation of the hypothesis, that the distinctions between matched and non-matched may be similar to what is known to occur with bullets, was anticipated to be evident as a distinction between the spatial extent of the individual regions of correspondence between matched and non-matched pairs. That is to say in bullets it is observed that there is an increase in the numbers of consecutively matching striae on the land impressions, which is essentially an increase in the size of the regions of perfect correspondence. In the two dimensional impression on a breech face one would expect this aspect of the correspondence to appear as an increase in the areas of the individual regions of continuity and if this is indeed the case then it should be possible to evoke more of a distinction between the matches and therefore create a large data base. This hypothesis turned out to be true and so we have been able to provide at least one quantitative measure of the level of correspondence in terms of numerical probabilities and an explanation of their occurrence. The breech face correspondences are similar in some sense to those that we see in bullets in that it is the extent of the regions of perfect correspondence that define the smaller probabilities of a random match occurring. In the case of bullets this can be distinguished in the bridge microscope as the distance in microns over which two profiles correspond exactly. For cartridge cases the probabilities can be defined in terms of the size of the areas of perfect correspondence of the breech face impressions that are being compared in square microns.

There is one notable distinction from bullets however and that is that there does not appear to be a great deal of difference in the amounts of impression evidence on the primer surfaces. This is in contrast to bullets where the number of striae can vary significantly and is responsible for the straightforward comparison of the total level of correspondence, or percentage of matching striae, being an inappropriate method of distinguishing a match from a non-match. Thus for cartridge cases the straightforward comparison of the total level of correspondence, or conventional cross correlation analysis often works well, however, we think it can be improved by performing multiple analyses using differently sized regions to determine the size at which the values of the correlation coefficients begin to change.

Although we refer to the 3-D data we extract from the confocal images as topographies this is not actually the case. This is because the acquisition times for collecting data that accurately reflect the surface topography take hours if not days to acquire and so what we are actually using are processed scans of much shorter duration. Although one cannot visually assess the unprocessed scans the similarities in the processed profiles can be readily distinguished and we have been able to demonstrate the consistency of the correspondence found using the NIST standard bullet.

The processed topographies differ from the surface contours in that much of the accuracy of the height information of the data points is lost and replaced with a determination of whether they contribute to recognizable features in the processed profile. In other words it is simply the locations of distinguishable high and low points that constitute the processed profiles and the matching of two profiles is determined by the extent to which these points correspond. Although not an arbitrary conversion the transformation of the data to a processed profile can probably have many equivalent forms but here we have used a combination of Gaussian and Fourier filters. The topographic information from the confocal scans is extremely noisy and the accuracy and precision of the instrumentation was very different for the primer surface of a cartridge case than for the standards that the manufacturers use to make these determinations. Furthermore there are some serious shortcomings for confocal application particularly that it is impossible to obtain reproducible topographies from the cartridge case surfaces at the resolution typically associated with firearms analysis nor to precisely compare them, regardless of the acquisition times. Although we were able to make some comparisons of the topographies of the surfaces we were unable to make the kinds of comparisons for example that would enable us to straightforwardly subtract the topographies from two primer surfaces, discharged consecutively from the same weapon, to distinguish the differences. This was of course a considerable setback to our approach, and although we were able to develop processing routines that enabled us to perform correlations and comparisons of the topography we have been unable to perform the kind of comprehensive assessment of the topography that we had hoped. The reasons for the differences in resolution, particularly in the height values of the topographic profiles, we believe have to do with the algorithms the microscope manufacturers use to determine the planes of focus of the scanned images. Indeed we think these routines are empirically refined for looking at flat specimens, particularly surface roughness on magnetic discs and silicon surfaces and seemed to vary from instrument to instrument based upon the topographies we obtained for the standard bullet in the various instruments that we tested. It is also unfortunate that the data files from our instrumentation cannot be converted to the acceptable formats for the three-dimensional computer aided design programs and that the processed data files cannot be exported from MountainsMap as surface profiles, only line profiles. MountainsMap is one of the standard software programs adopted by many of the microscope manufacturers to complement their own but there are hardware problems as well, particularly that the working distances of the 50X objectives are typically too small to accommodate the undulations of the primer surface, so it is not normally possible to obtain a complete set of stitched images without reverting to a lower magnification objective.

Another issue is that the cartridge case topographies can only be rotated and translated in the X-Y plane using the traditional software and so a complete rigid body rotation to bring the profiles into the best registry cannot be performed. Thus the matching of profiles to achieve the highest correlation coefficients relies on the coincidence of the surface of the two cartridge cases when the specimen are mounted, which is of course exactly the shortcoming to conventional optical microscopy we were hoping to overcome. Indeed to maximize the application of confocal microscopy to the comparison of cartridge case profiles it is apparent that software will have to be developed that enables the topography data to be exported to programs that can represent and compare them in three dimensions rather than two.

Thus the quantification of the topology of the cartridge cases in the end had to be done with processed topographies and after first maximizing the correlation coefficients between them it was possible to evaluate the distribution of the regions of similarity. The characteristics of the similarities can be quantified by using the same sort of software that is used to measure particle sizes and distributions and what we found to be the most useful feature appears to be the total area of the distinguishable regions of correspondence. Thus using mean, average or maximum values of these areas of correspondence, in the comparison of the fired cartridge cases, we should be able to improve the distinction that can be made between a match and non-match enabling a larger database to be constructed before false positives overwhelm the meaningful results. We were able to complete this analysis for only some of the breech face impressions because those that had not been sandblasted were supplied to us with only part of the breech faces having been machined. This was because of the poor fill associated with the casting of the slides, which led to various regions of the breech faces actually exhibiting the characteristics of a cast surface. These retrenched parts of the surfaces were also quite random and although the same machined portions of the breech face were not distinguishable in all ten slides there were overlapping regions in some of them that could be selected as having been derived from the same tool and occurring in the same location of the machined part.

Apart from the primer face analysis we had no success in making meaningful comparisons elsewhere on the cartridge case, which was particularly disappointing in the case of the firing pin impression because it is the area of the cartridge case most suited for examination at the higher magnifications appropriate for confocal analysis. In other words using 20-50x objectives compared to the magnifications at which firearms examination is normally conducted with a 4-5x objective. The regions of the cartridge case that are amenable to such analysis would necessarily have to be precisely located, so attempts were made to look at the very tip of the firing pin impression as well as specific regions that might be identified by triangulation from locations such as the tip of the firing pin impression and outermost location of the ejector mark. The precision that could be obtained by triangulation proved to be inadequate and the tip of the firing pin impression was marred by contamination at this level of magnification.

Thus we were able to make reasonable evaluations only for the breech face impression and this was effectively done by scanning the cartridge cases with a 20X objective and then using filters to remove the image detail that we anticipate could not be distinguished by an examiner using a 5X objective. The topography was assessed by stitching together confocal scans and then processing the entire array with a Fourier transform to remove the high-resolution detail. Although this processing can be performed using the MountainsMap commercial software, these topographic profiles can only be extracted for our purposes as single profiles across the images because the two dimensional outputs are at too low a resolution for meaningful comparisons. Although it was possible to extract the topographies as CSV files, they turned out to be too unwieldy to align and compare to each other in Excel. These various shortcomings of the commercially available software for our purposes necessitated the development of processing routines on an entirely different platform. We made several requests for software modifications that would allow us to continue to use the processing programs that we had purchased with the instrumentation, but they could not be fulfilled. After experimenting with a variety of different approaches we duplicated the MountainsMap processing routines we had developed in Mathematica, which enabled us to compare the two dimensional profiles. It is noteworthy that our version of MountainsMap actually has no capability for the direct one to one comparisons in 3-D such as aligning overlaying or subtracting the topographies from different samples although one of the reviewers thought that it is possible to do in later versions. Using Mathematica we have developed routines to perform these direct comparisons of the topographies as well as various types of cross correlation routines that enable us to compare segmented portions of each of the processed topographies to each other.

On the upside Mathematica is about a tenth of the price of the MountainsMap software and so more affordable to the crime laboratories and firearms investigators whilst the subroutines for doing the image comparisons are freely available.

Using the cross correlation algorithms in Mathematica, we are able to consistently demonstrate the distinction between the known matches and the known non-matches in much the same way that had already been done by the NIST group [1]. We also found that we were able to improve the distinction in the correlation coefficients for the impressions derived from the conventionally machined breech faces by extracting one-dimensional profiles and performing cross correlations on these profiles rather than the two-dimensional arrays. This is in essence duplicating the breech face comparisons that a firearms examiner might undertakes were he to align the machining marks in the same way as the striae on a bullet and could be used independently to make an assessment of a match to supplement the overall comparison of the surface topography. Thus in the same way as an examiner uses more than one type of correspondence to render an opinion one might consider employing multiple computer algorithms, rather than a single one, to assess the comparison.

Amongst the other alternatives we considered were some of the pattern recognition algorithms that are currently used for image analysis. Although we cannot use these types of routines to directly compare the topographic profiles, we can create gray scale images of the profiles where the contrast levels linearly reflect the value of the height above the lowest point in the array. This method of indirectly evaluating TIFF files proved to be most successful in the assessment of the topographic comparisons from the sand blasted breech face impressions and worked well even when the images were further reduced in resolution to speed up the process of comparison. We also found Morphological Component Analysis to be successful for matching the breech face impressions left on the primer face. Here the profiles are again converted to contrast images, and these can be overlaid and analyzed to distinguish the distributed areas of match in Mathematica. These areas can be tailored to recognize the different regions of match and the areas and distribution of each region can then be calculated. Given a binary image in which regions of match are represented by white pixels and regions of non-match are black, matching regions are determined by analyzing the connectivity of the white pixels. Matching pixels contribute to a region when they share an edge with another pixel in the region and the total number of pixels in each region is then a measure of the area. One of the important aspects to the comparison of the known matches and non-matches from the consecutively matched components is of course the alignment of the topographic profiles. This is fairly straightforward to do in the case of matched cartridge cases but the non-matching cases present a problem because there are no recognizable features to align to. To address this problem we developed a routine in Mathematica that optimizes the alignment by comparing small sections of the topography of one cartridge case with the whole surface of another by systematically rotating and translating the small section to the location where the cross correlation coefficient is a maximum.

The final aspect to this proposal was the determination of the probabilities associated with random matches in two-dimensions which was based upon the size of the individual areas of correspondence found by randomly superimposing binary images to determine how many permutations were required to generate the region of correspondence. We performed this analysis using both conventional image analysis as well as morphological component analysis to determine the probabilities of regions of specific size and obtained similar results. This was done using Mathematica to create random binary arrays to determine the areas of each region of match and the frequency at which they occur. The evaluation of the raw images produces a bimodal distribution of matching areas because the 8 adjacent pixel sites produce a great deal of connectivity, much of which is represented by singular interconnected strands. Although we find the same thing in the correspondence data of the experimental images it is in this case derived from the contribution of featureless topography, which can be excluded from the comparison by evaluating only the regions of indentation where an impression has been created. In the case of the theoretical images the thin strings of connectivity are eliminated when we filter the images using the same routines we use to obtain the profiles from the raw topographic scans and so we have used the same approach to process the data which produces a range of cluster sizes of the matching regions that correspond well for the random images and processed arrays from the known non matches but producer larges clusters in the case of many of the known matches.

## INTRODUCTION

The cartridge cases from two separate sets of 10 consecutively manufactured Ruger P345 and P94 pistol slides were examined to distinguish the similarities that exist and the ways that one might use to evaluate them quantitatively. Both sets were broached with the P345 having a machined surface finish whilst the P95 set had a sandblasted one, which is becoming a more common finishing method. The overall purpose behind the comparison of these two different sets of slides was to determine whether there are ways in which the comparison of the surface topographies from confocal images can be improved upon. The way in which the comparisons are usually done is with cross-correlation algorithms, which provide a measure of the extent of the similarities as a coefficient between zero and one. When the P95 cartridge cases were evaluated in this way at NIST in the early stages of this program the known matches were typically in the 0.75-0.9 range and the known non-matches were 0.2-0.25 [12]. This was actually an improvement over the values reported earlier in the original NIST study [1] that concluded that there is typically not enough of distinction between the correlation coefficients, ranging from essentially no distinction for the DeKinder set to 0.65 and 0.2 for the NBIDE set, to support a large database.

Thus we are looking into possible ways that can either separate these coefficients further or from which further distinctions can be made that exclude the false positives that limit the size of the database.

It was originally thought that impressions from the sandblasted surfaces would be devoid of subclass characteristics and therefore as close to a comparison of random features as possible whereas the machined surface impressions would exhibit the possibly confusing subclass features that could be distinguished by comparing the different breech faces for similar markings, which would otherwise be indistinguishable from random marks.

What was found however was that subclass characteristics could only be identified on the sand blasted breech faces surfaces and that these features did not transfer to the cartridge cases. There were clear striated marks on the conventionally machined breech face surfaces that were consistent with what might think were sub class features, but none of these could be aligned or matched to the other breech faces. Our evaluations of the breech faces from both types of surface finish could therefore be considered as an evaluation of random markings. The analyses of the cartridge cases utilized a variety of techniques to both process and interpret the images all of which is outlined in detail in the report. The assessment of the significance of these finding was assessed quantitatively whenever possible and the probabilities of different types of correspondences, particularly related to the size of regions of congruency and the proportions of matching pixels, were evaluated using random number schemes.

### METHODS FOR TOPOGRAPHY AND CONFOCAL IMAGING IN REFLECTION

During the very early stages of this program it became clear that the claims of the manufacturers, in terms of lateral and depth resolution, did not apply to the surface topographies that could be attained from cartridge cases. An exhaustive analysis of the precision and accuracy of the Olympus Lext 4000 microscope, which was the first microscope chosen, showed that although we could reproduce both the profiles of a NIST standards as well as the breech face impressions from our first set of consecutively manufactured components, we were having to use image acquisition times of the order of several hours and very precise positioning on the specimen stage. Indeed it became clear at this point that although accurate representations of the topography of the surfaces could be obtained in three dimensions we lacked the capability to reorient these surfaces to bring them into alignment. Furthermore the format of the reconstructed surfaces could not be exported in a format that could be read by programs such as AutoCAD or Solidworks. Thus the comparisons that could be made were based on the projections of the reconstructions, in other words the same cartridge case, when reoriented on the specimen stage, provided a different topography that could not be corrected for. The manufacturer was unable to make the necessary software modification we would have needed to ensure that we could gather and process the data for cartridge cases and this was a particularly unfortunate, but understandable business decision that Olympus had to make with regard to the costs involved in making these modifications. The instrument was replaced with a Zeiss 700

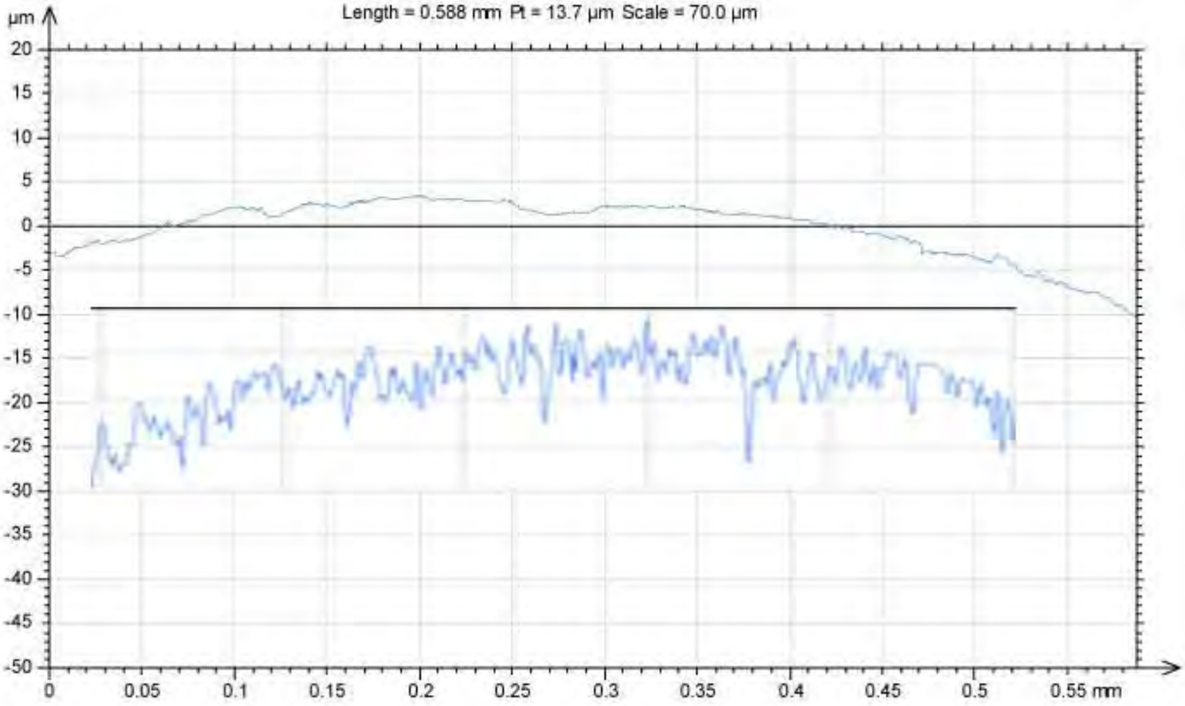
LSM instrument that is built on a much more flexible software platform that enabled us to incorporate some of the necessary modifications to the data acquisition and processing procedures however none of the microscopes had the software capability to actually manipulate the surface topographies in three dimensions.

The level of resolution that is required to distinguish the surface contours on a cartridge case using confocal microscopy is considerably greater than is required to distinguish them in a comparison microscope. This is because a series of images from different focal planes have to be recorded in order to construct the surface relief and so unless the acquisition times are extremely long the height profiles are going to be noisy enough to require filtering before they can be interpreted. In addition these reflection confocal microscopes cannot distinguish the small variations in depth that are associated with the impression evidence on the primer face at low magnification and so as will be discussed later we had to use magnifications of at least 20X. Obviously the surface topographies can be processed in a variety of ways but our aim here was to enhance the techniques that a firearms examiner currently uses and so it was important to reduce the image magnifications to those that a firearms examiner would use. This required additional filtering because in addition to the problems of image noise there is also a great deal of high resolution detail in the lateral dimensions that an examiner would never see and so this has to be removed from the topography so that it can be compared to the images that are normally seen in the comparison microscope.

These problems with the technique were addressed in the NIST study by carefully aligning the cartridge cases, which is what we tried to do here, but it has to be remembered that in the compilation of a database such precise alignment is likely unobtainable and so to take full advantage of confocal microscopy, software that can align the surface topography in three dimensions would have to be implemented to correct for the errors in positioning.

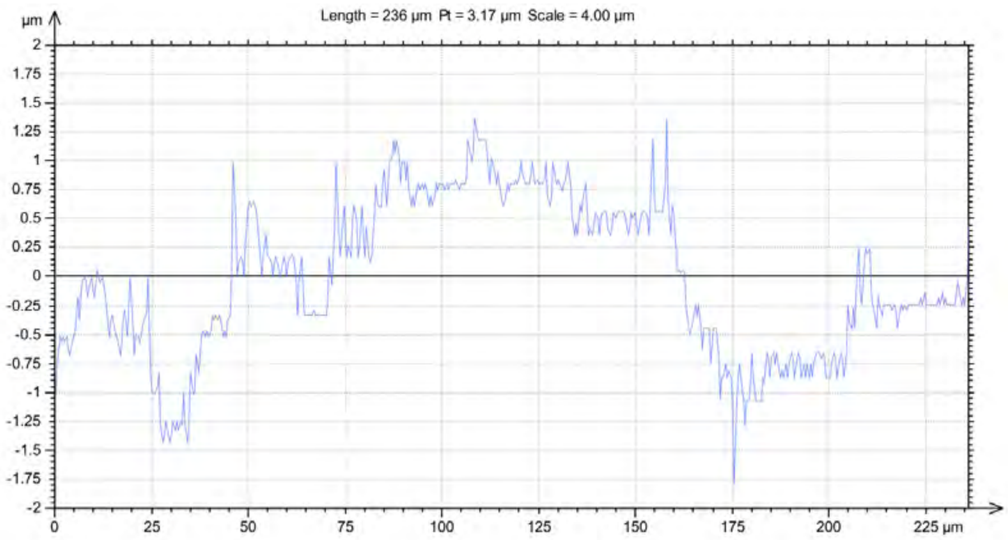
Amongst the conclusions of the NIST study [1] was that the correlations that they did on the topographic profiles from cartridge cases fired from the same gun were not different enough from those fired from different guns of the same type to satisfactorily distinguish between large numbers of cartridge cases. This is of course reminiscent of the bullet identification problem that Biasotti encountered in the 50's, that straightforward comparisons do not yield good results [6], however the problem does not appear to be as severe in cartridge cases because there is not the large variation in the quantity of the impression marks. That the probabilities associated with the matching of single features is considerably larger than for sets of consecutive features is why we specifically evaluated the spatial extent of the areas of identical topography as well as the other methods that could potentially be used for identification. This work has also included an evaluation of the distinctions in correspondence at different levels of resolution at different magnifications and the differences that the data processing routines, that ultimately define the topographic contours that are being compared, have on these profiles. Examples of the different routines we have investigated include Gaussian and polynomial filters, height profile selection using a variety of techniques for detecting the major contours in the profiles to reduce the amount of detail as well as Fourier analysis to extract detail in specific ranges of dimension. That a standard cartridge case was unavailable in the early stages of this program, we were having to use the standard bullet for this work which originally limited our comparisons to one- dimensional profiles, which were typically better than 96% using the NIST, cross correlation algorithm. The major problem we have found with confocal microscopy for the evaluation of cartridge cases is that we have to use very much higher magnifications to accurately reproduce surface topography than a firearms examiner would use. This is exemplified in figure 1, which is a comparison of the measurements of the variation in height across one of the land impressions of the NIST standard bullet. The height profile of the NIST standard bullet using a 20x objective is the topmost graph and the same profile taken with a 10x objective is shown using the same confocal settings.

**Figure 1.**

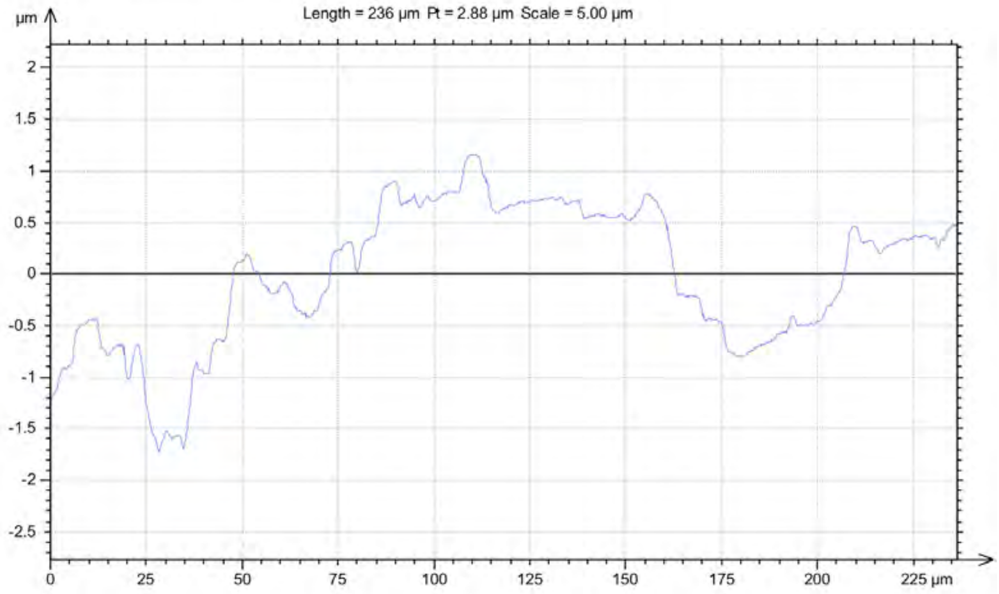


The data at 5x is even worse and it is clearly impossible to take meaningful data in the confocal microscope at the magnifications that firearms examiners currently use for tool mark evaluation. This problem can be overcome by stitching together images taken at higher magnification, which although time consuming is not a fundamental drawback; however, even at the higher magnifications there are still problems with the data. This is exemplified in figure 2, which is a comparison of the data obtained using 20x and 50x objectives in far greater detail.

**Figure 2.**



20x image of the unetched standard bullet

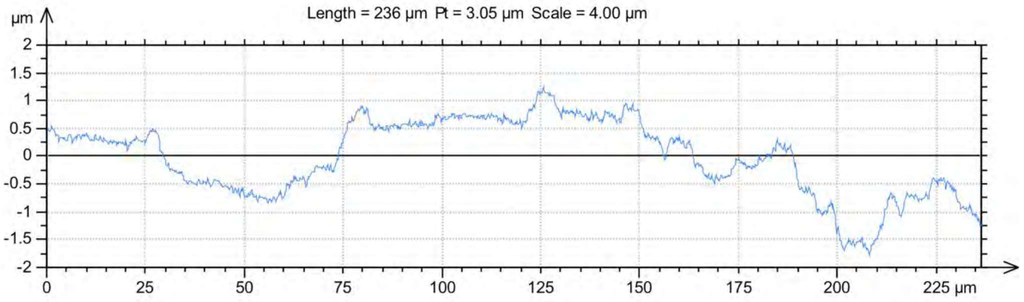


50x image of the unetched standard bullet

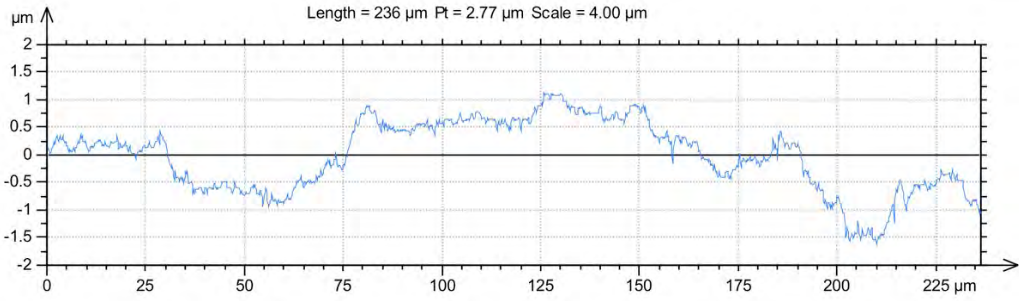
Here the 50x objective provides an accurate representation of the standard bullet on the sub-micron scale whilst the 20x data clearly does not. We believe this to be mostly because of the errors associated with distinguishing the planes of focus at the lower magnification and we encountered exactly the same problem with the LEXT confocal microscope, except in that case it was exacerbated by the way the software algorithms had been optimized. The consequences of these difficulties is that there is a great deal more information in the profiles taken at the higher magnification, which stands in the way of being able to clearly distinguish the surface detail that a firearms examiner relies upon. We have found that problem cannot be solved by simply superimposing multiple scans or averaging and is clearly not just a signal to noise problem. What these profile comparisons tell us is that the resolution problem in confocal microscopy is rather different from a conventional microscope in that rather than smoothing out the finer detail as the magnification is reduced, anomalous detail of much greater magnitude is actually being introduced. This is apparent in all the lower magnification images where anomalous fine scale detail tends to obliterate the topography.

What is surprising however is that at the higher magnifications much of what appears to be the same kind of anomalous detail is in fact real and we can see this in figure 3, which is a comparison of the profiles for two different types of the standard bullet. The first is one directly after it has been machined and the second is one that has been exposed to an etchant to reduce the specular reflection in the optical microscope. The latter is the standard bullet that can be purchased and the level of detail at high resolution is due to topography derived from the etching, which is clearly visible in the Scanning Electron microscope, although we were not permitted by NIST to evaluate the un-etched bullet they provided to us in this manner.

**Figure 3.**



50x unetched standard



50x etched standard

This fine detail is eliminated by the filtering routines that we use for processing the breech face impressions to reduce the data acquisition times and we have been investigating the consequences of the NIST filtering routines along with some of our own in an attempt to determine the lowest magnification objective and the shortest scan times that should be used. A routine was developed in MountainsMap® 6.2 to specifically optimize this for the CSM 700 microscope, which reduced the lateral resolution to about a micron but maintained the high values of the correlation coefficients between both the processed images from the same sample and from the known matches to it. The routine consists of the following functions:

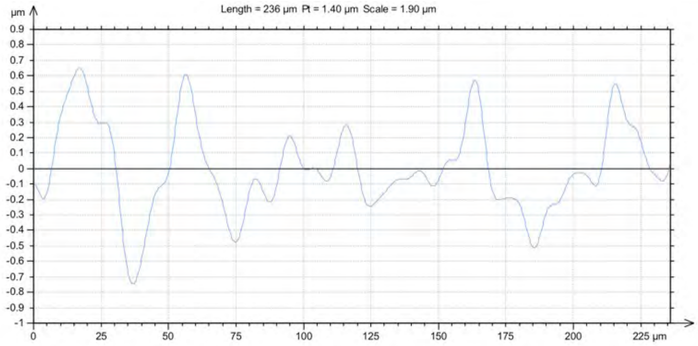
1. Zoom - this allows cropping out regions of interest. The step is included when the whole breech face impression is examined on the primer face and is used to remove the regions associated with the firing pin impression that are beyond the lowest depth recorded in the confocal scan.

2. Level - this software corrects for the inclination, so that the majority of the surface is represented as orthogonal to the stage of the microscope using a least squares method

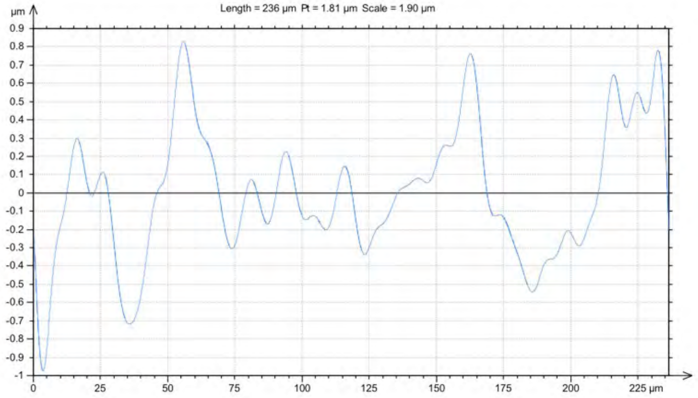
3. Fourier Transform - the Fourier transform step where low and high pass filters are used to remove the noise and fine details from the confocal data.

An example of what can be achieved is shown below, in figure 4, which is a comparison of two profiles from the standard bullet where we have a comparison of the reconstructed profile using 20x and 50x objectives after Fourier transforming to select a limited range of spectral frequencies.

**Figure 4.**



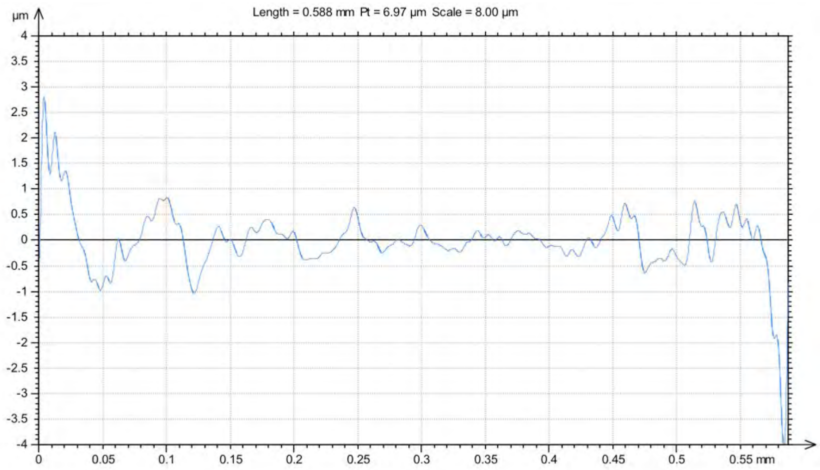
Fourier transformed 20x image of the etched standard bullet



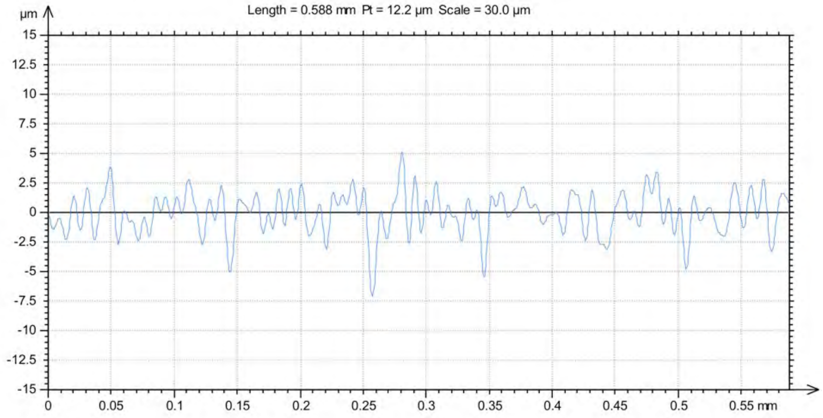
Fourier transformed 50x of the etched standard bullet

Unfortunately, this method and the others we have tried are totally ineffective when a 10x objective is used, as shown in the comparison with the 20x data in figure 5. Additionally, in developing a template for analysis using MountainsMap® 6.2, there are issues with the FT routine. Whenever adjustments are made, the FT setting reverts to a default setting, thereby, eliminating the possibility of recreating the previous FT setup or making fine adjustments. In addition, Mountains® 6.2 has problems processing data that involve cartridge cases because the data file are often too large for the software to process and when it can processes them the software is unable to save the images in a high resolution format for further analysis.

**Figure 5.**



Fourier transformed 20x image of unetched standard bullet

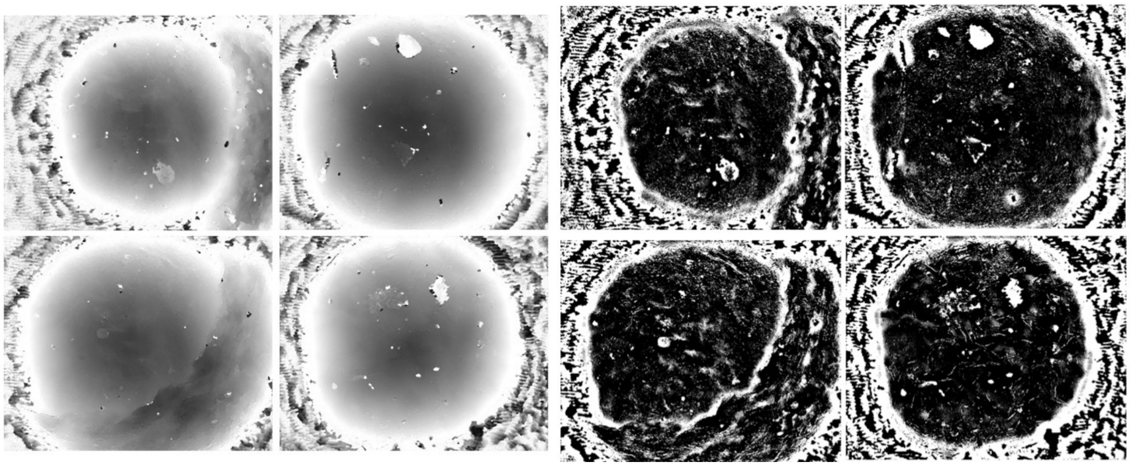


Fourier transformed image of 10x unetched standard bullet

All of these profiles are derived from single scans and since the cross correlation coefficient to the NIST theoretical bullet profile is routinely better than 95% with a 50x objective it is quite clear that the method has application. Nevertheless confocal microscopy is incapable of producing accurate topographic images at low magnification and it would seem to be impractical to utilize raw confocal profiles, without some sort of processing routine.

That the proportion of reliable detail and the accuracy of the profiles is so much better with the higher magnification objectives means that the confocal microscope is actually far better suited to the evaluation of small areas with fine detail rather than large areas of coarse detail which is what firearms examiners typically use. Although profile stitching can be accurately done with an automated stage the amount of data collection required to duplicate the optical microscopy approach of something like the NIBIN system, in other words to simply replace the optical microscope with a confocal microscope, would be far from straightforward. This is because for a 50x objective to scan the area equivalent to the field of view of a 5x objective would require a hundred accurately stitched images and the desktop computers supplied with the instrumentation were incapable of even constructing the 16 images associated with a 20x objective. The problem can of course be circumvented by evaluating localized regions of the fired cartridge cases, such as the tip of the firing pin impression or specific locations of the primer face that can be identified by triangulation. We investigated this possibility to determine whether there were sufficient differences in the correlation coefficients of matched and non-matched impressions to warrant examining these smaller regions instead. The very center of the firing pin was chosen first because it is a region of the cartridge case that can be most straightforwardly located, captured and compared in a single image at 20x. The left-hand image in figure 6 is an example of 4 raw confocal images of cartridge cases fired using the same slide and firing pin and on the right are the same 4 images after being filtered.

**Figure 6.**



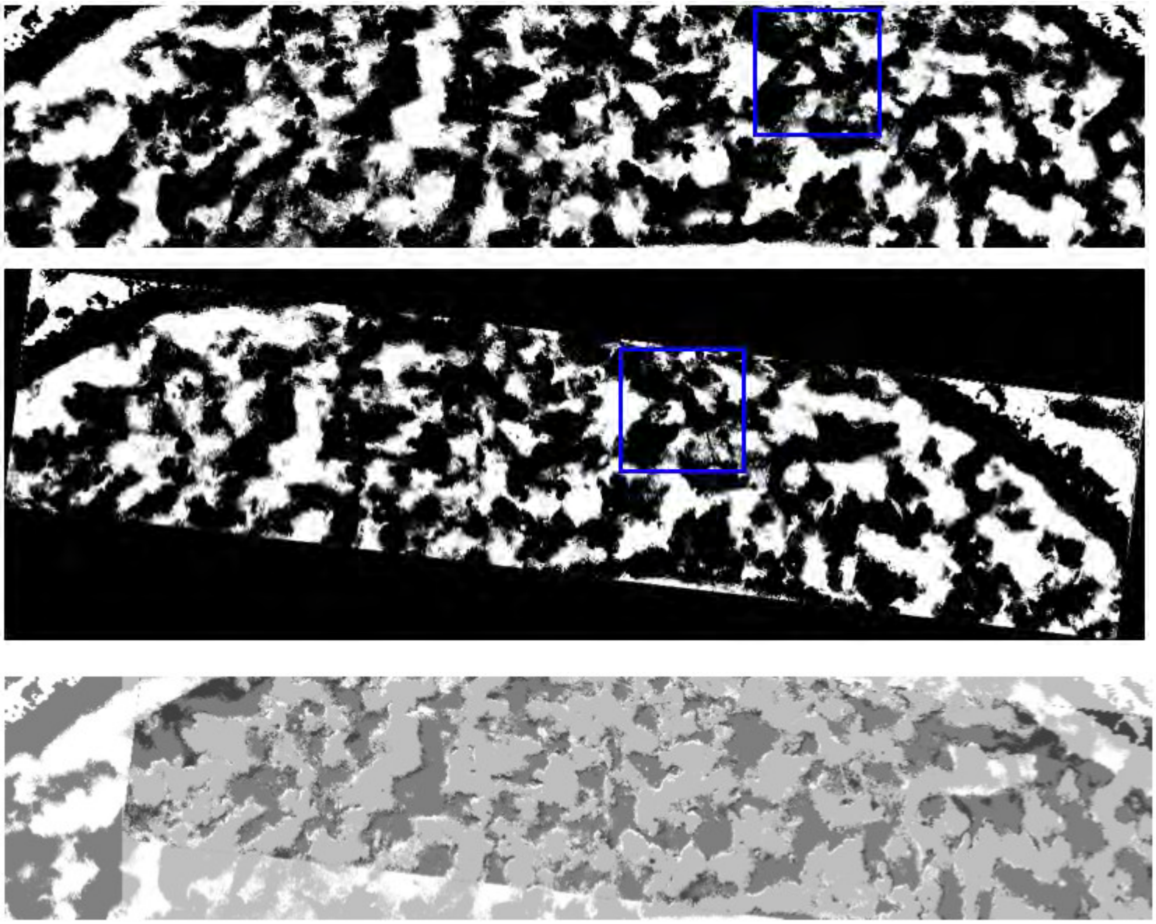
The individual filtered images of the firing pins show very few if any characteristics at this magnification that would be useful for individualizing a spent cartridge case to the parent firearm.

This disappointing result was because contaminating residues mask much of the fine surface detail of the firing pin. The results were improved by cleaning the firing pin between successive firings but not by cleaning the cartridge cases. Our attempts to extend to other distinguishable small regions by triangulation of the breech face, ejector and firing pin locations also failed to produce useful results.

## Methods for the Automatic Alignment of Images

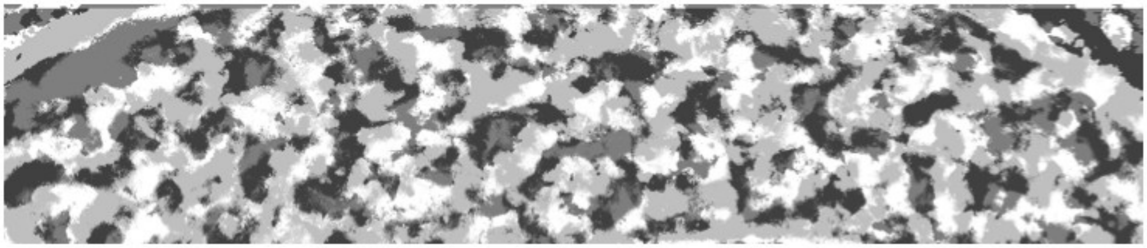
One of the problems associated with the comparison of the topographical data from different cartridge cases is knowing that they are being compared under optimum conditions. Dealing with known matched topographies is obviously easier than known non-matched ones because there are features such as the ejector mark and firing pin impression that can be used as a guide, whereas in an obviously dissimilar comparison there may be no visual clues at all to help with the alignment leading to a considerable bias in favor of finding correspondence in known matches. The optimum comparison of non-matched cartridge cases is therefore critical to the distinction between matched and non-matched firings, which is of course the basis for any conclusion about the feasibility of a large functional database. Thus rather than rely upon a visual assessment we created a computer program to align and compare breech face images of matching and non matching cartridge cases in exactly the same way and to determine the configuration when the correlation coefficient is a maximum. The program reads in two images, scales down the size of each image, and performs Gaussian filtering to remove some of the noise. There are two separate search phases within the program. In the first search phase, equal-sized sub images are extracted from each of the reference and test images, and a correlation coefficient between the two is calculated using a two-dimensional Fourier transform. While the reference sub image is held steady, the test sub image is stepped over the entire image and correlation coefficients are calculated at each location as long as both sub images are on the breech face and not the surrounding noise. The reference sub image is then stepped and compared to the entire test images. This process repeats until the entirety of each image has been compared and then one of the images is automatically rotated and the process repeats itself. Due to limitations with the Mathematica processing power, the search algorithm must either be run a few times to incorporate a wide range of angles, or one image rotated to be close to the angle of true alignment prior to the second search phase which is designed to refine the placement of the test sub image along the y-axis. Holding steady the position of the reference sub image and the x-coordinate and angle of the test sub image, the test sub image is moved vertically in small steps to find the area of best fit. Again, the best match is determined by the greatest correlation coefficient. Figure 7 is an example of the two sub images highlighting the region of best correspondence between the test and reference images followed by the subtraction of the two images showing the regions of correspondence in gray.

**Figure 7.**



An overlay between two cartridge cases that were not fired from the same slide is shown in figure 8.

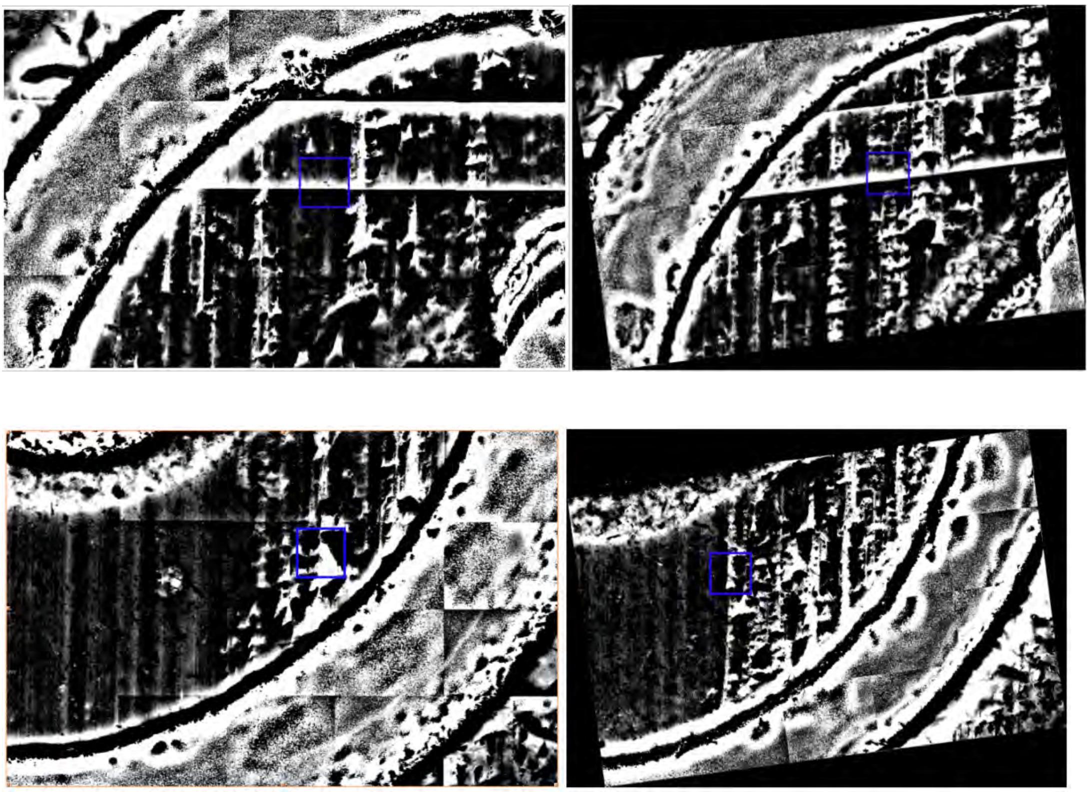
**Figure 8.**



### RESULTS OF SUB CLASS DETERMINATIONS

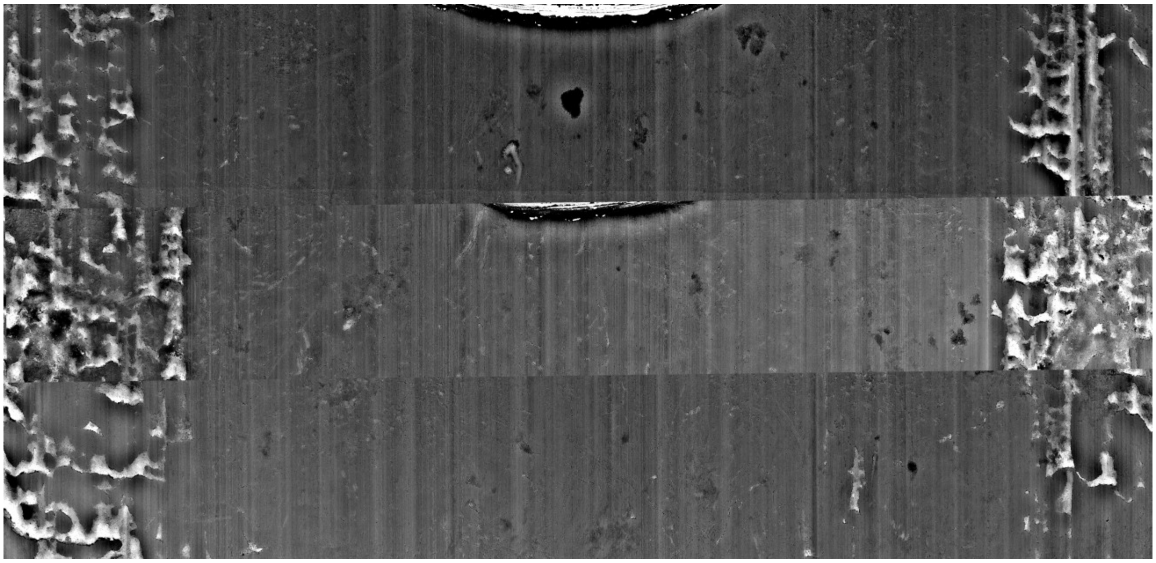
Although the machined surfaces of the 10 consecutively manufactured slides look like they have subclass characteristics, under closer inspection, this was not the case. Cartridge cases from each slide were broken down into quadrants and the striations were visually compared to each other and exhibited no resemblance. The images were also processed through Mathematica to determine the correlation coefficients which were in the range of around 0.16 to 0.44 except in regions where the images where stitched together poorly where they rose to a level of 0.66. Figure 9 shows some examples of the processed images where the blue box indicates the region of maximum correlation.

**Figure 9.**



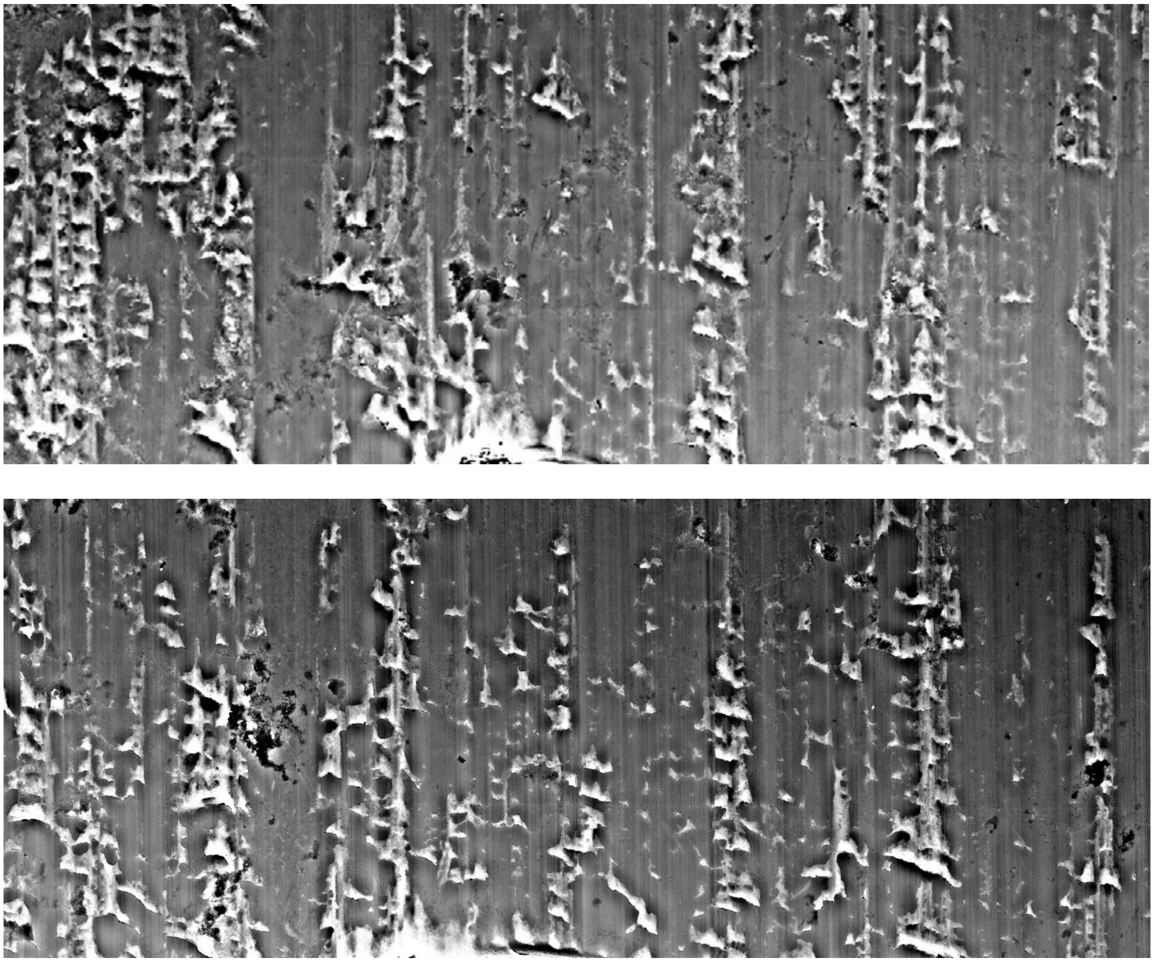
Examples of sections of these scans of the breach face from slide 7 and slide 8 where the machined surfaces have been prepared as a montage is shown in figure 10 and clearly the patterns suggests there are no subclass characteristics. This section of the breech face was just under the firing pin and the images have been inverted and sharpened to bring out the contrast using photoshop.

**Figure 10.**



The portion of the breech face above the firing for slide 7 and slide 8, shown in figure 11, are also completely different and again show no significant correlation or match.

**Figure 11.**



### Results of Cross Correlations for Determining a Match

The Pearson's correlation coefficient, r, can be used to compare two topographies or 2-D confocal profiles and is defined as:

$$r = \sum(x_i - x_m)(y_i - y_m) / (\sum(x_i - x_m)^2)^{1/2} (\sum(y_i - y_m)^2)^{1/2}$$

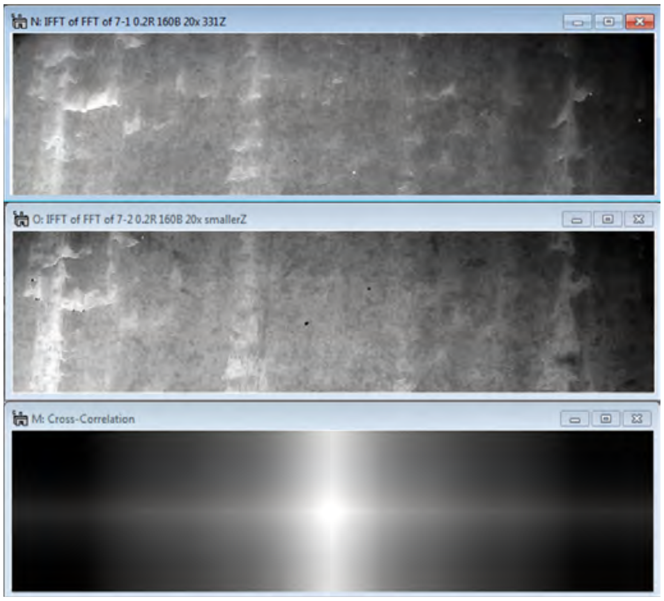
where $x_i$ is the value of the $i^{th}$ pixel in the topography or profile of the first array, $y_i$ is the value of the $i^{th}$ pixel in the second array, $x_m$ is the mean value of the pixels in the first array, and $y_m$ is the mean of the values in the second array. The correlation coefficient (r) has a value of 1 if the two arrays are absolutely identical and 0 if they are completely uncorrelated. This is the algorithm we have been using in Mathematica. The equivalent in MountainsMap is referred to as an intercorrelation routine and although the details of the algorithm are not provided it appears to be fairly similar and also invariant to linear transformations and so insensitive to variations in the magnitude of the pixel values associated with the brightness setting of the confocal microscope. The concerns we have about the comparisons are that the processing and filtering that we are using to create the profiles, although preserving the lateral coordinates (x and y) with reasonable accurately, does not do so well for the height values. Nevertheless theses algorithms provide a routine method of comparison for the profiles we are comparing and as shown by Thorburg et al. [4] such comparisons although disappointing in one of their breech face studies, the De Kinder set [11] where the coefficients essentially overlap the approach did show promise in the NBIDE set with a clear distinction with means differing from 20% to 65% for the non matched and matched cartridge cases. This distinction was improved upon by Weller et al. [12] with the set of sand blasted breech faces where the matched cases increased to 85% and we obtained similar results with our comparisons of both the sand blasted and machined breech face surfaces. This is interesting because the sub class characteristics do not appear to be responsible for the discrepancy suggesting that this may be related to a surface hardening of the sand blasted surfaces that makes them more resistant to changes associated with subsequent firings.

Nevertheless, the conclusion of the NIST study was that the cross correlation algorithms they used could not sufficiently distinguish breech face markings to support a database of the size that would be necessary for a National compilation and why improvements need to be made.

Although the processing parameters we are using to modify the topography scans are different from those available on the NIST website we typically see a distinction of about a factor of 1.5 in the cross correlation coefficients between matching and non-matching impressions of the unprocessed arrays when the comparisons are made at particular radial distances from the geometric center of the cartridge case using an algorithm developed in Mathematica that brings the two data arrays into registry when the cross correlation is a maximum. This ratio is improved to a factor of four in the processed images although the absolute values of the coefficients are reduced by a factor of three.

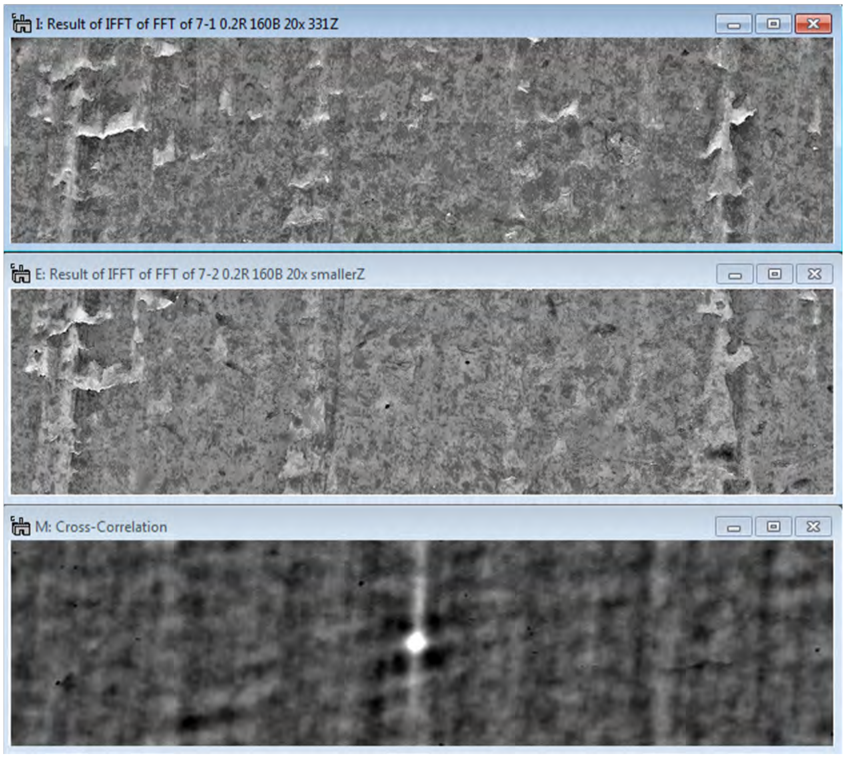
An example showing how the 2-D cross correlation don't work as well for the raw topographies is shown in figure 12 where we have the raw images for a cartridge cases fired consecutively along with the cross correlation image, which has a value of 0.929 and is centered at 2048 X 512 pixels.

**Figure 12.**



In figure 13, we show a pair of processed, background subtracted, images from cartridge cases from the same slides and the derived cross correlation function with a value of 0.1698, approximately centered.

**Figure 13.**



The differences in the magnitudes of the cross correlation functions between the raw images and the processed images arises because of the way the intensities are calculated and should not be a concern as long as the comparisons involve cross correlations obtained from images processed in the same way.

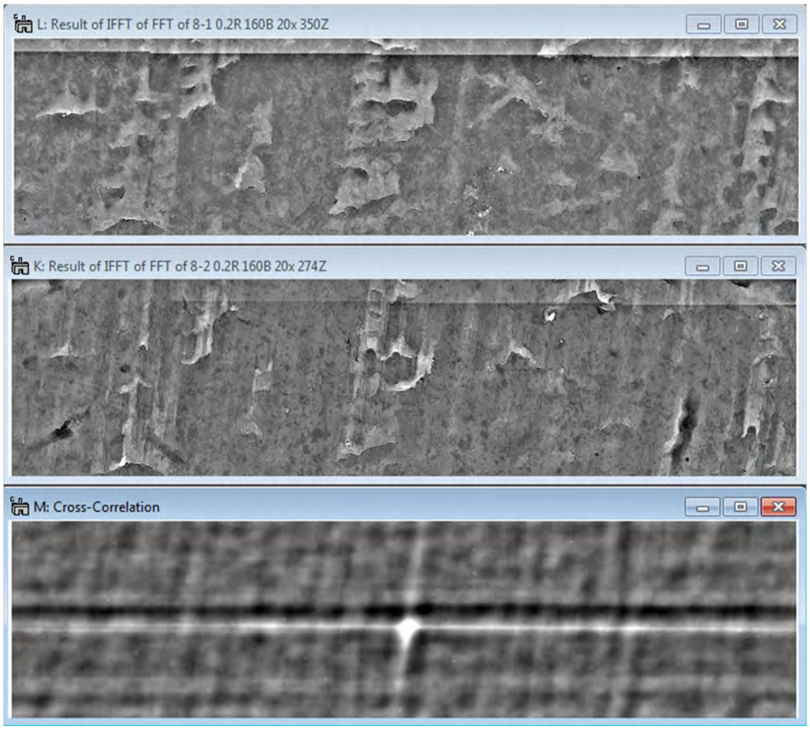
It is noteworthy that in both examples the cross correlation function is well defined although in the processed pair of images the center spot is much improved.

This can be compared to images obtained from matching cartridge cases where the cross correlation function is less well defined and this example is shown in figure 14 for the raw images.

**Figure 14.**

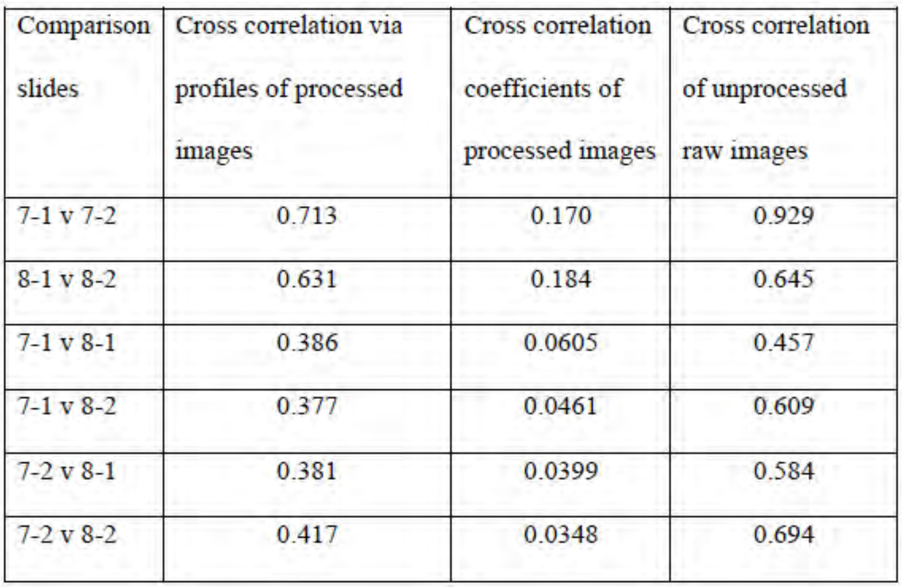
The definition is clearly improved in figure 15, which is from the processed data.

**Figure 15.**



The images from the different slides were invariably less well defined than those from the matching ones and the cross correlation from the raw images also reflects this. However by processing the images with background subtraction the differences in the cross correlation become far more consistent as can be seen from the data in table 1.

**Table 1.**



| Comparison slides | Cross correlation via profiles of processed images | Cross correlation coefficients of processed images | Cross correlation of unprocessed raw images |
|---|---|---|---|
| 7-1 v 7-2 | 0.713 | 0.170 | 0.929 |
| 8-1 v 8-2 | 0.631 | 0.184 | 0.645 |
| 7-1 v 8-1 | 0.386 | 0.0605 | 0.457 |
| 7-1 v 8-2 | 0.377 | 0.0461 | 0.609 |
| 7-2 v 8-1 | 0.381 | 0.0399 | 0.584 |
| 7-2 v 8-2 | 0.417 | 0.0348 | 0.694 |

This table also includes the results from an alternative technique which we explored because the pattern matching does not seem to work well on the impressions from machined breech faces, which may well have to do with the fact that there is essentially a repeating pattern along the length of these marks. This technique involves a direct determination of the presence of matching consecutive sequences and in the example here we used LMS text images for 4 cartridge cases, two of each having been fired from the same weapon. We determined the profiles by taking scans orthogonal to the striations on the cartridge cases and used a peak locating routine to determine the presence of the major minima. These profiles were then evaluated to determine the number of consecutively matching striations and in the one to one comparisons we found only five sequences for the known matching pairs. This being somewhat inconclusive, we did a cross correlation analysis of the profiles and found the same level of improved differences when comparing cartridge cases fired from the same weapon to those from different weapons. Again the processed values obtained from raw images are much less conclusive, presumably because the extraneous noise creates unreliable cross correlation values. Thus the cross correlation between single profiles, although not the best match criterion for bullets, appears to be a reliable measure of finding matches for cartridge cases fired from machined breech faces.

In all these examples the image processing of the LMS text images consists of initially importing the text images into ImageJ, after removing the header information in Excel, to form images that can be saved as tiff files. The image is duplicated and one of the duplicate images filtered through a 50 pixel, 25 micron, Gaussian blur filter. This filtered image is subtracted from the original to form a workable image with the background subtracted. These images are then binned and used in this format for the pattern matching routine. For the profile determination a selected area of the image is Fourier transformed and then inversely transformed with a 20-micron band pass filter. The profiles are determined from a 250 – 500 pixel wide transverse to the linear features from similar length regions. In the same manner cross correlation of the images is done comparing identical sized areas on the two images.

## RESULTS FOR DETERMINATIONS WITH PATTERN RECOGNITION ALGORITHMS

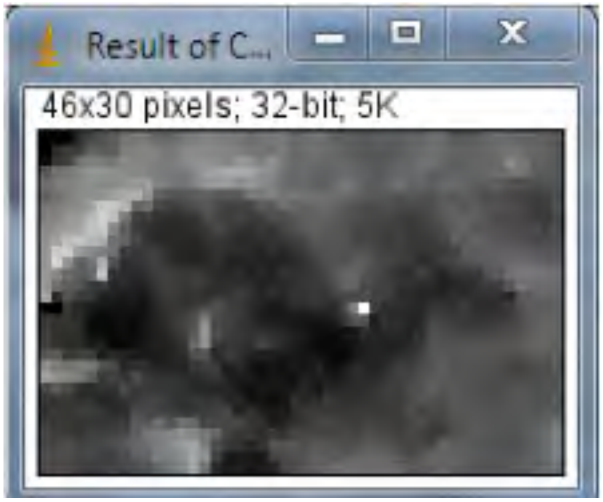
The approach we are exploring here is the use of pattern matching, something that is the basis for several image processing schemes. For this we are using a free-ware software package, ImageJ, readily available on the internet. ImageJ is written in Java code and as such allows third party development of add-ins, or plug-ins, for a variety of purposes. The plug-in algorithm denoted as Feature Finder is particularly useful for the pattern matching of the 3-D profiles and the analysis procedure consists of importing the processed LCM file into ImageJ, duplicating it, creating a background image by means of a Gaussian blur and subtracting this background image from the original to provide a processed image that retains all the original features but is normalized by the subtraction. The contrast in this processed image is enhanced to highlight the features and a particularly interesting feature is chosen as the prototype for matching. Although the choice of the prototype region for matching is subjective, we have found that any number of prototypes give the same results. The prototype image is processed through the other cartridge case images using Feature Finder in ImageJ to see if any matches are found. An example of the comparison of three confocal images from cartridge cases derived from the consecutively manufactured breech faces is shown next (figures 16 and 18) for 5 LMS text images of fired cartridge cases, 3 from one weapon and 2 from another, where we found perfect match and no-match results.

Each individual LMS image was about 5000 X 1000 pixels, with the pixel dimension of 0.4594 microns. A rather distinctive feature, 368 X 240 pixels, was chosen from of the images and used as the prototype template for the matching. As the area of the prototype is approximately 1/50th of the area of the image, in effect each cartridge case image constitutes 50 individual searchable images. We also created a 5000 X 1000 pixel image consisting of random numbers as the extreme case. All-in-all we had six 5000 X 1000 pixel images with 300 368 X 240 pixel searchable domains. We chose the prototype from one of the cartridge case in the group of 3 fired from one weapon so we would expect to find 3 matches in the database of the 300 images, which we did. The three matching topographical images are shown in figure 16.

**Figure 16.**

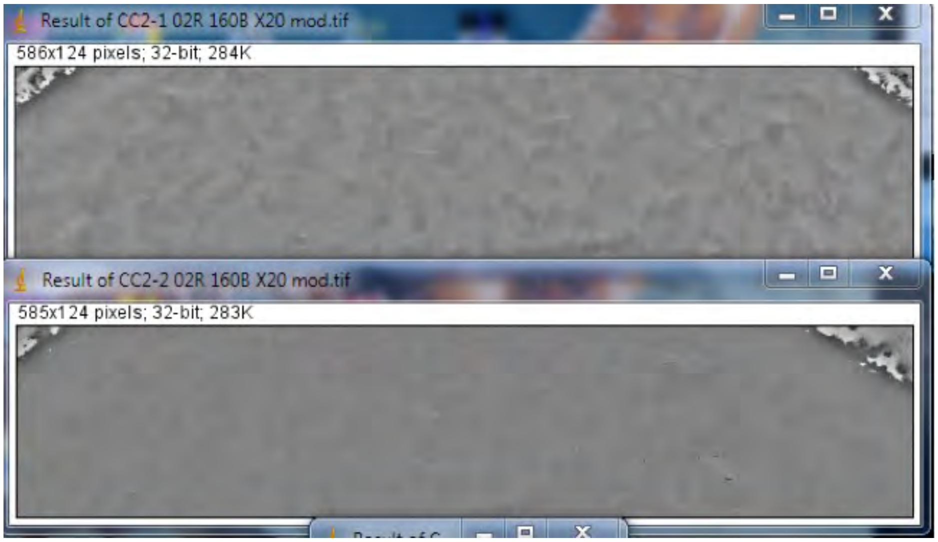
Figure 16 shows the three cartridge cases from the same weapon that were identified using a small prototype feature, shown in figure 17, which was chosen from a cartridge case from one of the slides from the set with the sand blasted finish.

**Figure 17.**



The match location is denoted by the cross in the image and for the limited number of cartridge cases we have evaluated we consistently find a match with cartridge cases fired from the same weapon, and no matches with cartridge cases fired from a different weapon (Figure 18).

**Figure 18.**

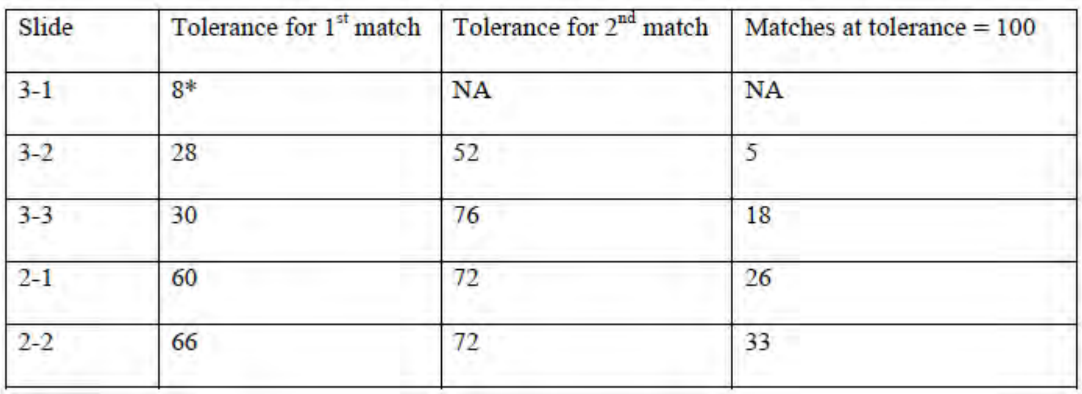


To speed up the pattern matching process with the computer we can reduce the image size from approximately 4000 X 800 pixels by binning. We have used of 8 X 8 and 16 X 16 binning and find both to give the same success in matching. In the 16 X 16 binning the original image is reduced to 250 by 50 pixels. A typical prototype might be 48 X 48 pixels, which when binned 16 X 16 is only 3 X 3 pixels, which is actually a bit small for reasonable pattern matching. In the case of the 16 X 16 binning the time to scan a single image is less than a second.

When performing this analysis we can also adjust the tolerance, which determines how much a feature may deviate from the prototype. A value of 0 requires an exact match with the prototype, while a value of 100 means that the deviation equals the variance of the prototype or that a lot of random images should match the prototype although we found no matches, even at a tolerance of 100, for the artificially generated random number images we created.

When the search routine is sped up by reducing the image size by binning, the tolerance for an exact match is not quite 0. The time required to search one original 5000 X 1000 pixel images takes about 10 minutes and reducing the size of the images using an 8 X 8 binning leaves about 590 X 124 pixels and 46 X 30 pixels for the prototype. The time to search on image is now less than 3 seconds and in the case of 8 X 8 binning, which we used here, the tolerance for an exact match using the image from which the template was chosen was 8. Setting the tolerance to 30 we again found matches in the 3 cartridge cases fired from the same weapon and no matches from the cartridge case fired from the other weapon. To determine a match in the cartridge case fired from the other weapon we had to set the tolerance to greater than 60 and then found a match at the edge of the image. In any event, setting the tolerance to 60 relaxes the deviation so much that a match can be found in almost any image but by keeping the tolerance below 30 we did not compromise the test sufficiently that we felt comfortable in finding only positive matches. If we did not bin the search times are rather long to incorporate into the search algorithm of a large database and so a sensible procedure would be to initially screen using an 8 X 8 binning and then to evaluate the potential candidates using the original images. As an example the data from the pattern matching exercise on five of the 5 cartridge cases is also given below in table 2. In this case there were no matches found using the random number generated image even for a tolerance of 100, so it is not included in the table. Table 2 shows the results of matching three out of three first matches for a database of 300 images and shows the tolerance for the second match and the number of matches at a tolerance of 100.

**Table 2.**



| Slide | Tolerance for 1st match | Tolerance for 2nd match | Matches at tolerance = 100 |
|---|---|---|---|
| 3-1 | 8* | NA | NA |
| 3-2 | 28 | 52 | 5 |
| 3-3 | 30 | 76 | 18 |
| 2-1 | 60 | 72 | 26 |
| 2-2 | 66 | 72 | 33 |

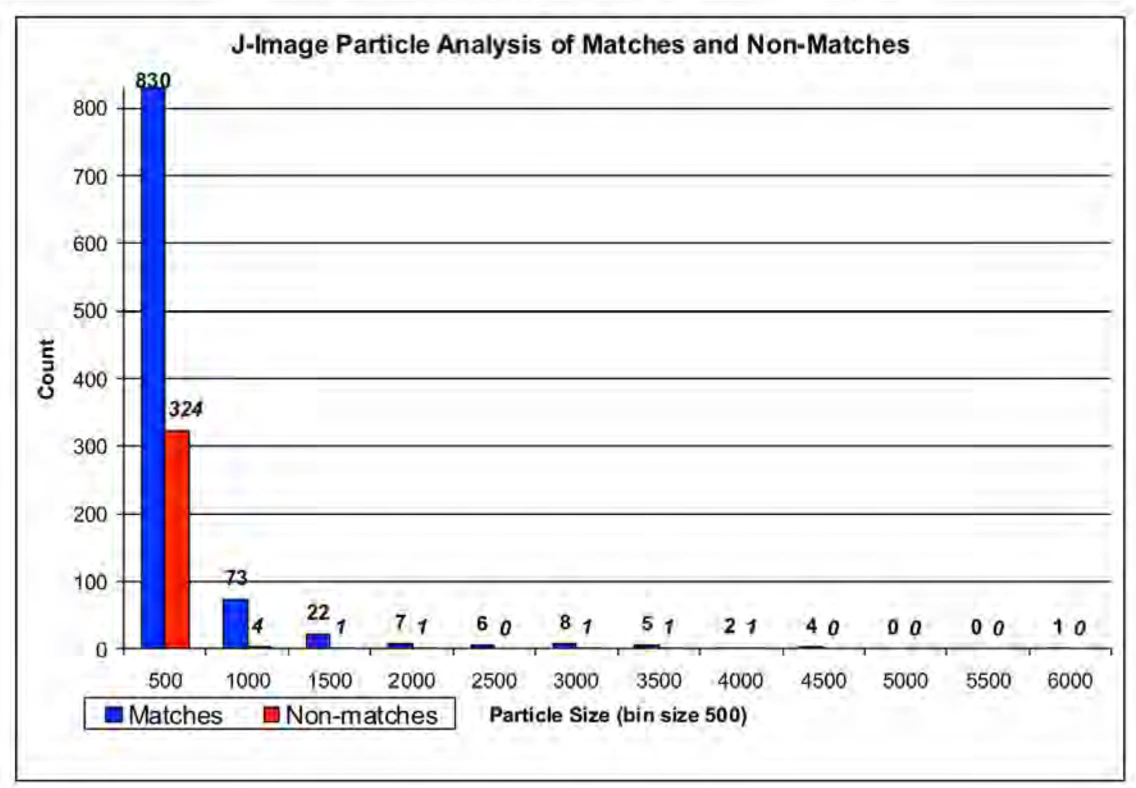
The prototype was determined from cartridge case 3-1 and compared to firings 3-1, 3-2 and 3-3 from slide 3 and 2-1 and 2-2 for slides 2. The table clearly shows that the tolerance for the first match for cartridge cases fired from the same weapon is significantly less than that required to find the first match in cartridge cases fired from a different weapon. The entire images were scanned and the first matches from the cartridge cases derived from the same slide were confirmed to be in the same region of the image. The tolerance value of 30 was needed to find them compared to the tolerance value of 8 that was needed to find the first match from a duplicate image from the same cartridge case that had been binned (8 X 8) after the prototype had been established. Thus anything found with a tolerance below 30 would be appropriate for a comparison of the raw images.

### METHODS FOR INTERPRETING AND COMPARING CONFOACL IMAGES

The original expectation was that we would be able to use confocal microscopy to directly compare cartridge case topographies and to distinguish the regions of identical correspondence, but even after several hours of scanning at the highest resolution the noise in the images was far too high to accomplish this without image processing. What we originally hypothesized was that when the topographies were compared, in the orientation that provided the best match or correlation that the cartridge cases fired from the same weapons would not necessarily contain more matching pixels but that the matching pixels would aggregate in larger clusters. This was based on the observations originally made by Biasotti for bullets [6], which was that it was the extent of the correspondence rather than the proportion that provided the most satisfactory criterion for identification. We have subsequently taken several different approaches to address this issue and the original attempt, to compare the distribution of the impression markings transferred to cartridge cases, was the subject of Todd Weller's thesis, which is attached as an appendix. This work involved the comparison of the impressions from the consecutively manufactured sand blasted Ruger P-95DC pistol slides that were interchanged in the same semi-automatic pistol. These comparisons were made using the confocal microscopy facilities at

NIST and are the ones that showed more promising correspondence characteristics than those they had previously studied. Nevertheless, when we compared the correspondence of the raw confocal scans at the position where the correlation coefficient is a maximum we found no significant difference between the distributions of the correspondence from the subtractions of the profiles from the matched or non-matched breech faces. However, when we repeated these experiments with carefully aligned optical images we did find measurable differences, which seemed to support the idea that the regions of matched correspondence were larger. Figure 19 below is an example the comparison is made for particle clusters increasing in size by increments of 500 pixels. Bearing in mind that at least one large cluster is likely to be present, because the images are orientated so as to maximize the correlation coefficient, there is a drop from 40% to 5% in the proportion of the number of clusters below and above 500 pixels in size.

**Figure 19**.



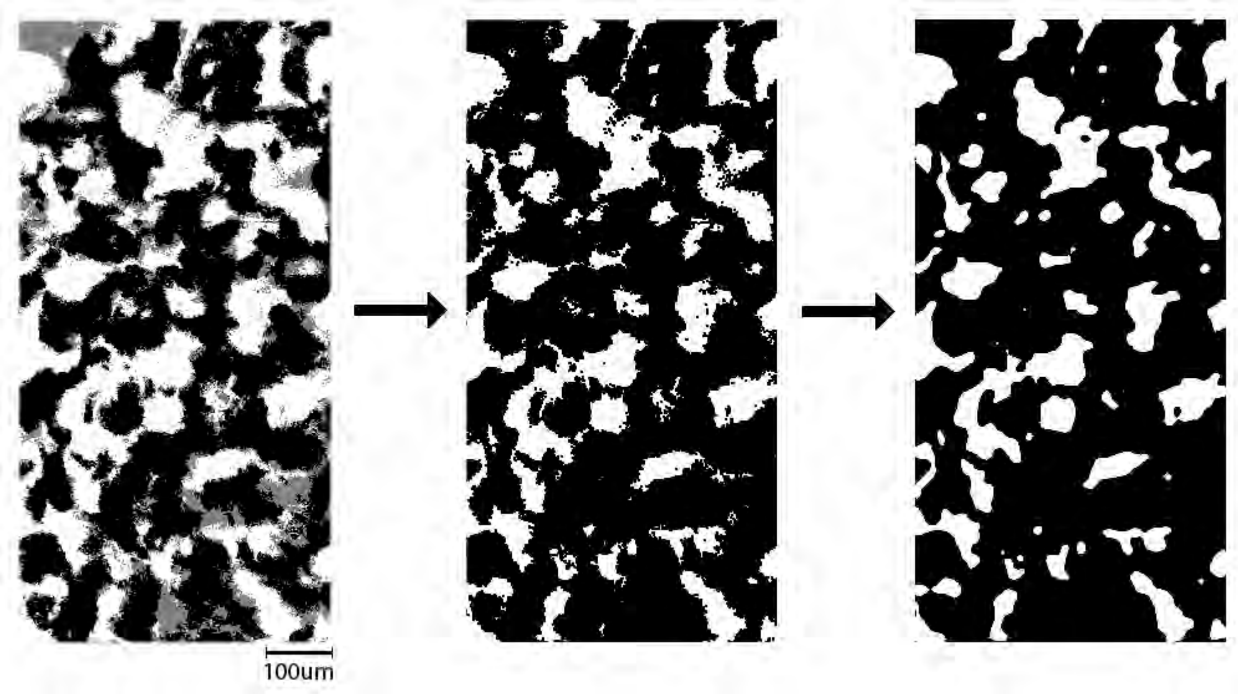
Nevertheless, we were unable to substantiate this idea with our first attempts at comparing the topographies obtained with confocal microscopy probably because of the signal-to-noise problem affecting the accuracy with which the height profiles can be distinguished.

At the time this work was done we were unable to compare the filtered output of the surface topography because the MountainsMap software cannot provide a two-dimensional output. As a result, we had to work with the data in an Excel format, which is far more difficult to bring into registry for subtraction than the images themselves forcing us to develop other options for image registration and comparison.

We finally accomplished this using confocal images that were processed, overlaid, and binarized in Mathematica. During the binarization process, only the overlapping feature maxima were considered regions of match. The binarized images were then imported into ImageJ and smoothed using a Fourier transform to limit the remaining small regions of noise without altering the overall percentage of matching features between two cartridge cases. Particle size analysis was then performed on the resulting image. The results indicate that the number of the regions of correspondence is approximately the same for both matches and non-matches, but the size of the regions in a known match case are consistently larger.

Figure 20 is an example of the processing routine from a known match.

**Figure 20.**



The first image of the flow shows the overlay of two images where white regions correspond to overlapping maxima, black to overlapping minima, and grey to regions of non-match. The second image illustrates the regions of interest that are retained, which are the overlapping maxima, and the third is the result after the smoothing function. Some other examples of fully processed known matches are shown in figure 21.

**Figure 21.**

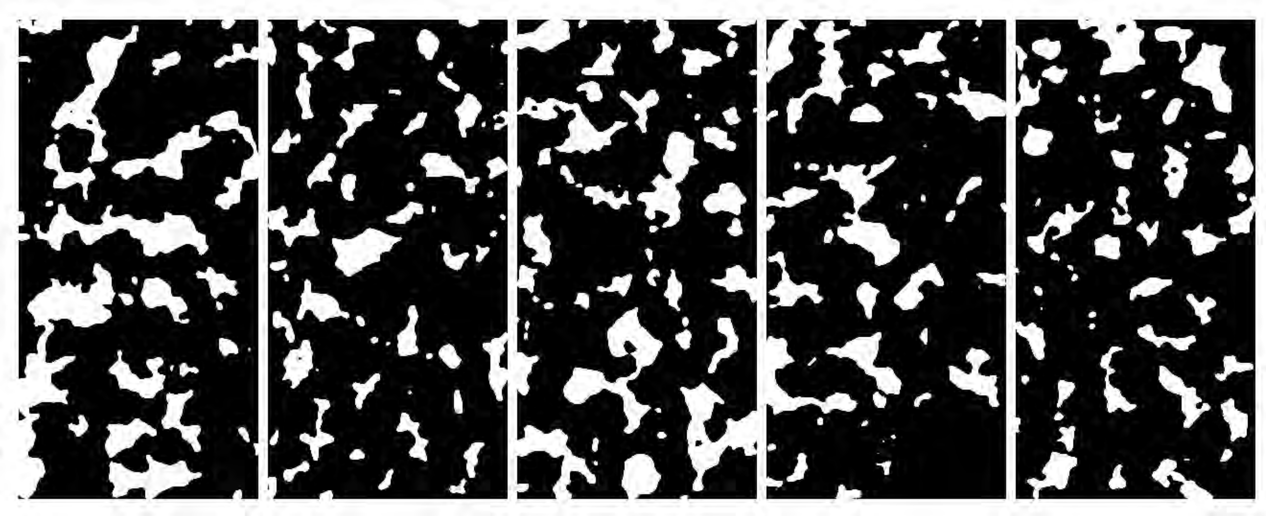


Figure 22 show the processing routine for a known non-match, as well as some other examples of fully processed known non-matches, which are shown in figure 23.

**Figure 22.**

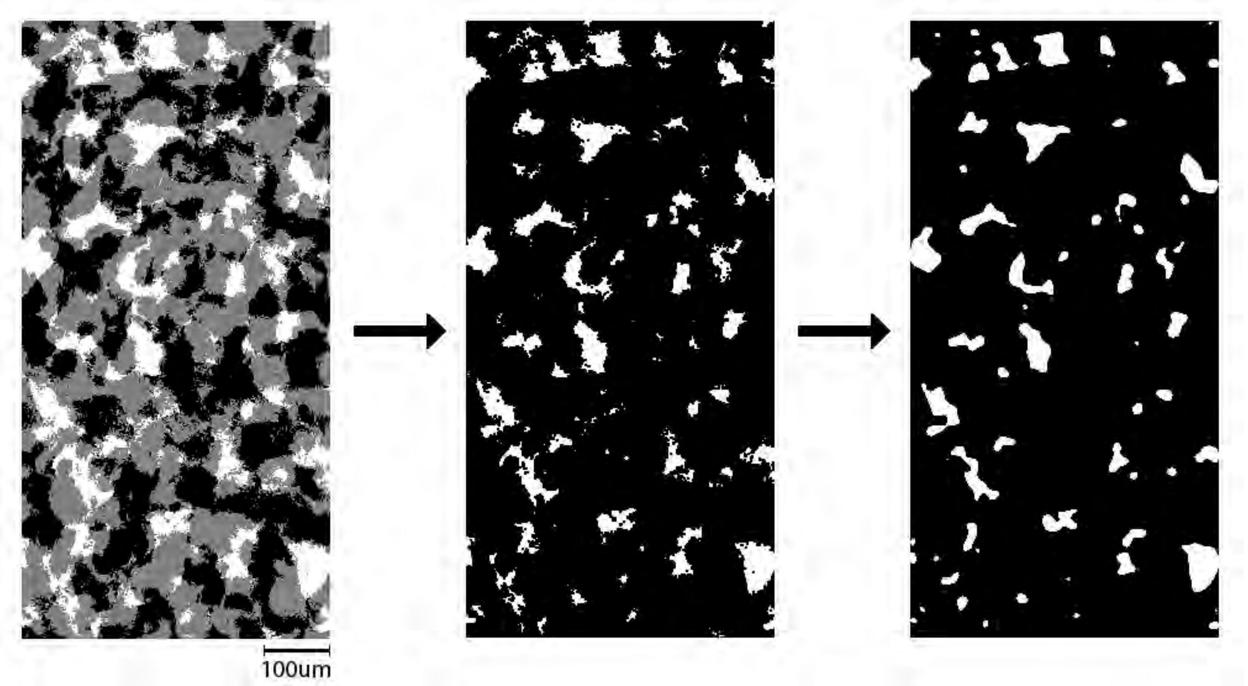
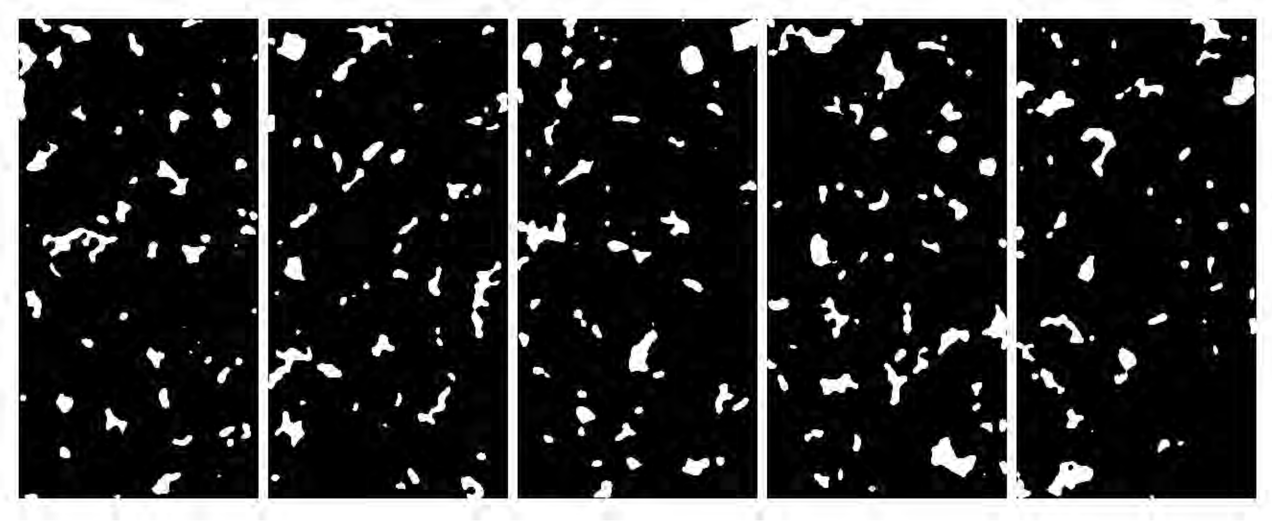


**Figure 23.**



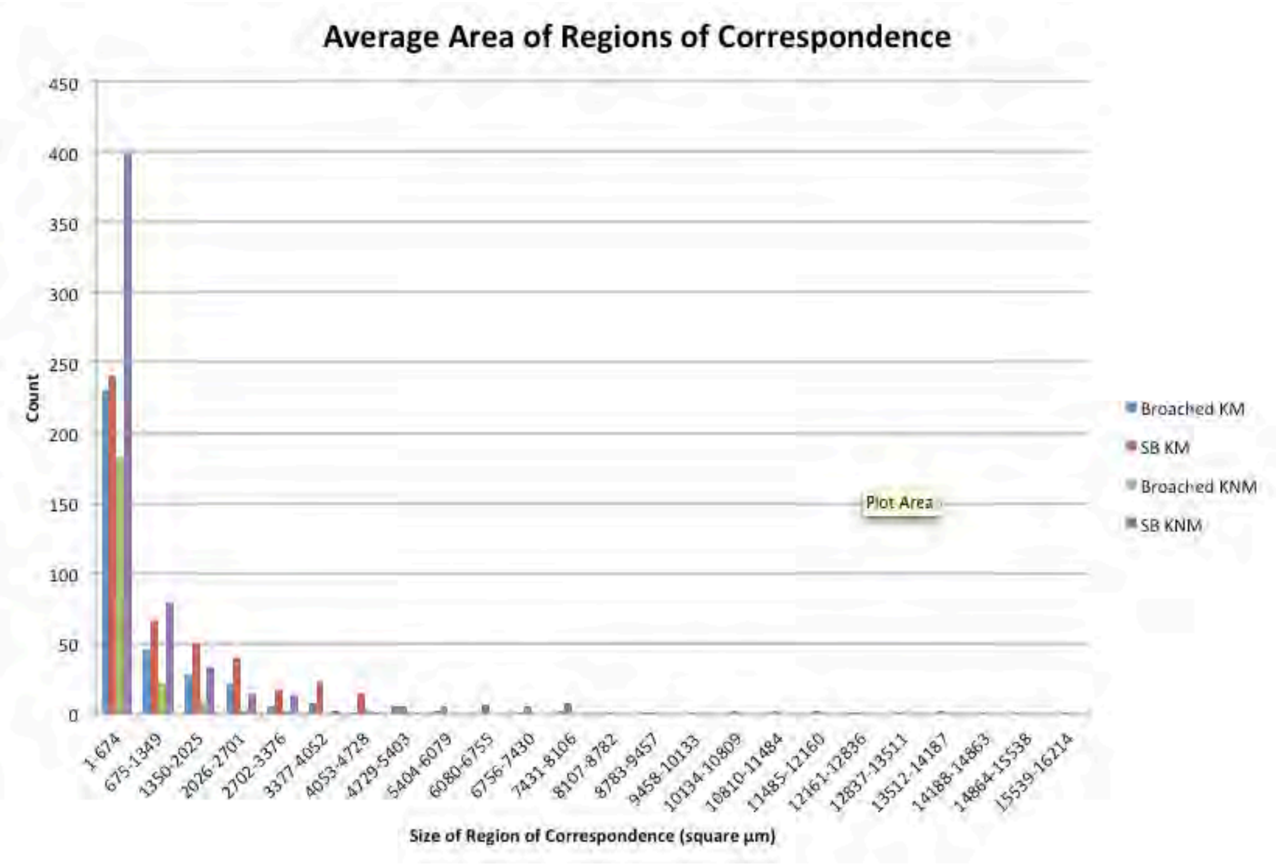
The difference in the correspondence characteristics are visually obvious and there are probably numerous ways in which this distinction can be exploited as an identification criterion. For example using ImageJ, we can apply particle size analysis to these smoothed images to determine the size and extent of the regions of correspondence in each image. Table 3 displays the average number of matching regions found in the different sets of overlays, along with the average area and perimeter of each region of correspondence.

**Table 3.**

| | | Number of Matching Regions | | Average Area of Regions of Correspondence ($\mu m^2$) | | Average Perimeter of Regions of Correspondence ($\mu m$) | |
|---|---|---|---|---|---|---|---|
| | | Mean | Standard Deviation | Mean | Standard Deviation | Mean | Standard Deviation |
| Broached | Match | 35.4 | 7.7 | 977.5 | 313.6 | 134.8 | 29.0 |
| | Non-match | 22.1 | 3.9 | 394.0 | 126.2 | 73.0 | 13.6 |
| Sandblasted | Match | 50.1 | 10.4 | 1916.0 | 597.4 | 194.4 | 42.5 |
| | Non-match | 54.3 | 5.7 | 571.1 | 78.7 | 94.1 | 7.2 |

We found that the number of regions of correspondence doesn't differ significantly between the matching and non-matching cases; however, the average area and perimeter of the regions in the matching case were larger than in the non-matching case. While there isn't a distinct separation between the cases at a 95% confidence level, the average area of the regions of correspondence in known non-matches are smaller by a factor of about 2.5 in the broached case and a factor of 3 in the sandblasted. The histograms of the average areas of correspondence also show the distinction between known matches and known non-matches and these are shown below for both cases where the areas of correspondence are given in square microns (figure 24). The areas of correspondence in the known non-matches rarely exceed 0.005 square millimeters whereas those from the cartridge cases fired from the same slides can be as large as 0.016 square millimeters.

**Figure 24.**



Figures 25 and 26 show the same data as figure 24 on a condensed scale, for the broached and sandblasted cases.

**Figure 25.**

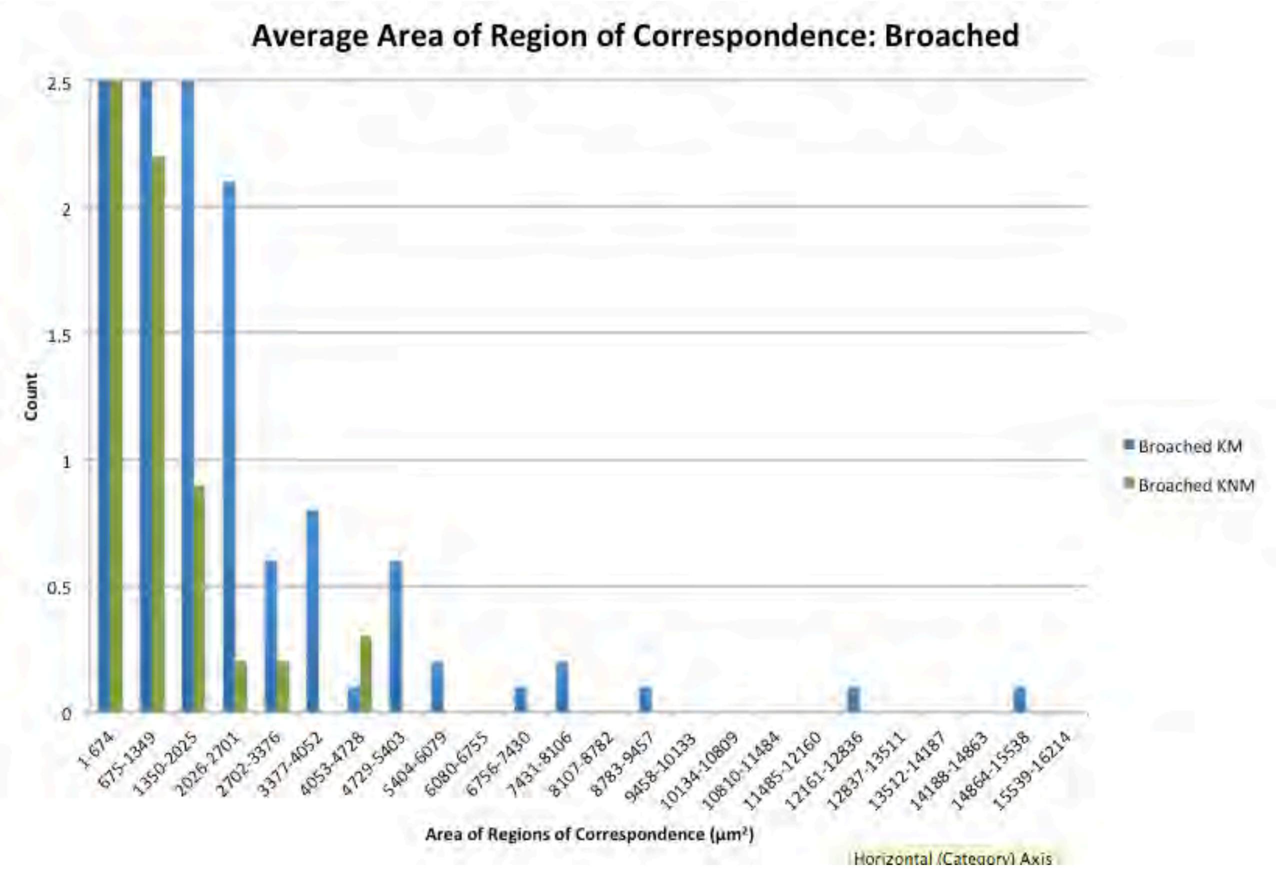
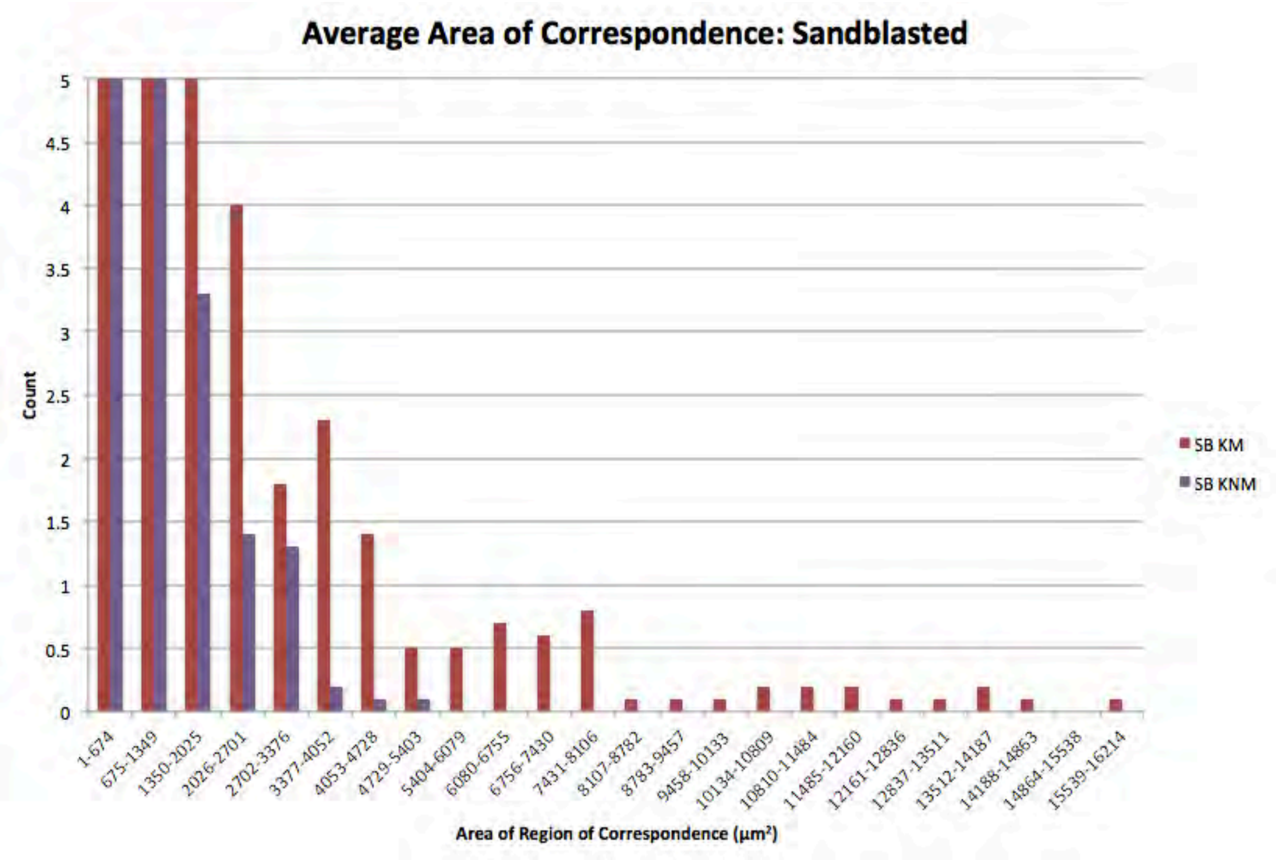
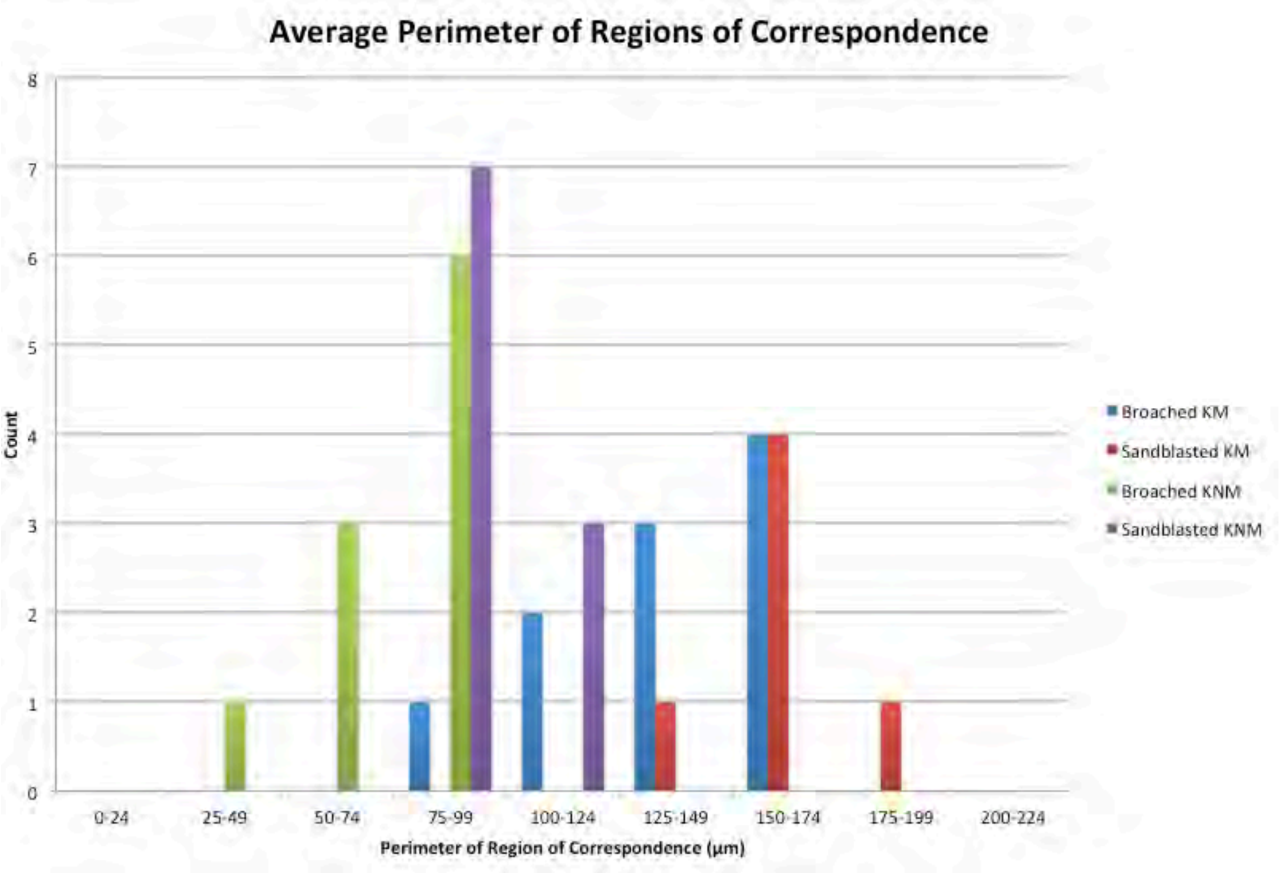

Average Area of Region of Correspondence: Broached
Count
2.5
2
1.5
1
0.5
0
1-674
675-1349
1350-2025
2026-2701
2702-3376
3377-4052
4053-4728
4729-5403
5404-6079
6080-6755
6756-7430
7431-8106
8107-8782
8783-9457
9458-10133
10134-10809
10810-11484
11485-12160
12161-12836
12837-13511
13512-14187
14188-14863
14864-15538
15539-16214
Area of Regions of Correspondence (μm²)
Broached KM
Broached KNM
Horizontal (Category) Axis

**Figure 26.**



Also useful are the measurements of the interfaces that separate the regions that correspond from those that do not and figure 27 shows the average perimeter of the regions of correspondence for the different datasets.

**Figure 27.**



Here again we find the lengths of the boundaries reflect the presence of the larger regions but the interpretation is not straightforward because the regions of correspondence are not isolated clusters, which is what the particle analysis routines are designed to measure. Indeed in the well-impressed and highly matched regions it is the regions of non-correspondence that are isolated. Nevertheless the distinctions can be quantified although not algebraically and we reverted to the analysis of randomly generated binary images, representing an overlay, to quantify the results and determine the probabilities of different sized areas of correspondence which are shown next.

All of these observations are consistent with our original hypothesis that by examining the extents of the regions of highest correspondence and counting the frequencies and size distribution of these occurrences it should be possible to improve the cartridge case matching algorithms. Furthermore, using numerical models to determine the probabilities associated with particular sized regions of correspondence, we can quantify the significance of any particular match.

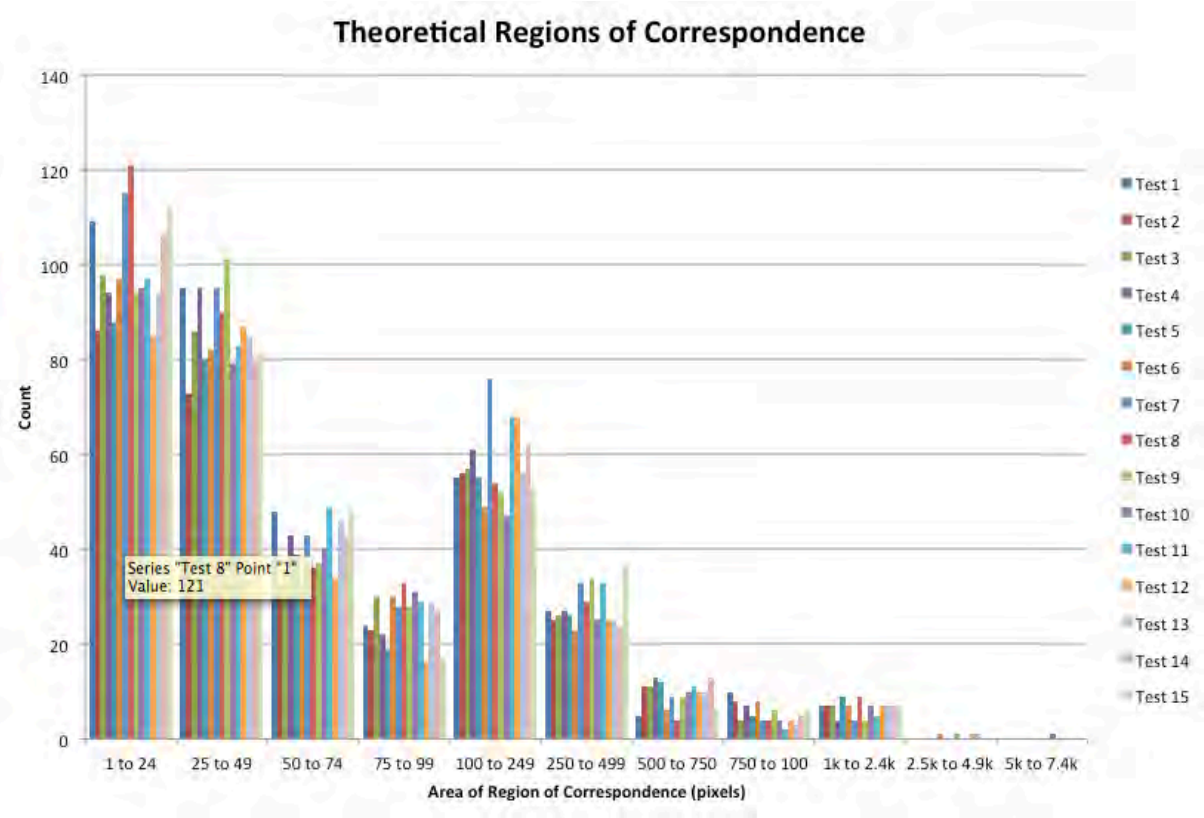
Another observation that we were able to make was that the actual changes to the breech face as an impressing surface appear to produce significantly less variation in the sequential cartridge cases than we see in bullets. This is almost certainly contributing to the greater success of the cross correlation evaluation of cartridge cases but we anticipate even better results if the bias towards larger regions of correspondence being associated with a match is taken into account.

### MATHEMATICAL MODELING AND THE NUMERICAL PROBABILITIES

The subjective interpretation of the significance of a tool mark comparison is at best a simplistic approach to a complicated problem, and in some instances, it can be totally misleading. Although common sense would seem to dictate that the more correspondence there is the greater the likelihood that the tool marks are derived from the same object, it was demonstrated by Biasotti in the 1950's [6] that this premise could not be validated for bullets and that only the extent of the correspondence was a valid determinant. This is because the large variations in the density of the impression marks significantly affect the probabilities for one-dimensional correspondence and although the same has not been established for cartridge cases our experiments have shown that there is indeed a consistency to the larger size of the individual areas of correspondence in matching cartridge case. That we were unable to develop of an algebraic approach we have evaluated the various ways in which correspondence can be quantified in two dimensions based upon the behavior of random images. Using Mathematica, a random number generator creates two-dimensional arrays, where ones represent a one-to-one pixel match of two overlaid images. Morphological Component Analysis or Image Analysis can then be applied to these arrays in order to determine the areas of the contiguous regions of match. By repeating this analysis over thousands of randomly-generated arrays and recording the frequencies of the size of the areas of the matching regions, we can ascertain the likelihood of obtaining a matching region of particular area and a numerical probability that the cartridge cases have a common origin.

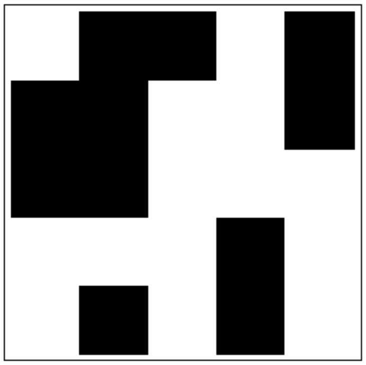
Although one might anticipate a systematic decrease in the number of the areas of correspondence as they become progressively larger this turns out not in fact to be the case when all possibilities of a contiguousness are considered. The consequence of considering all eight of the near neighbors to the individual pixels results in a large contiguous elongated region to the random images that essentially weaves it's way through the images like a long string. Thus there is actually a bimodal distribution to the size of the areas that match. Figure 28 displays the bimodal distribution seen in 15 of the randomly generated overlays; however, the data has been smoothed slightly to make the trend more visible.

**Figure 28.**



The bimodal characteristic can be removed by either restricting the contributions from the near neighbor sites, which we have done in the morphological component analysis or by filtering and thresholding prior to image analysis. An example of a portion of one such array using morphological component analysis restricting it to four near neighbor site, thus excluding diagonal continuity is exemplified in the next figure. Here the image (figure 29) has been converted it into a binary-colored grid with black pixels representing ones, pixels that match, and white pixels representing zeroes, pixels that don't match.

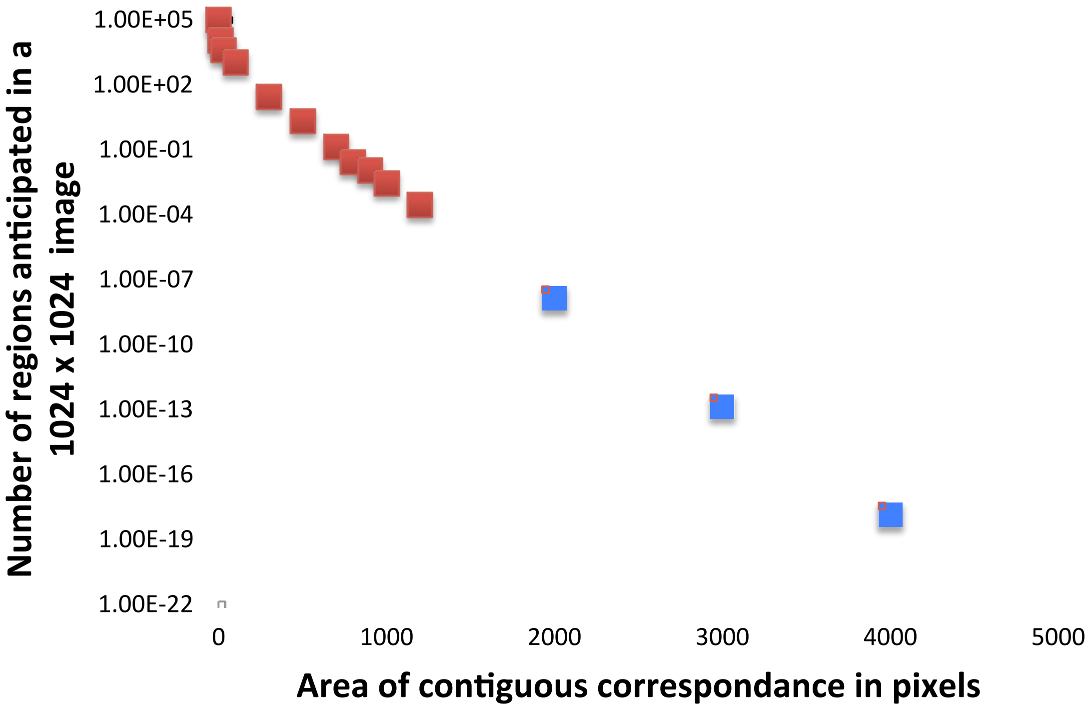
**Figure 29.**



In this simplified example of the numerical probability approach using an array plot of dimensions 5x5, Morphological Component Analysis would output four regions of match with areas 6, 2, 2,and 1.

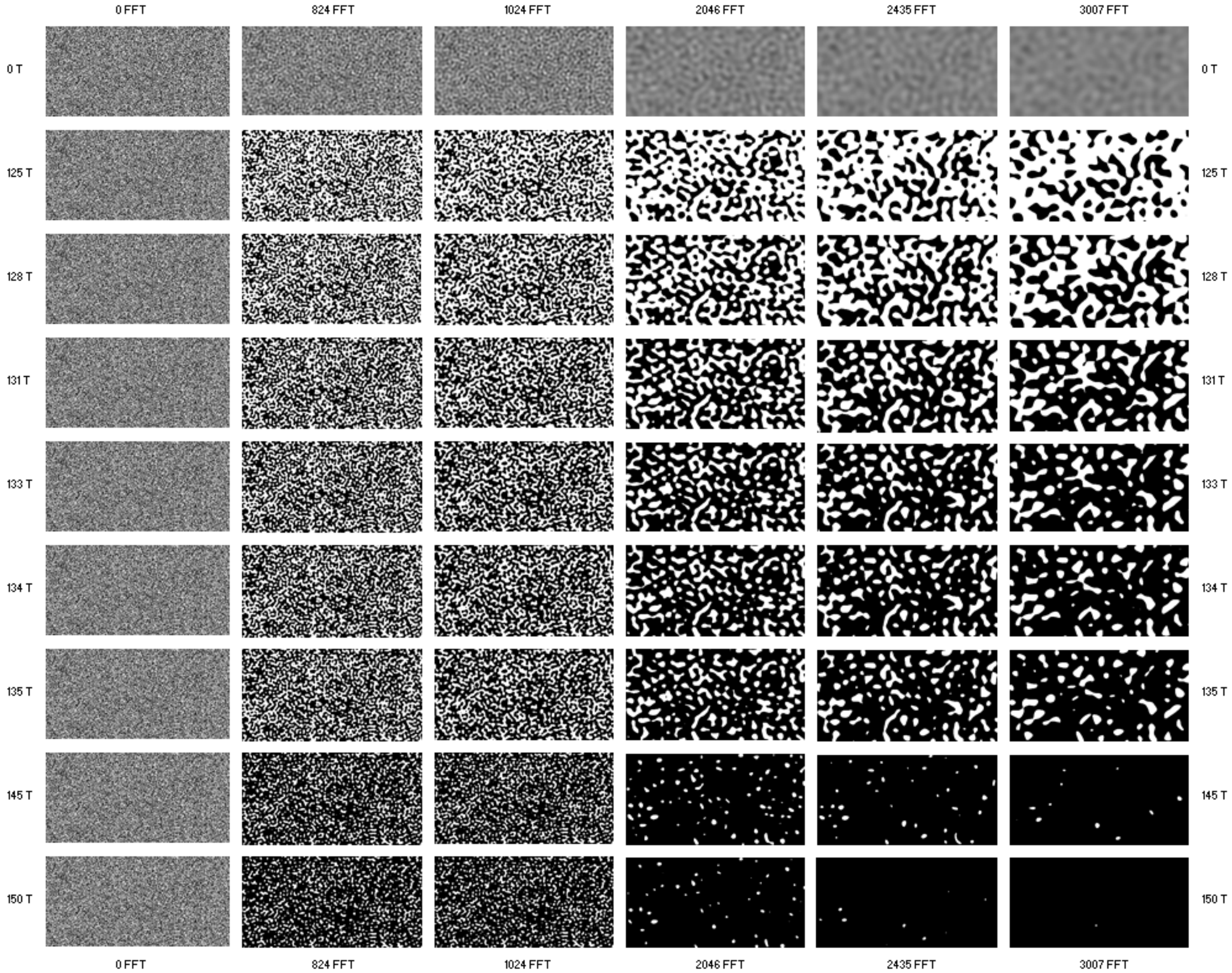
The results produced after creating 5,000 random 1024x1024 array generations are shown in figure 30, the data points are depicted in red and the blue points are extrapolations that indicate the trend.

**Figure 30.**



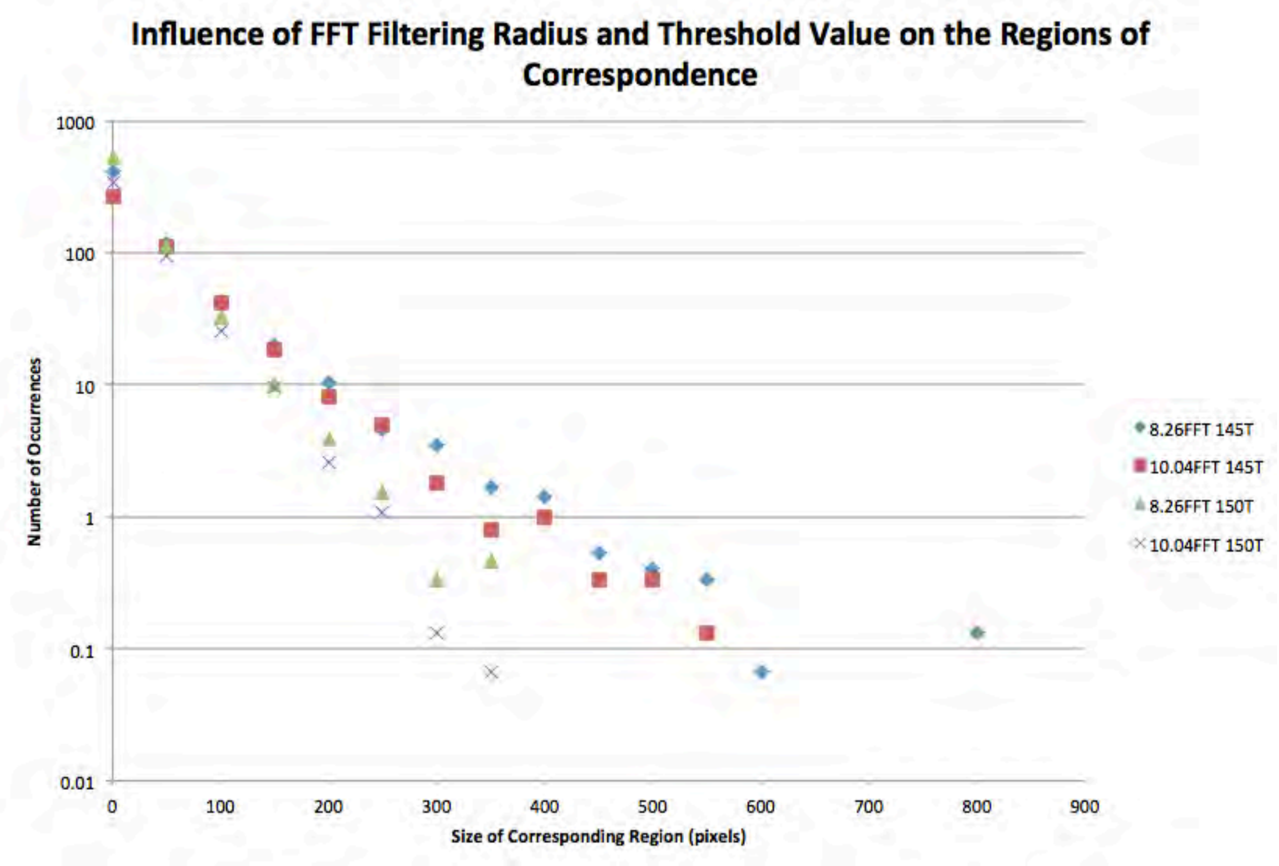
Using the image analysis routines in ImageJ we see the same consequences of different filters and thresholding criteria on the second peak in the random image comparisons. Although the second peak is real it is clearly not the sort of continuity that would contribute to a subjective match because the connectivity is very narrow in the regions that are filtered out and would be below the resolution that an examiner could distinguish. Figure 31 exhibits the influence of filtering radius and threshold level on the connectivity of the matching regions.

**Figure 31.**



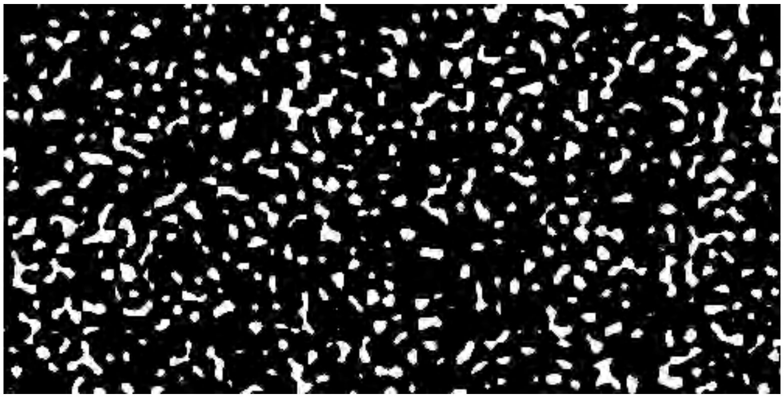
In the figure, each column represents a different filtering radius for smoothing with the Fourier transform, increasing in value across the figure. The different threshold levels used after filtering are shown in each row below, increasing down the figure. Four images, combinations of 8.26 and 10.04 filtering radii and 145 and 150 threshold levels, seemed to exhibit a decreased continuity of matching features while maintaining the overall pattern of the images. This data was tested using particle size analysis and the following trends (figure 32) were obtained.

**Figure 32.**



The data indicate the best trend with a radius of 10.04 pixels and a threshold of 150. As can be seen in figure 33, the majority of the connectivity is avoided without drastically changing the overall shape of the features at these parameters.

**Figure 33.**



## CONCLUSIONS

### Discussion of Findings

The conclusions that can be drawn from this work indicate that although cross correlation algorithms may be unable to distinguish between large numbers of confocal cartridge case images this does not necessarily reflect on the validity of the techniques of comparison microscopy. In the first place confocal microscopy has the capability to make far more accurate comparisons of the surfaces of cartridge cases than is currently being realized. This is principally because of software limitations and the inability to rotate the 3 dimensional images that are possible to obtain, in their entirety. It is also noteworthy that the one to one assessment of cartridge cases in a comparison microscope is far superior to the comparison of recorded images and although conventional optical microscopy is far more suited to the detection of the surface irregularities associated with this type of impression evidence, providing high contrast images with very low noise in short periods of time the specificity of the illumination conditions and specimen orientation cannot approach that of a comparison microscope. Although confocal microscopy has the potential for reconstruction and manipulation of the surface topography, thus eliminating the variables associated with illumination and orientation, this has yet to be fully realized with the instrumentation that is currently available and so even the success we have had in improving the distinctions between matching and non-matching cartridge cases still falls short of the one to one optical comparison.

Nevertheless in terms of the interpretation and assessment of the surface profiles of cartridge cases using confocal microscopy it is clearly possible to improve upon the application of correlation techniques by taking into account the extent of the individual area of correspondence much in the same way that imposing consecutive matching criteria reduce the probabilities of the random occurrence of matches in bullets. It is also apparent that advantage could also be taken of other common techniques that are used for image matching and evaluating the similarities in different types of signals including pattern recognition and Morphological Component Analysis and the incorporation of these types of comparisons to the search algorithms have the potential to significantly increase the size of a functional database before it is overwhelmed by false positives. Furthermore in the same way that probability distributions can be predicted for bullets using algebraic expression that describe the random occurrence of particular regions of linear correspondence the prediction of area correspondence using randomly generated images can also provide quantitative measures of the likelihood of regional overlap. Indeed regions of overlap exceeding 1500 pixels from processed confocal images can be taken as a million to one chance of occurring at random.

## Implications for Policy and Practice.

The implications of this study pertain to several of the issues facing the field of cartridge case evaluations including support for the methodology in terms of recognizable features that can be used by the examiner for quantifying the correspondence that they see, the determination of alternative approaches to the way in which current search algorithms could be improved for data base applications as well as a comprehensive evaluation of the techniques of confocal microscopy as they pertain to this particular discipline. Clearly the successful substitution of confocal microscopes for the optical microscopes currently used for imaging cartridge cases for database purposes is going to require at least some software development although the adoption of quantitative measures, including not only the overall proportion of correspondence but the correspondence of regions above a particular size, could be utilized immediately by an examiner to determine the significance of a match, based upon the calculations we have developed for the determination of area correspondence by random chance.

## Implications for Further Research

Further research in this area that would be of direct benefit would be the development of computer software that truly compares the reconstructed topography rather than projections from them, which is currently the case for all the commercial systems that have been examined. We are confident enough however, in the significance of the results, that the implementation of these methods and the gathering of data to create a prototype database should accompany, if not precede any future research in the area.

## REFERENCES

1. Cork, D. L., Rolph, J. E., Meieran, E. S. and Petrie, C. V. *"Ballistic Imaging: Report of the Committee to Assess the Feasibility, Accuracy and Technical Capability of a National Ballistics Database"* National Academic Press Washington D. C. 2008.
2. AFTE Committee for the Advancement of Science of Firearms & Toolmark Identification, *"The Response of the Association of Firearms and Tool Marks Examiners to the National Academy of Sciences 2008 Report Assessing the Feasibility , Accuracy, and technical capability of a National Ballistics Database* August 20, 2008", AFTE Journal V.40. # 3, Summer 2008 PP234-244.
3. Geradts, Z. J. ,Bijhold, J., Hermsen, R. and Murtagh, .F., *"Image matching algorithms for breech face marks and firing pins in a database of spent cartridge cases of firearms"* Forensic Science International, 119, 1, 97-106, 2001.
4. Vorburger, T.V., Yen J.H., Bachrach, B., Renegar, T.B., Filliben, J.J., Ma, L., Rhee, H.G., Zheng, A., Song, J.F., Riley, M., Foreman, C.D., and Ballou, S.M. "Surface topography analysis for feasibility assessment of a national ballistics imaging database." *NISTIR 7362, NIST. 2007;*

5. Howitt, D. G., Tulleners, F., Cebra K. C., and Chen, S. J. *"A Calculation of the Statistical Significance of Matched Bullets,"* Journal of Forensic Sciences, 53, 4: 868-875,2008.
6. Biasotti, A. A. 1959. "*A Statistical Study of the Individual Characteristics of Fired Bullets,"* Journal of Forensic Sciences, Vol. 4, no.1, pp. 34-50.
7. Abramoff, M.D., Magalhaes, P.J., Ram, S.J. *"Image Processing with ImageJ".* Biophotonics International, 11, 7, pp. 36-42, 2004.
8. Rasband, W.S., ImageJ, U. S. National Institutes of Health, Bethesda, Maryland, USA, http://imagej.nih.gov/ij/, 1997-2012.
9. Schneider, C.A., Rasband, W.S., Eliceiri, K.W. *"NIH Image to ImageJ: 25 years of image analysis"*. Nature Methods 9, 671-675, 2012.
10. Pearsons cc coeff
11. De Kinder, J., Tulleners, F. and Thiebaut, H. *"Reference Ballistic Imaging Database Performance*", Forensic Science International, 2004;140:207-215.
12. Weller T. J., Zheng A., Thompson R. and Tulleners, F. *"Confocal Microscopy Analysis of Breech Face Marks on Fired Cartridge Cases from 10 Consecutively Manufactured Pistol Slides".* J. Forensic Sci, 57, 912-917 (2012)

## DISSEMINATION OF RESEARCH FINDINGS

Only conference presentations and the Thesis by Todd Weller have been disseminated at this time. We have not received copies of these proceedings, one at NIST and the other the NIJ conference in Florida but our copies of these papers as well as the proceedings of the CAC where papers were presented and abstracts published along with Weller's thesis are included as attachments.