The National Ballistics Imaging Comparison (NBIC) Project

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Abstract: In response to the guidelines issued by the American Society of Crime Laboratory Directors/Laboratory Accreditation Board (ASCLD/LAB-International) to establish traceability and quality assurance in U.S. crime laboratories, a NIST/ATF joint project entitled National Ballistics Imaging Comparison (NBIC) was initialized in 2008. The NBIC project aims to establish a National Traceability and Quality System for ballistics identifications in crime laboratories within the National Integrated Ballistics Information Network (NIBIN) of the U.S. NIST Standard Reference Material (SRM) 2460 Bullets and 2461 Cartridge Cases are used as reference standards. 19 ballistics examiners from 13 U.S. crime laboratories participated in this project. They each performed 24 periodic image acquisitions and correlations of the SRM bullets and cartridge cases over the course of a year, but one examiner only participated in Phase 1 tests of SRM cartridge case. The correlation scores were collected by NIST for statistical analyses, from which control charts and control limits were developed for the proposed Quality System and for promoting future assessments and accreditations for firearm evidence in U.S. forensic laboratories in accordance with the ISO 17025 Standard.

Keywords: Forensic science, ballistics identification**,** standard reference material, standard bullet, standard cartridge case, NIBIN, NBIC.

1. Introduction

In the late 1990s, the National Integrated Ballistics Information Network (NIBIN) was established in the United States [1,2]. The network currently includes approximately 200 installations nationwide, in which the Integrated Ballistics Identification Systems (IBIS*) [3] are used for ballistics signature acquisitions and correlations. To establish measurement traceability and quality assurance for laboratory assessment and accreditation using the ISO 17025 standard [4], the National Institute of Standards and Technology (NIST) in collaboration with the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) developed Standard Reference Material (SRM) 2460 Bullets and 2461 Cartridge Cases [5]. NIST also developed a two-dimensional (2D) and three-dimensional (3D) Topography Measurement and Correlation System for ballistics signature measurements [5-7]. In response to the guidelines recently issued by the American Society of Crime Laboratory Directors/Laboratory Accreditation Board (ASCLD/LAB-International) to establish traceability and quality assurance in U.S. crime labs [8], NIST and ATF have recently completed a joint project entitled the National Ballistics Imaging Comparison (NBIC) to establish a National Traceability and Quality System using the SRM bullets and

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

cartridge cases for NIBIN's acquisitions and correlations. In this paper, the NIST SRM Standard Bullets and Cartridge Cases Project, the NIST 2D and 3D Topography Measurement System and the proposed Traceability and Quality System are introduced in Sections 2 to 4. The correlation result, statistics analyses, control charts and control limits are described in Sections 5 and 6. Finally, in Section 7, quality assurance for NIBIN acquisitions and correlations is discussed.

2. The NIST SRM 2460/2461 Standard Bullets and Cartridge Cases Project

The NIST SRM 2460 Bullets and 2461 Cartridge Cases were developed as reference standards for ballistics laboratories to help verify that the computerized optical-imaging equipment in those laboratories is operating properly, to establish ballistics measurement traceability and quality assurance, and to promote laboratory assessment and accreditation in accordance with the ISO 17025 standard [4]. The SRM bullets are designed as both a "virtual" and a physical ballistics signature standard [5]. The virtual standard is a set of six digitized bullet profiles (see Fig. 1) used as the reference profiles to machine bullet signatures on the SRM bullets. The six profiles also serve as the reference standard for measurements of the machined bullet signatures on the SRM bullets, and help ensure that these measurements are traceable to the SI unit of length. These profiles were originally traced with a stylus instrument on six master bullets fired at the

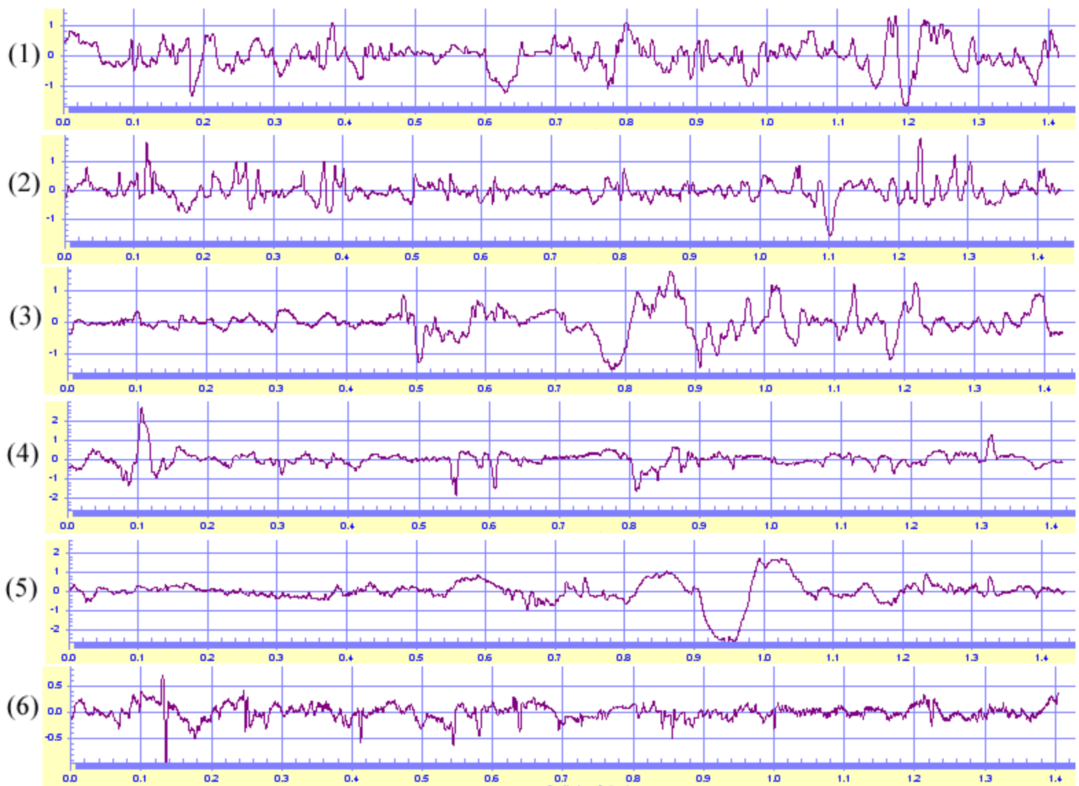

Figure 1. The virtual bullet signature standard consists of six digitized bullet profile signatures measured by a stylus instrument on six master bullets fired at the ATF and FBI. The virtual standard profiles shown above are modified profiles after curvature removal and Gaussian filtering defined in national and international standards [9,10] with a short wavelength cutoff of 0.0025 mm and a long wavelength cutoff of 0.25 mm. The vertical scale is in µm; the horizontal scale is in mm.

Figure 2: A SRM 2460 Standard Bullet (left) and a SRM 2461 Standard Cartridge Case (right).

National Laboratory Center of ATF and the Federal Bureau of Investigation (FBI) under standardized shooting and recovering procedures [5]. Each bullet was fired by a different handgun and the profile signature was taken only on one selected Land Engraved Area (LEA). An LEA is a region on the bullet that contains the impression of one of the lands of a rifled barrel. There are several lands in a rifled barrel and, consequently, there will be an equal number of LEAs on a bullet. The virtual standard (six bullet profile signatures, see Fig. 1) was stored digitally and used for control of the tool path of a numerically controlled (NC) diamond turning machine at the NIST Instrument Shop to machine the bullet signatures onto the SRM bullets [5]. Twenty SRM bullets were manufactured at the same time with each setup; forty SRM bullets have been produced so far. The virtual standard is also available from the NIST website for the Surface Metrology Algorithm Testing Service (SMATS) [11]. At this site, the user can download the LEA profiles and directly compare them with the corresponding LEA profiles measured on the SRM bullet with the user's own topography measurement system. Alternatively, the user can compare the surface topography parameters, such as the rms-roughness *Rq*, of the virtual standard profiles with parameters obtained from the corresponding profiles on the user's SRM bullet. Comparisons of profiles performed at NIST will be discussed in Section 3.

A SRM bullet is shown in Fig. 2, left. It contains six LEAs, each having a unique bullet signature manufactured by the NC diamond turning machine with a 5° twist, which helps to make the SRM bullet look like a real bullet. The material was made of oxygen-free, high conductivity (OFHC) copper rod with about a 1 mm thick pure-copper coating to avoid the crystal boundary effect in the diamond turning process [5]. After machining, a specially designed chemical etching process was used for roughening the surface of the bullet to improve its diffuse reflection without changing the bullet signatures and make the SRM bullet appear like a real bullet when observed under an optical microscope. Then, a commercial corrosion protection process was applied to the surface of the SRM bullets.

A SRM cartridge case is shown in Fig. 2, right. The SRM cases are manufactured by an electro-forming technique in which a master cartridge case fired at the National Laboratory Center of ATF is placed into an electrolytic tank where a negative replica is fabricated on the surface of the master. By repeating the same process on the negative replica, a positive replica is produced. These replicas from the single master comprise the set of SRM cartridge cases.

The reproducibility of the SRM bullets depends on the virtual standard and the NC diamond turning process. The reproducibility of the SRM cases depends on the master cartridge case and the electro-forming process [12]. Both SRM bullets' and cases' reproducibility are higher than 95 % when measured by the cross correlation function maximum CCF_{max} (see Section 3). Production of the SRM cases is currently in progress; about 150 SRM cases are scheduled for certification and sell in 2011.

3. NIST 2D and 3D Topography Measurement and Correlation System

The NIST 2D and 3D Topography Measurement and Correlation System is initially designed for topography measurements of ballistics signatures of SRM bullets and cartridge cases. Two parameters are used for quantitative representation of the similarity of surface topographies: a NIST proposed parameter called the signature (or topography) difference D_{s} and the cross correlation function maximum CCF_{max} [6]. The parameter CCF_{max} is the maximum value of the cross correlation function (CCF), which occurs when the two correlated surface topographies, the measured topography $Z_{(B)}$ and the reference topography $Z_{(A)}$, are registered at their maximum correlation position. At this position, a topography difference $Z_{(B-A)}$ is calculated that equals the difference between topography $Z_{(B)}$ and $Z_{(A)}$. The topography difference parameter, D_{s}, is defined as a ratio of the mean-square roughness Rq^2 of the topography difference $Z_{(B-A)}$ and the mean square roughness of the reference topography $Z_{(A)}$ [6]:

$$D_{\mathrm{s}} = Rq^2_{(B-A)} / Rq^2_{(A)}. \qquad (1)$$

When the two compared topographies $Z_{(B)}$ and $Z_{(A)}$ are exactly the same (point by point), D_{s} is equal to zero (and CCF_{max} must be 100 %). And when D_{s} equals to zero, the two compared surface topographies must be exactly the same [6]. Both parameters are given here because the value of CCF_{max} is not sensitive to a difference in scale height between two topographies with similar shape, whereas the value of D_{s} is sensitive to a scale difference [6].

For data acquisition, the topography measurement system includes a stylus instrument for contact measurements of 2D bullet signatures and a confocal microscope for non-contact measurements of 3D cartridge case signatures. A correlation software program is designed for topography registration and for calculating the parameters D_{s} and CCF_{max}. So far, 240 bullet profiles on 40 SRM bullets, one profile for each of the six Land Engraved Area (LEA) of the SRM bullet, have been measured using the stylus instrument with the 2D correlation program. The measurement results show high reproducibility for both the measurement system and the manufacturing process of the SRM bullets: all the CCF_{max} values are higher that 95 % and most of them are even higher than 99 % [7]. A procedure was developed for reporting the maximum value of D_{s} and minimum value of the CCF_{max} with 95 % confidence level [13]. 3D topography measurements for the breech face, firing pin and ejector mark of the SRM cartridge cases using a confocal microscope have recently been completed.

Figure 3 shows a user screen for a 2D bullet profile signature correlation of S/N SRM 2460-001 standard bullet (signature $Z_{(B)}$, shown as the second profile from the top) with the virtual

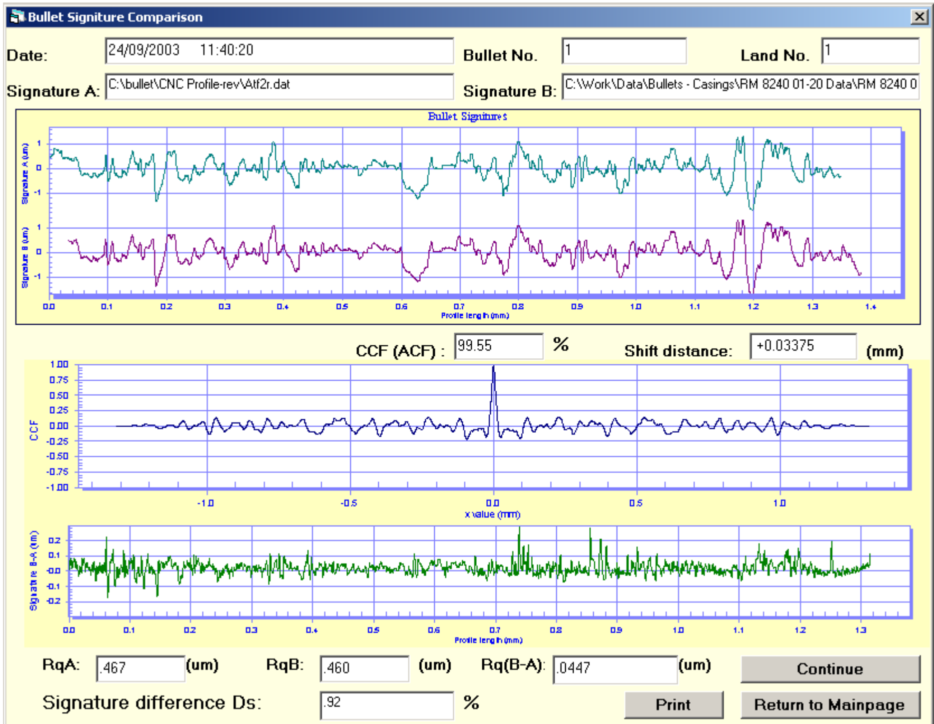

Figure 3. User screen for a bullet profile signature correlation of S/N SRM 2460-001 Standard Bullet (Signature B, shown as the second profile from the top) and the virtual standard (Signature A, shown on the top). The bottom profile shows the signature difference (B – A); the cross correlation function maximum $CCF_{\max}$ = 99.55 % ± 0.12 % (k = *2*), the signature difference D_s = 0.92 % ± 0.26 % (k = *2*).

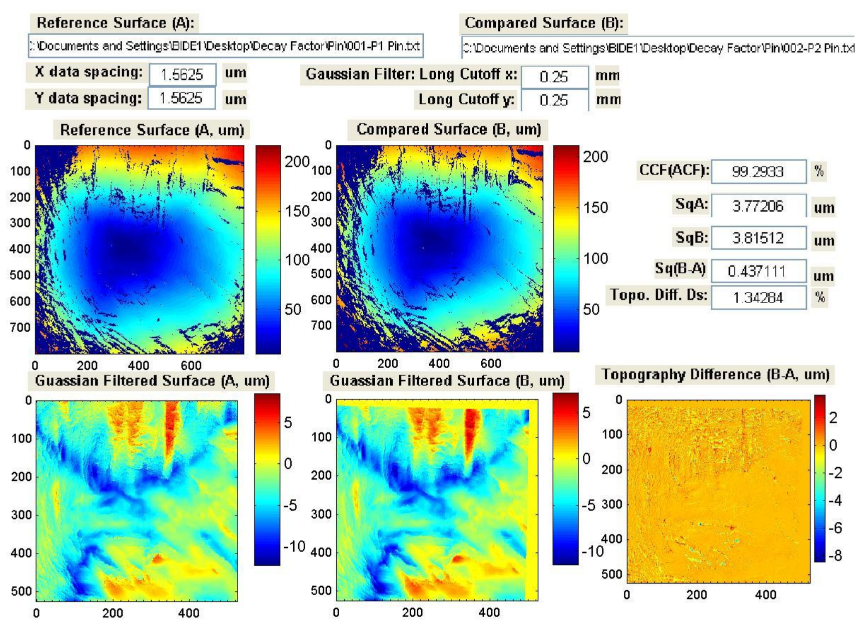

Figure 4. Topography correlation of firing pin images between prototype SRM Cartridge Cases 001 (top, left, used here as a reference) and 002 (top, right). The bottom row shows filtered images for 001 (left) and 002 (middle) cartridge case and the topography difference (right); $CCF_{\max}$ = 99.29 % ± 0.039 % (k = *2*), D_s =1.34 ± 0.70 % (k = *2*).

standard (signature $Z_{(A)}$, shown on the top). The bottom profile shows the signature difference $Z_{(B-A)}$. The cross correlation function maximum CCF_{max} is calculated to be 99.55 % ± 0.12 % ($k = 2$). The signature Difference D_s is calculated to be 0.92 % ± 0.26 % ($k = 2$).

Figure 4 shows a 3D topography correlation of firing pin images between prototype SRM Cartridge Case 001 (top, left, used here as a reference) and 002 (top, right). The bottom row shows filtered images for 001 (left) and 002 cartridge case (middle) and the topography difference (right). The Gaussian filter long wavelength cutoff length is 0.25 mm. The CCF_{max} = 99.29 % ± 0.039 % ($k = 2$), D_s =1.34 ± 0.70 % ($k = 2$).

Besides the topography measurements for SRM bullets and cartridge cases, the NIST topography measurement system has been used for tests of ballistics identifications in designed experiments, and has produced matching accuracies for cartridge cases and bullets higher than those of a commercial system for all experiments thus far [14,15]. It can also be used in other areas such as instrument characterization in surface metrology [16] and surface defect testing [17].

The NIST proposed CCF_{max} and D_s parameters have several features [6]:

- They are common available algebraic concepts and may be calculated from surface measurements traceable to the SI unit of length.
- The same parameters CCF_{max} and D_s can be used for quantifying signature differences for both 2D bullet profiles and 3D cartridge case topographies.
- For any 2D profile and 3D topography correlation, the minimum signature difference D_s is equal to zero (and CCF_{max} must be 100 %), which occurs when, and only when, these two profiles or topographies are exactly the same (point by point).
- Because surface information of all 2D or 3D data points is used for correlation, the CCF_{max} and D_s parameters have potential for improved accuracy of identification relative to methods using features obtained from subsets of the data points [14,15].
- Besides ballistics identifications, the CCF_{max} and D_s parameters can be generally used for topography measurements and correlations in other areas [16,17].

4. The Proposed Traceability and Quality System for NIBIN Acquisitions and Correlations

According to the *International vocabulary of metrology - Basic and general concepts and associated terms (VIM)* [18], ***metrological traceability*** is defined as:

> *property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.*

By the above definition, three key steps for establishing the metrological traceability for the topography measurements and imaging correlations of 2D and 3D ballistics signatures are proposed [19]:

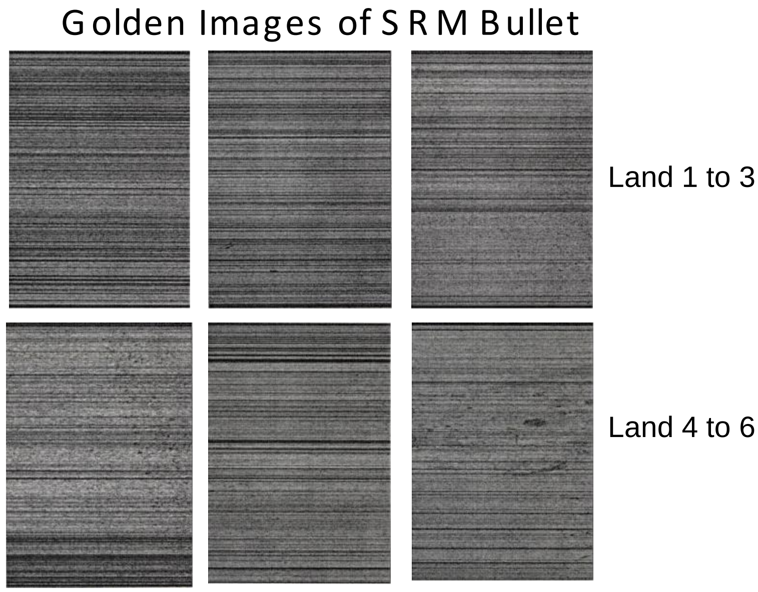

Figure 5. The Golden Image of six Land Engraved Areas (LEA) of the SRM 2460 Standard Bullet.

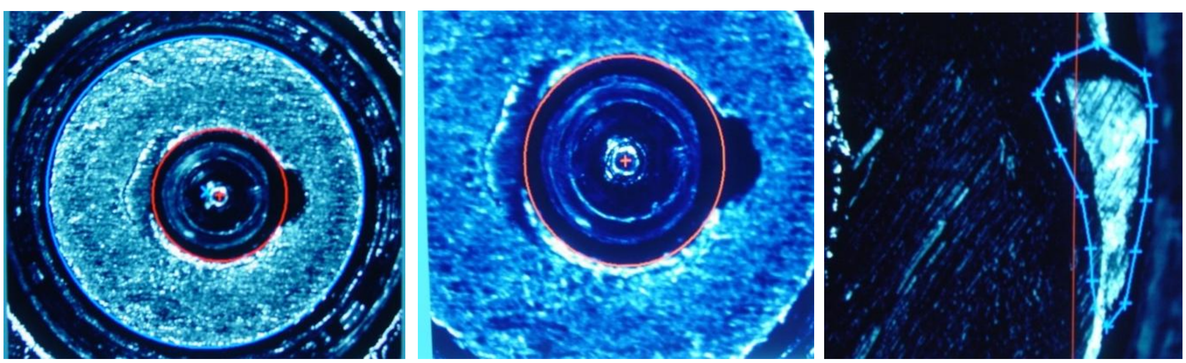

Figure 6. The Golden Image of the breech face (left), firing pin (middle) and ejector mark (right) of the SRM 2461 Standard Cartridge Case.

- Establish a reference standard, the NIST SRM bullets and cartridge cases, which are used as a reference for both the topography measurements at NIST and the imaging correlations for NIBIN acquisitions.
- Establish an unbroken chain of calibrations from the national laboratories, NIST and the National Laboratory Center of ATF, to local laboratories and customers using the SRM bullets and cartridge cases as reference standards. The unbroken chain of calibration covers both topography measurements at NIST and image correlations for NIBIN. For the topography measurements, the measurement traceability is established using the virtual/physical SRM standard and the proposed parameters D_s and CCF_{max}. For the image correlation systems like IBIS, the traceability is established by image acquisitions of SRM bullets and cartridge cases at local IBIS sites, and correlations with the image

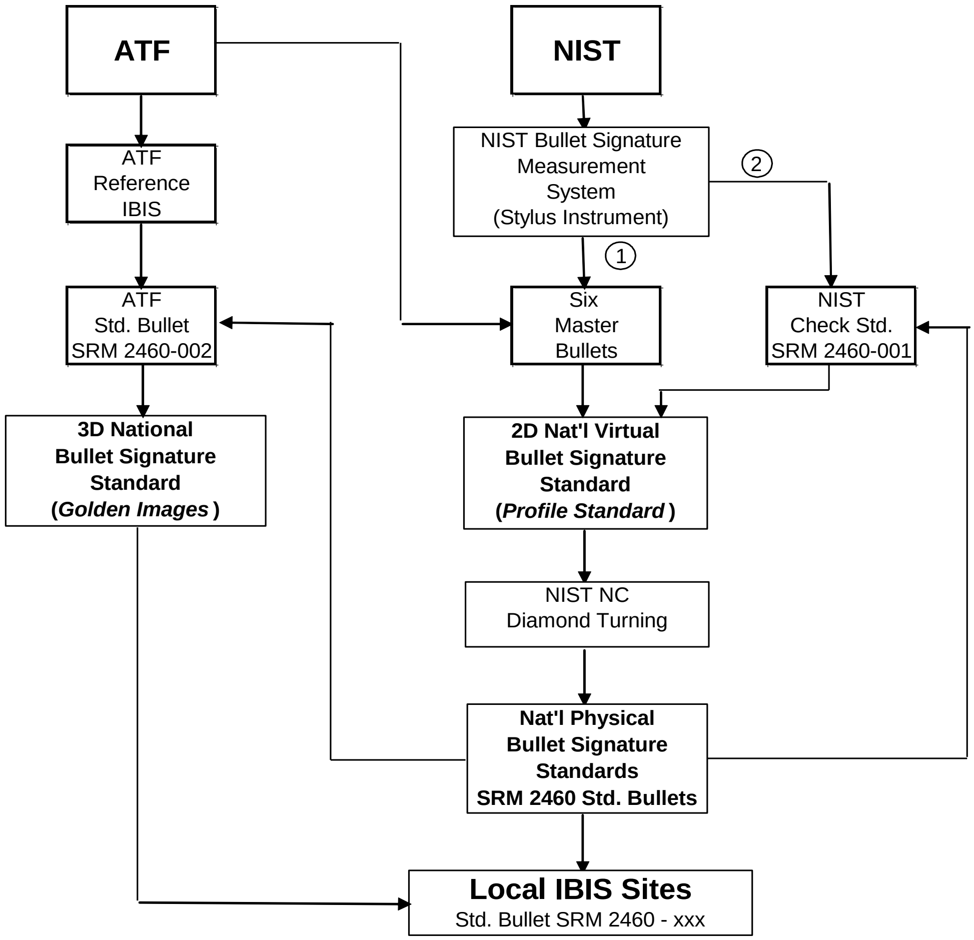

Figure 7: Establishment of a Traceability and Quality System for NIBIN acquisitions and correlations.

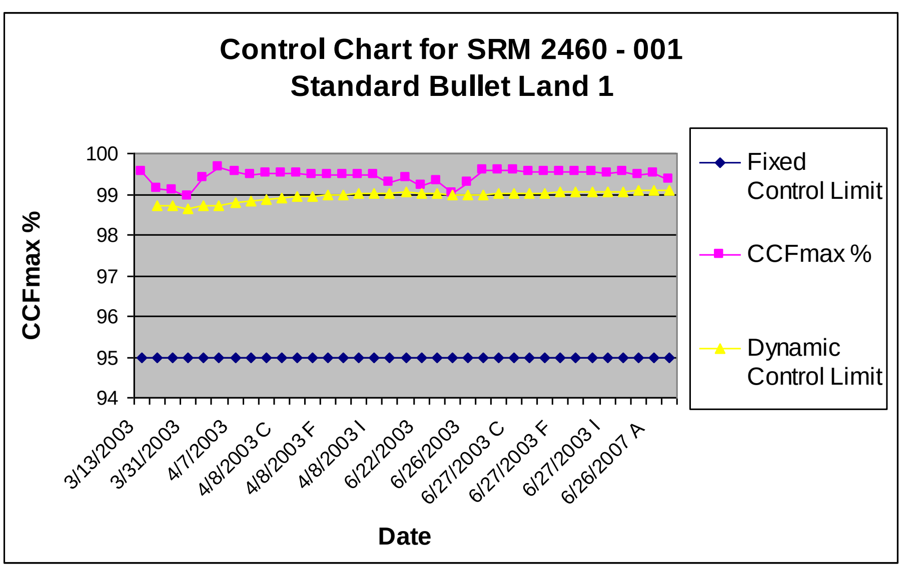

Fig. 8. A control chart for NIST check standard SRM 2460-001, LEA 1.

standard, termed the "Golden Images" (see Fig. 5 and 6, to be discussed later) established at the National Laboratory Center of ATF.

- Evaluate measurement uncertainty for both the topography measurements and imaging correlations.

A flow diagram for the establishment of a Traceability and Quality System using the SRM bullets is shown in Fig. 7. The six master bullets were profiled by NIST as shown by branch 1. The resulting set of six digitized 2D profile signatures was used as the virtual standard (see Fig. 1) that determined the tool path of a numerically controlled diamond turning machine at NIST to produce the physical standard of the SRM bullets. One of them, numbered SRM 2460-001, was kept at NIST as a check standard for measurement quality assurance, as shown in branch 2 of Fig. 7. Since 2003, this check standard has been routinely measured and correlated with the virtual standard more than 35 times and has demonstrated high measurement reproducibility: all the correlation values $CCF_{\max}$ are higher than 99 % [20]. Figure 8 shows the control chart for 35 measurements of LEA 1 of the NIST check standard SRM 2460-001. The top line shows the 35 correlation results of $CCF_{\max}$, the bottom line represents the specified control limit of 95 %. The middle line is a "dynamic control limit" based on the measured data, which was proposed and used by NIST for measurement assurance of surface calibrations [21]. The dynamic control chart will be further discussed in Section 6.

Another SRM bullet, numbered SRM 2460-002, was sent to the National Laboratory Center of ATF as a reference standard. After the topography measurements at NIST, all the SRM bullets were imaged at the National Laboratory Center of ATF using their reference IBIS system under standard operating conditions [22]. A set of the best images with the highest correlation scores was selected as the Golden Image (see Fig. 5). By acquiring images of the SRM bullets at local IBIS sites, and correlating the images with the Golden Image, differences in IBIS operating conditions between the local IBIS sites and the National Laboratory Center of ATF can be detected. This system, therefore, can enable both the topography measurements of ballistics signatures at NIST to be traceable to the virtual standard and the SI unit of length; and the image correlations at local IBIS sites to be traceable to the Golden Images of ATF's National Laboratory Center.

A similar approach is used for SRM cartridge cases. Fig. 6 shows the Golden Image established at the ATF National Laboratory Center for the breech face (left), firing pin (middle) and ejector mark (right) of the SRM cartridge cases. The proposed traceability and quality system for SRM cartridge cases also includes 3D topography measurements at NIST and image acquisitions and correlations for NIBIN.

5. The National Ballistics Imaging Comparison (NBIC) Project

During the 2008 NIBIN Users Congress held on June 17th and 18th in Orlando, FL, a protocol for the National Ballistics Imaging Comparison (NBIC) Project was initiated at the first NIST/ATF Workshop and agreed upon by ballistics experts across the country. The project goal is to establish a Traceability and Quality System for ballistics signature measurements in U.S. crime laboratories within the NIBIN. NIST SRM 2460 bullets and 2461 cartridge cases are used as reference standards. By repeating tests of the SRM bullets and cartridge cases at local IBIS sites, and correlating the images with the Golden Images established at the ATF, control charts and control limits were developed for quality assurance of ballistics acquisitions and correlations in NIBIN. The quality assurance system can then be used for detecting and exploring any quality problems arising from operators' acquisition procedures, IBIS systems and correlation networks, as well as from the SRM standards themselves.

All participants agreed to use their IBIS for image acquisitions and correlations of a SRM bullet and a SRM cartridge case. These tests include three phases:

- Phase 1 - Measurement repeatability tests: Ten repeat tests in one or two days on a single SRM bullet and cartridge case by the same IBIS operator under the same measurement setup and the same instrument calibration. Detailed measurement setup and calibration procedure can be found in [13,22].
- Phase 2 - Short term measurement reproducibility tests: Four weekly tests (including one from the Phase 1 tests) on the same SRM bullet and cartridge case by the same IBIS operator under different measurement setups and different instrument calibrations.
- Phase 3 - Long term measurement reproducibility tests: 12 monthly tests (including one from the Phase 1 tests) on the same SRM bullet and cartridge case by the same IBIS operator under different measurement setups and different instrument calibrations.

In summary, the protocol called for 24 acquisitions of both a SRM bullet and a cartridge case for each participant over the course of about a year. The correlation scores were entered on a spreadsheet designed by NIST for statistical analyses, from which control charts and control limits were developed for the proposed Traceability and Quality System.

19 ballistics examiners from 13 IBIS sites participated in this project from July 2008 to July 2009. The first set of test data was sent to NIST in September 2008. Based on the data analyses, a feedback report was sent to the participating examiners in October 2008, and discussed at the second NIST/ATF workshop held in New Orleans on January 8th, 2009. After October 2008, significant improvements were observed for some IBIS sites that previously had low IBIS scores before the feedback report. The second set of test data was sent to NIST between February and March, 2009. The final set of test data was sent to NIST in September 2009. After statistical analyses, draft control charts and control limits were developed for the proposed Traceability and Quality System. The third workshop was held from March 23rd to 24th, 2010 in St. Louis to review the overall project to that time and summarize the draft control charts and control limits.

6. Statistical Analyses, Control Charts and Control Limits

Figure 9 shows the initial collective distribution of IBIS correlations for breech face (BF), firing pin (FP) and ejector mark (EM) scores [22] of SRM cartridge cases (top), and for the Max Phase (MP) and Max LEA (ML) scores [22] of the SRM bullets (bottom). The MP represents the total score of six LEAs at their maximum registration position of the two correlated bullets; the ML represents the maximum score of any individual LEA. One of the 19 examiners only participated in Phase 1 tests of SRM cartridge case. The collective distribution models are, roughly speaking, close to a Gaussian distribution except for the ejector mark scores, which include a lot of correlation scores either close or equal to zero (to be discussed in Section 7.3).

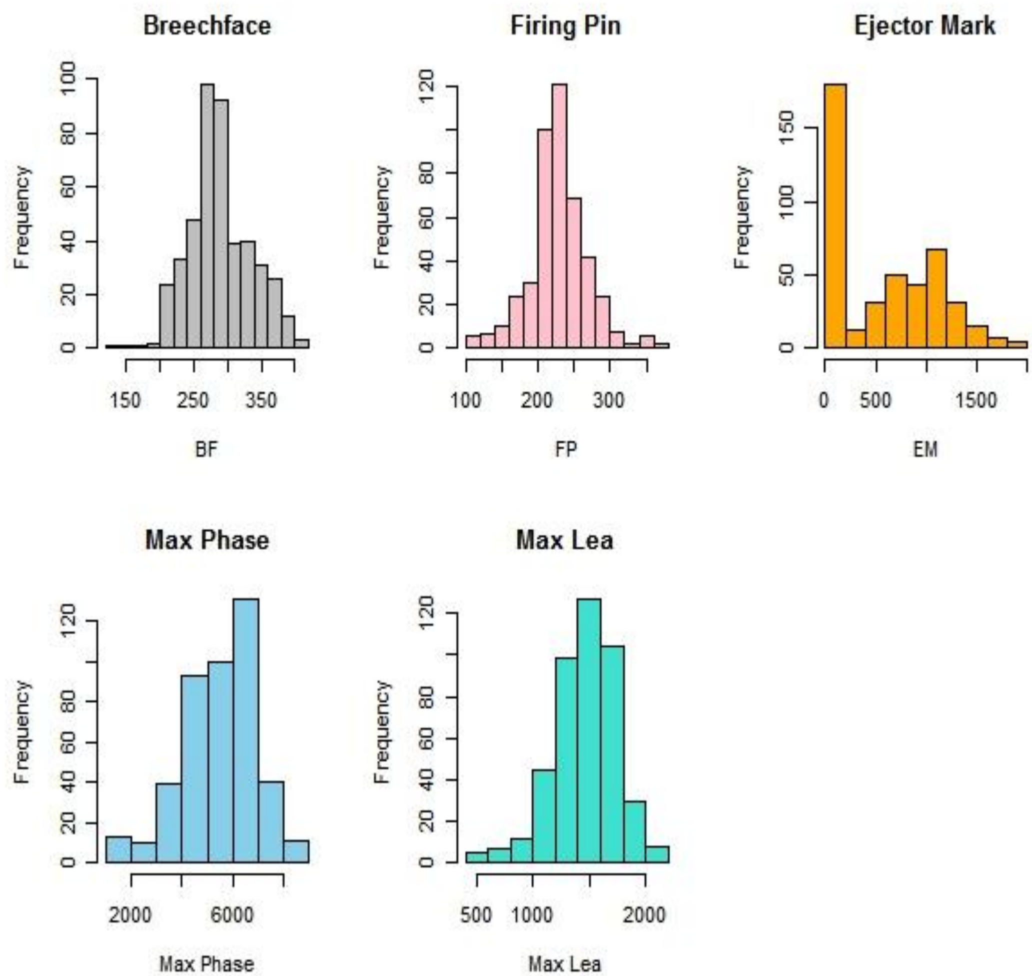

Figure 9. The collective distribution of initial IBIS correlation scores of 19 examiners for breech face (BF), firing pin (FP) and ejector mark (EM) scores (before correction) of the SRM cartridge cases (top), and the Max Phase (MP) and Max LEA (ML) scores of the SRM bullets (bottom). The correlations were performed with respect to the Golden Images (see Fig. 5 and 6) housed in the Region 6 Server of the NIBIN at the ATF National Laboratory Center, Ammendale, MD.

Table 1. Control limits for Max Phase and Max LEA scores of SRM bullets, and for breech face, firing pin and ejector mark scores of SRM cartridge case with a one sided 95 % confidence level

	Mean	Standard deviation	95 % Control limit
Maximum phase	5562	1373	3404
Maximum LEA	1498	273	1049
Breech phase	276	38	214
Firing pin	233	38	171
Ejector mark	968	345	400 (After correction)

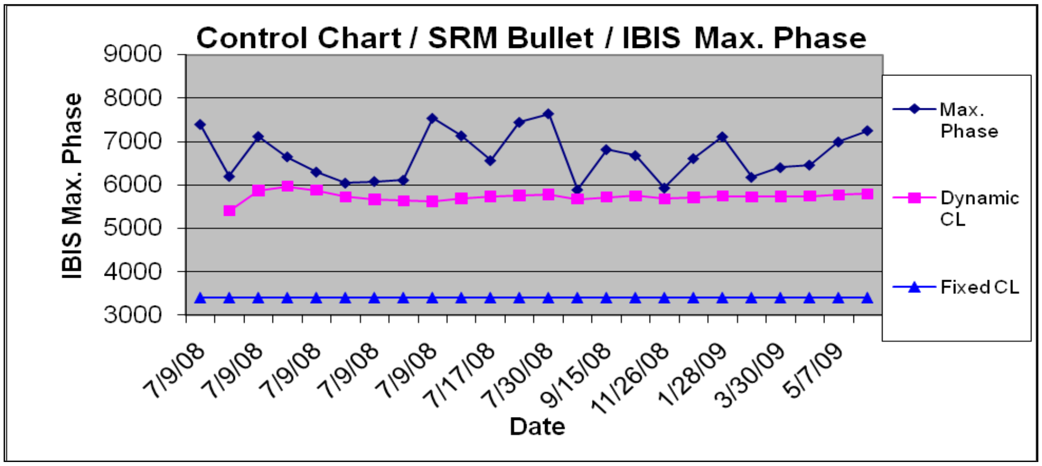

Figure 10. A dynamic control chart for IBIS max phase scores of a SRM bullet

For the Gaussian distribution, the one sided control limit (CL), which controls the low values only, with a 95 % confidence level can be calculated as

$$CL = (\mu - 1.645\ \sigma), \qquad (2)$$

where μ and σ represent the collective mean and standard deviation, respectively. 1.645 is the *t*-factor of Gaussian distribution corresponding to a one sided 95 % confidence level for the control of low IBIS scores. Some correlations show unstable scores in Phase 1 tests, hence, only the correlation scores of Phase 2 and 3 tests are used for developing the control limits. Table 1 shows the control limits for the IBIS MP and ML scores of the SRM bullets and the IBIS BF, FP and EM scores of the SRM cartridge cases. The control limit for EM scores (400) is calculated from a new set of re-corrected scores which will be discussed in Section 7.3.

For each examiner, when the correlation scores are entered in the spreadsheet, a dynamic control chart with dynamic and fixed control limits is automatically generated. One example is shown in Fig. 10 which is a dynamic control chart of IBIS Max Phase scores of a SRM bullet, based on 24 inputs of an examiner for about a year period. The top line represents the correlation scores; the middle line represents the dynamic lower control limit, CL_D, corresponding to approximately a one sided 95 % confidence level, which is calculated by:

$$CL_D = \mu_N - 1.645\sqrt{\frac{1}{N}\sum_{i=1}^{N}\mu_N - X_i}\,, \qquad (3)$$

where

$$\mu_N = \frac{1}{N}\sum_{i=1}^{N} X_i\,,$$

X_i is the value of the parameter, i is the index, and N is the number of tests performed. The dynamic control limit reflects a variation trend of the correlation scores. When the correlations

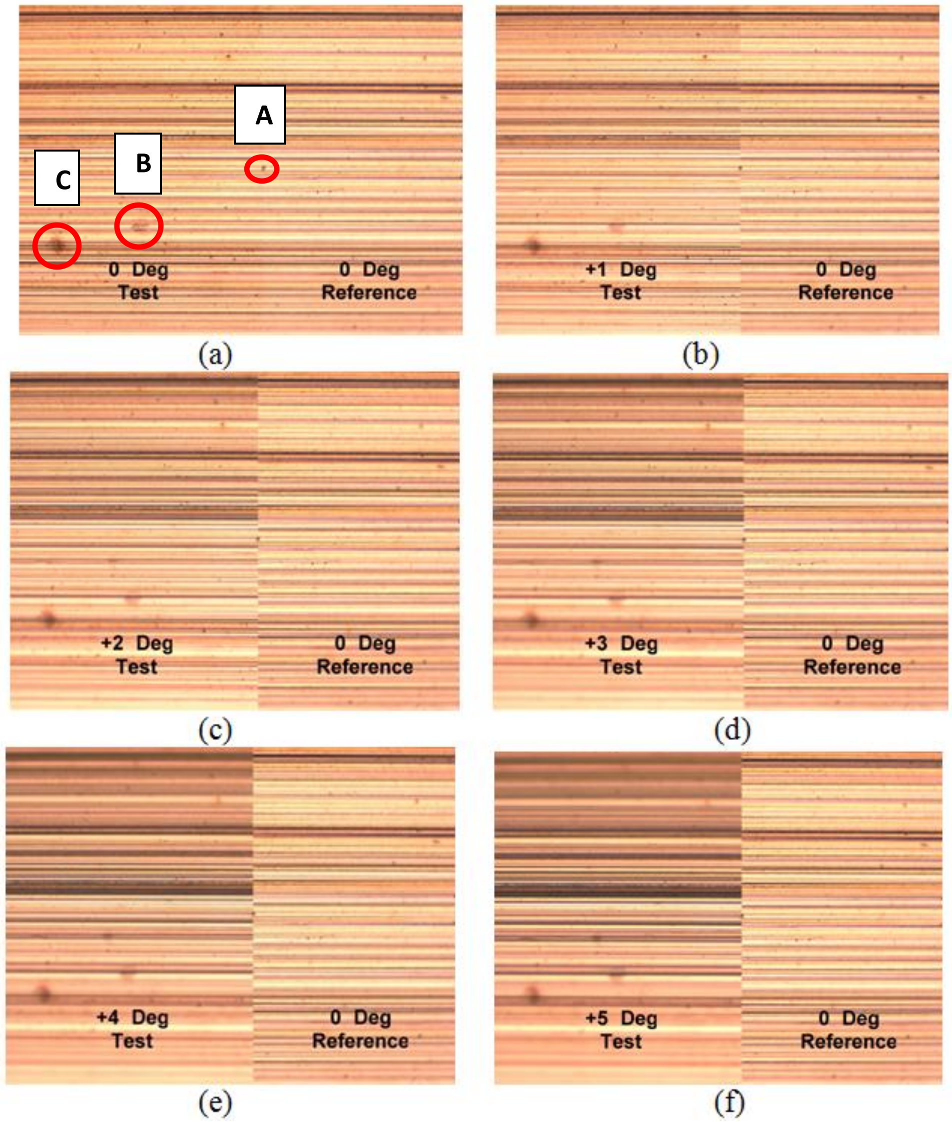

Figure 11. The effect of lighting direction on the change of image patterns of LEA 1 of SRM bullet S/N SRM 2460-038 at: (a) 0°, (b) +1°, (c) +2°, (d) +3°, (e) +4° and (f) +5° position. The rotation uncertainty for the rotary stage is estimated as ±0.1° ($k = 2$). The circled defects A, B, C shown in Fig. 11a indicate that the same portion of surface remains in the left hand field of view for images a – f.

scores are below the dynamic control limit, it provides an early warning sign for the ballistics examiners. The bottom line in Fig. 10 shows the fixed control limit (CL) for the Max Phase scores of SRM bullets (CL = 3404) with a one sided 95 % confidence level as shown in Table 1.

7. Quality Assurance for NIBIN Acquisitions and Correlations

Three major uncertainty sources for NIBIN acquisitions and correlations may come from:

1. Operator, acquisition process, and IBIS acquisition hardware including the optical microscope.
2. IBIS correlation software and NIBIN correlation network.

3. Calibration and reference standards including the SRM bullets and cartridge cases.

During the IBIS project, we selected some questionable IBIS correlations from the control charts and analyzed their corresponding images, by which we have identified different quality problems associated with the operator and acquisition procedure, with the IBIS correlation process, and even with the SRM standard cartridge case itself.

7.1. Quality problems from the IBIS operator and acquisition process

In ballistics image acquisition, lighting conditions including the type of light source, the light direction, the intensity, the color and material reflectivity, and the image contrast have a significant effect on imaging quality and correlation scores, and should be standardized and well controlled. Even for standardized lighting conditions such as the automatic lighting [22] used in the IBIS microscopes, variations caused by the measurement setup and acquisition process may significantly affect signature acquisitions and correlations.

We have recently tested how the lighting direction can change the image patterns of a bullet LEA in an optical microscope. The same LEA of a SRM bullet is imaged in an Olympus optical microscope. The optical axis is kept stationary, but the bullet is rotated around its central axis by a rotary stage so that the relative lighting direction is changed from 0° to ±5° [23]. The rotation uncertainty for the rotary stage is estimated as ±0.1° ($k = 2$). In Fig. 11, the left hand images obtained with the relative lighting direction varying from 0° to +5° are compared with the right hand image taken with the lighting direction at 0°. A small surface defect “A” as shown in the center of the LEA (see Fig. 11a) is used for alignment of the left and right hand images to avoid registration error. When the lighting direction is the same 0°, the two striation patterns are essentially identical (Fig. 11a). This indicates a high degree of repeatability in the imaging system. When the bullet rotation of the left image is changed to +1°, some image differences can be observed (Fig. 11b), but their image patterns are similar. When the bullet rotation changed to +2° and +3°, the differences in image patterns become significant (Fig. 11c and 11d). When the bullet rotation is changed to +4° and +5°, the image changes become so significant that the image patterns would likely be concluded as “non-matching” when compared with the reference image at 0° (Fig. 11e and 11f).

Although the microscope images of bullet striations can change significantly with lighting direction, the surface topography itself and the surface defects do not change and can still be identified if the topography can be accurately measured (see Fig. 3) or if the defects can be clearly imaged independent of surface orientation. From the six left hand images in Fig. 11, the circled defects pattern A, B, C shown in Fig. 11a persists unchanged with the changing of the relative lighting directions.

The above experiments only demonstrate the effect of lighting direction on the image patterns of the fine striations: a few degrees of change in the lighting direction can totally change the image patterns. Other instrument conditions, such as light intensity, spectral distribution, and recorded image contrast, also affect image quality, and should be controlled and documented. A procedure for maintaining the correct lighting direction is provided by the IBIS Operation Manual [22]. In this procedure, a scanned laser beam ‘paints’ two stripes on the top and bottom

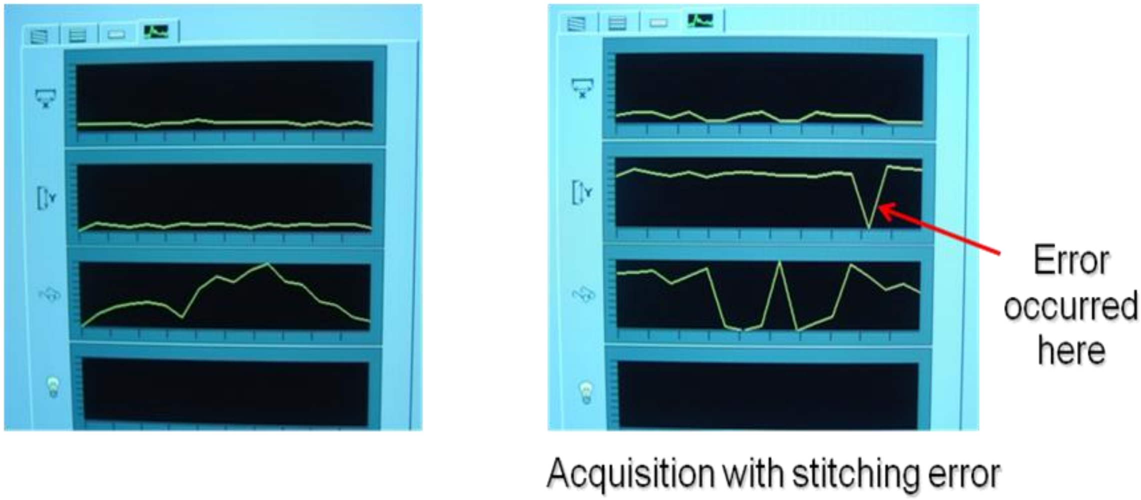

Figure 12. Two IBIS user screens show the X-translation values (top plots) and the Y-translation values (middle plots) [22]. For a typical acquisition of IBIS, the Y-translation plot shows very little variation in the Y-translation value (left, middle), whereas the other Y-translation plot (right, middle) reveals an error in the image stitching operation. See text for more explanation on the X-Y translations.

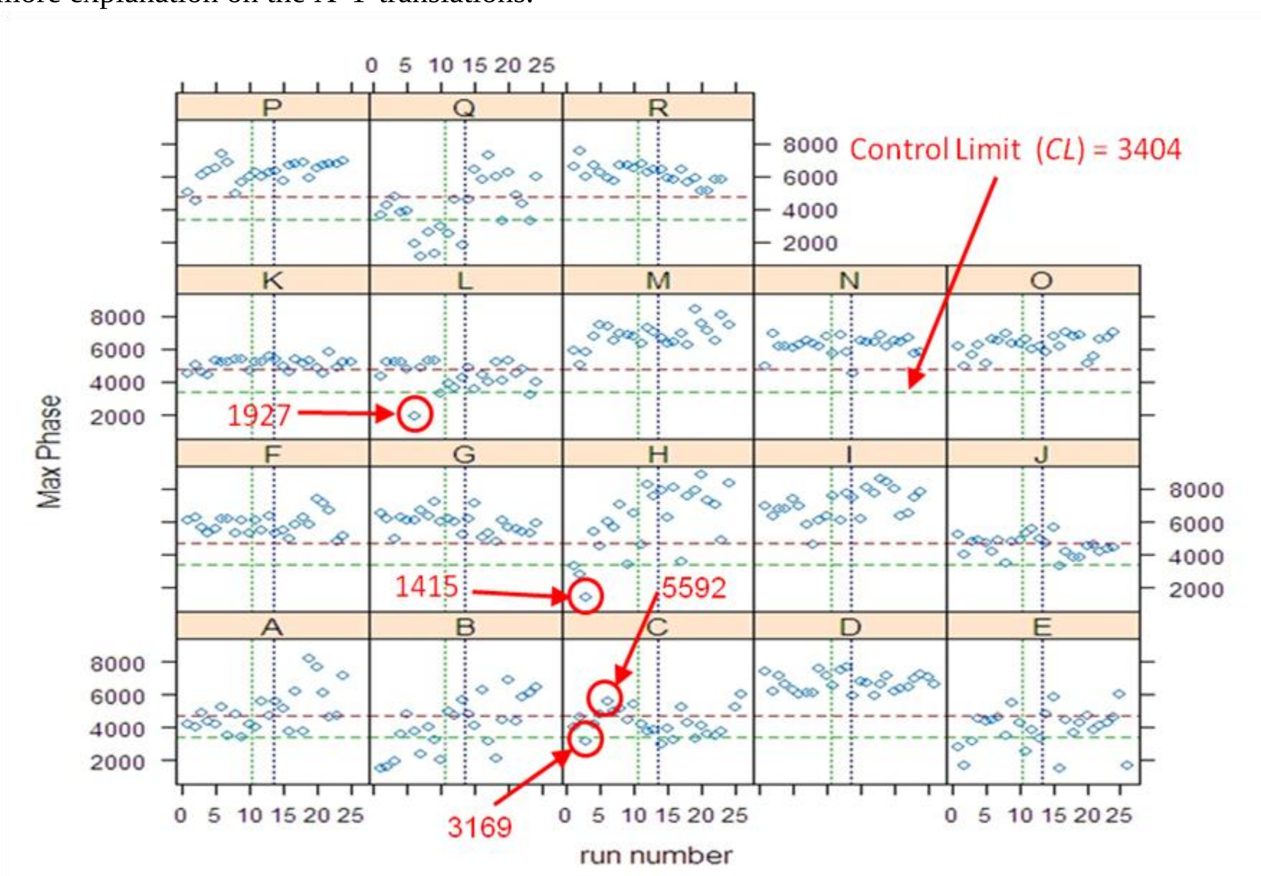

Figure 13. Collective Max Phase correlation scores for SRM bullets for 18 NBIC participants. The vertical dotted lines indicate the demarcation between Phases 1, 2, and 3 tests. The dashed red line represents the initial estimated control limits and the dashed green line represents the final control limit. See text for more explanation on these control limits.

shoulders of a bullet LEA that are used for adjusting the bullet position when acquiring an image on one of the bullet's LEAs. Both the IBIS Operation Manual [22] and the NIST Certificate of SRM 2460 Standard Bullets [13] specify that the "Anchor positions for top and bottom shoulders of each LEA must be set correctly," and that "Translation/rotation needs to be adjusted at both shoulders to ensure that the laser stripes are parallel throughout the land impression." If the anchor positions and laser stripes are set incorrectly, significant differences between the operator's lighting condition and the standard lighting condition [13,22] may occur. The IBIS standard lighting alignment conditions were used at the National Laboratory Center at ATF for capture of the Golden Images. These conditions must be reproduced by the operators in local IBIS sites in order to achieve high correlation with the Golden Images. The standard lighting alignment conditions can be established by correct measurement setup as described in both the NIST SRM Certificate [13] and the IBIS Operation Manual [22].

In addition to the change in lighting conditions discussed above, errors in the IBIS image stitching could also affect image correlation. The IBIS microscope captures images at a small part of the Land Engraved Area (LEA) each time, and stitches these images together as a whole image for correlation. A rotation and X-Y translation stage is used for the rotating and translating the bullet so that different parts of the LEA could be synchronously imaged with a designed overlap for image stitching. The rotation stage rotates the bullet around its central axis (or the X-axis), the Y-stage moves the bullet in the direction perpendicular to the X-axis. If the rotation-translation stage works insynchronously, the IBIS microscope may produce disjoint images of the LEA striations caused by the stitching errors, which are indicated by a large deviation in the pixel plot of Y-translation (see the right-middle plot in Fig. 12) [23]. Whatever the cause, the acquired images and correlation scores may be invalid and the images may need to be reacquired.

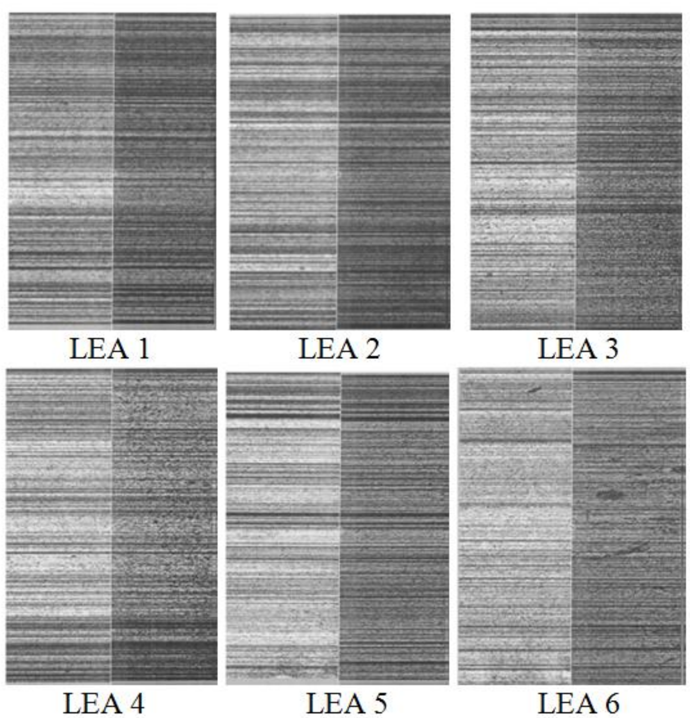

Fig. 14a. Correlation images of SRM bullet between a local IBIS site (left) and the Golden Image (right), the Max Phase score of 5592 is well above the control limit of 3404.

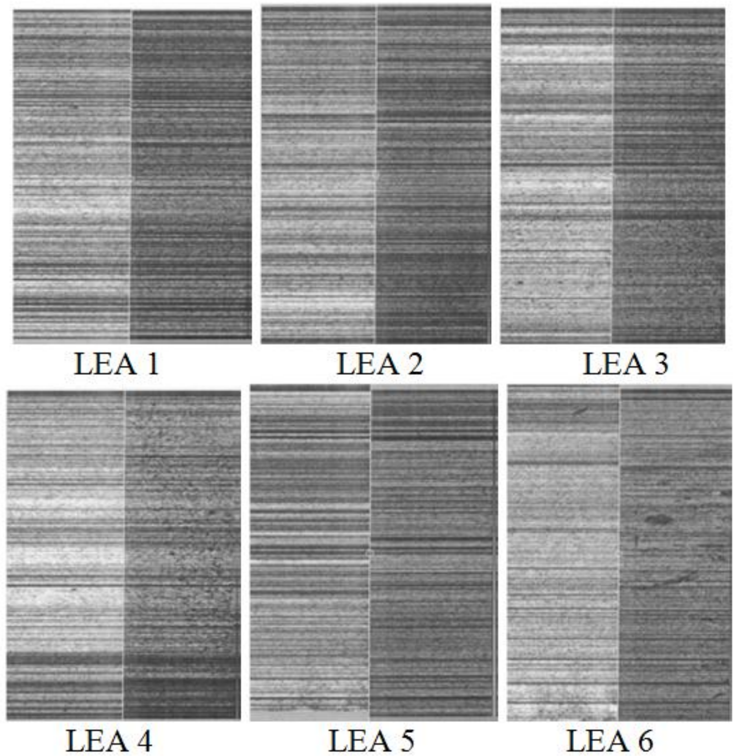

Fig. 14b. Correlation images of SRM bullet between a local IBIS site (left) and the Golden Image (right), the Max Phase score of 3169 is just below the control limit of 3404.

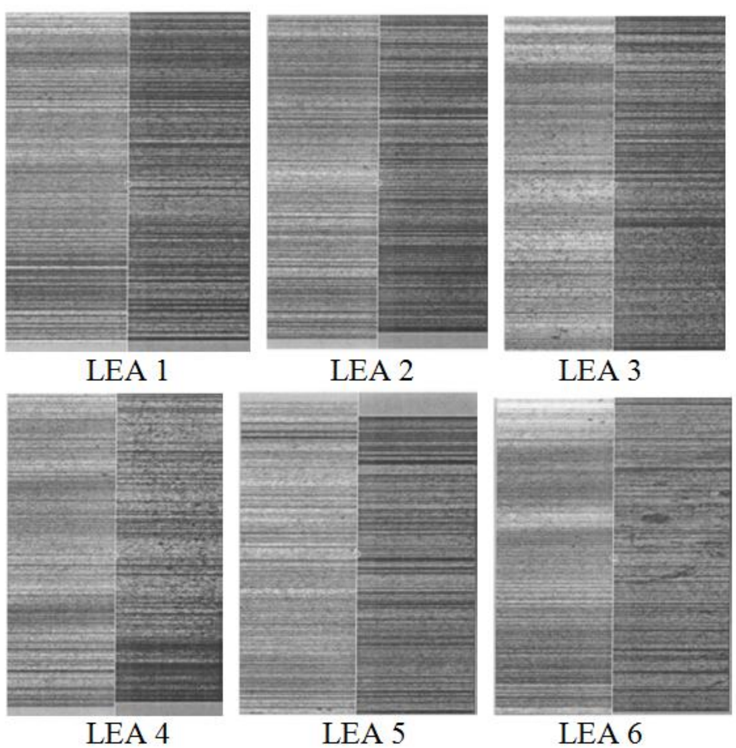

Fig. 14c. Correlation images of SRM bullet between a local IBIS site (left) and the Golden Image (right), the Maximum Phase score of 1415 is far below the control limit of 3404.

Another quality issue for image acquisition of SRM bullets is the control of the LEA width. In the Appendix of the SRM Certificate [13], it is specified that “Anchor positions for top and bottom shoulders should be set such that the difference of LEA width is no more than ±0.08 mm (±0.003”) from the nominal LEA width.” The nominal LEA width of SRM bullets can be found in the SRM Certificate [13]. If the LEA width shows significant difference from the specified width, the acquired images may show “scale differences” with respect to the Golden Image, i.e., the acquired images have the same image pattern but are either wider or narrower than the Golden Image. That may also result in decreased correlation scores.

Figure 13 shows a summary of the Max Phase scores of SRM bullets from the 18 NBIC participants. Each took 24 correlations over the course of a year. The vertical dotted lines indicate the demarcation between Phases 1, 2, and 3 tests. The dashed red horizontal line represents the initial estimated control limit from previous IBIS acquisitions from 2002 to 2006 performed at ATF, FTI (Forensic Technology Inc. Canada) and the IBIS training center in Largo, FL. The green dased horizontal line represents the control limit (CL) calculated from the correlation scores of the NBIC project (CL = 3404, see Table 1), which is lower than the initial estimated control limit. Four sets of correlations are selected for discussion: the first set is for a correlation score of 5592, which is well above the control limit of 3404; the second set (3169) is just below the control limit; and the other two sets (1415 and 1927) are far below the control limit. Figure 14 shows the sets of IBIS images corresponding to the 5592, 3169, and 1415 scores (see left hand images) each juxtaposed with the Golden Images established at the ATF (right images). For the first set of images with maximum phase score of 5592 (see Fig. 14a), all six LEA images show close striation patterns with the Golden Images. However, the images for LEA 5 and LEA 6 show minor scale differences, i.e., the operator’s images (left) have the same pattern but are wider than the Golden Image (right).

For the second set of images with Max Phase score of 3169 (see Fig. 14b) just below the control limit of 3404, more significant image differences (when comparing with Fig. 14a) from the Golden Images are found, such as in LEA 5 in Fig. 14b. For the correlations with Max Phase scores of 1415 and 1927, which are far below the control limit of 3404, most of the image patterns show significant differences with the Golden Images. One set of the images with maximum score of 1415 is shown in Fig. 14c. That indicates an invalid image acquisition.

Generally speaking, whenever a Max Phase score falls below the control limit (3404), it may be caused either by a problem in the measurement setup just prior to acquisition of the SRM bullet, or by the image stitching problem described above. Quality problems in the image acquisition of SRM bullets can be avoided by strictly following the operation procedure described in the SRM Certificate [13] and the IBIS Operation Manual [22]—by carefully checking every procedural detail including the ‘laser stripes’ and anchor positions at both shoulders of the LEA, the LEA width, and by looking for disjoint images and for large deviations in the Y-translation plot on the IBIS screen (Fig. 12).

It should be noted that for correlation scores higher than the control limit, minor imperfections in the correlation images might still be found (see Fig. 14a, LEA 5 and 6). If the correlation scores are just above but very close to the control limit, it might be necessary to check the correlation images and operation procedures to pinpoint possible quality problems.

7.2. A quality problem discovered and corrected with SRM cartridge cases

The control chart and control limit also helped us to find a quality problem with the SRM cartridge cases. Figure 15 shows the collective correlation scores for breech face (BF) of SRM cartridge cases for 19 participants. Each took 24 correlations in three phases over the course of a year but one examiner "S" participated in Phase 1 tests only. The control limit, shown as the dashed green horizontal line, is calculated to be 214 (see Table 1). The dashed red horizontal

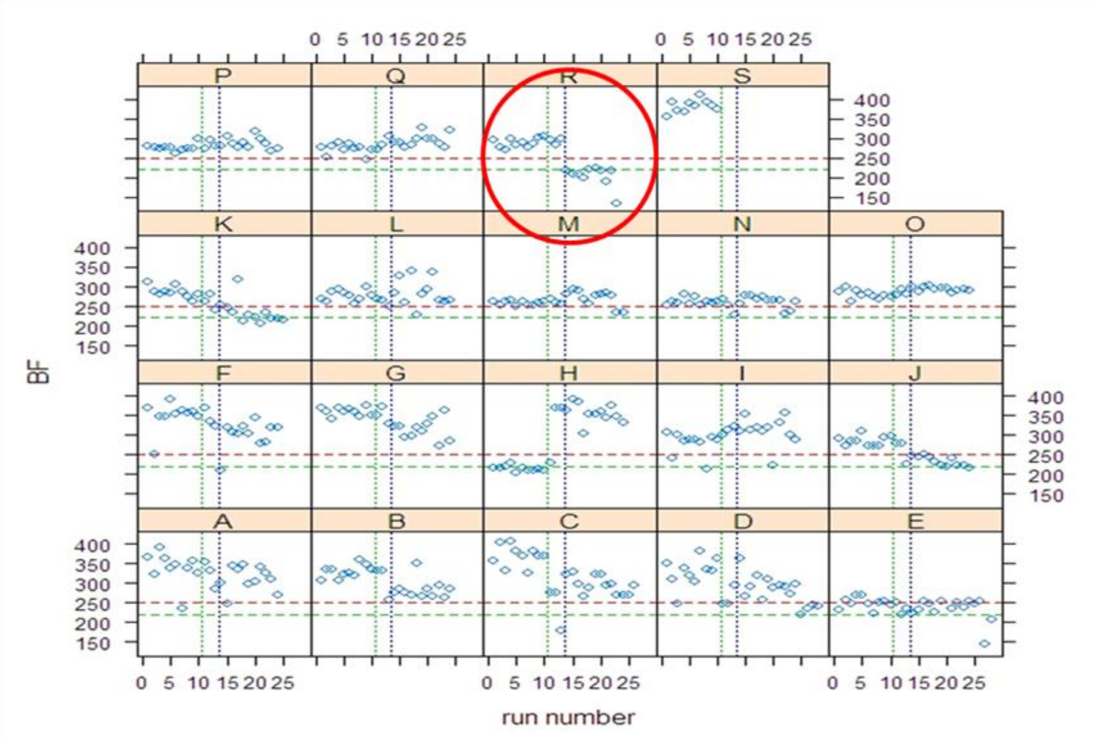

Figure 15. Collective correlation scores for breech face (BF) impressions of SRM cartridge cases for 19 NBIC participants with respect to the BF Golden Image. The vertical dotted lines indicate demarcation between Phases 1, 2, and 3 tests. The dashed red line represents the initial estimated control limits and the dashed green line represents the final control limit. See text for more explanation on these control limits.

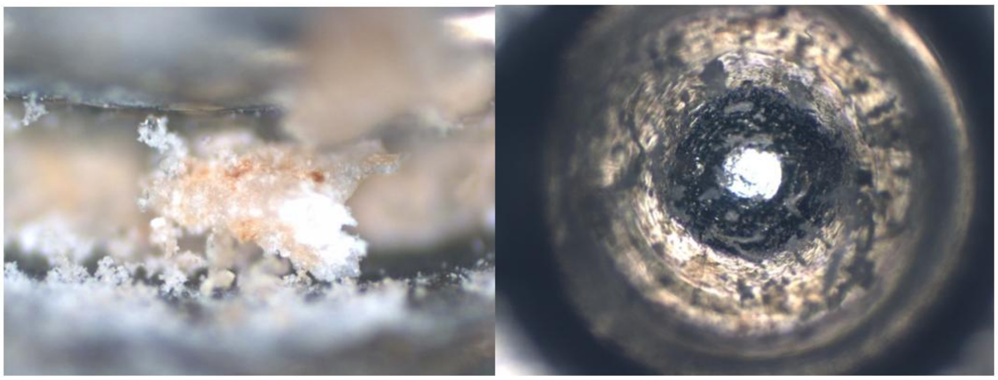

Figure 16. Surface contamination on the surfaces of the breech face impression on a SRM cartridge case (left) and on firing pin impression of another SRM case (right), both are likely caused by a soldering process during the manufacture of the SRM cartridge cases.

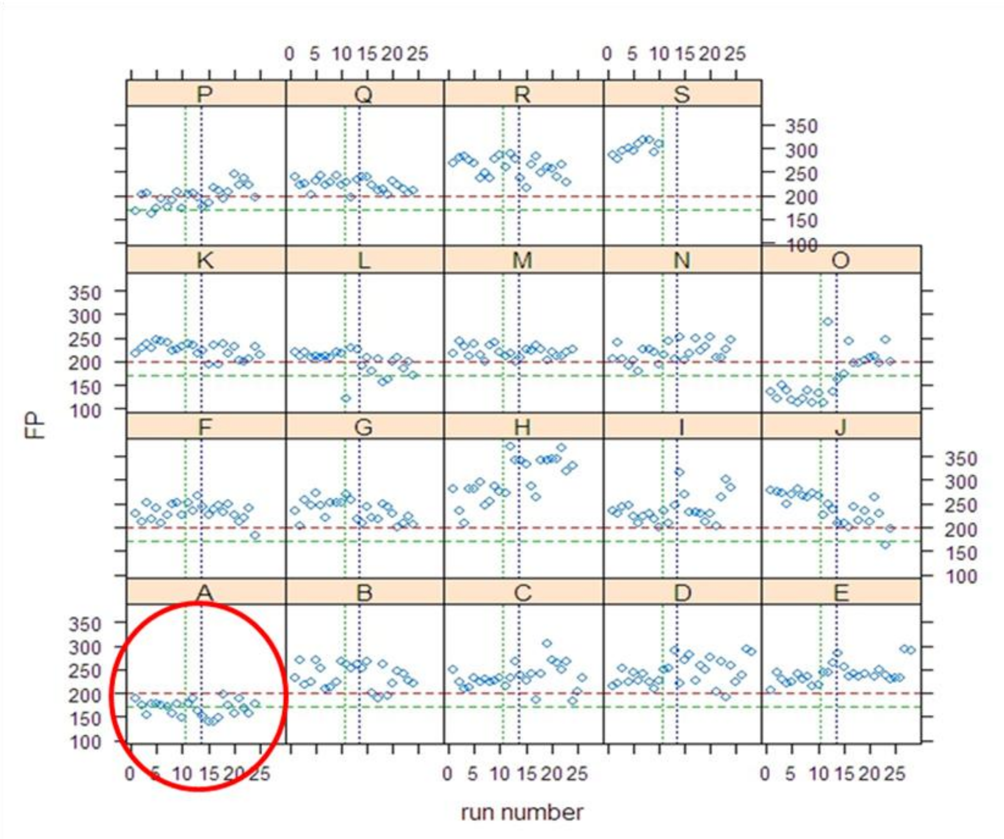

Figure 17. Collective correlation scores for firing pin (FP) impressions of SRM cartridge cases for 19 participants with respect to the FP Golden Image. The vertical dotted lines indicate demarcation between Phases 1, 2, and 3 tests. The dashed red line represents the initial estimated control limits and the dashed green line represents the final control limit. See text for more explanation on these control limits.

line represents the estimated control limit as mentioned before. It can be seen that the breech face scores of examiner "R" show a sudden drop below the control limit after the Phase 2 tests. This SRM cartridge case was then sent to another IBIS site for a verification test by another examiner; and the correlation score again fell below to the control limit. Upon checking this SRM cartridge case in a microscope, some surface contamination was found (see Fig. 16 left) which had not been found during the initial inspection and topography measurement at NIST.

The same problem was also found on the firing pin impression of another SRM cartridge case. Figure 17 shows the collective correlation scores for the firing pin impressions (FP) of SRM cartridge cases for 19 participants. One examiner "S" participated in Phase 1 tests only. The control limit is 171 (see Table 1). It can be seen that correlation scores for examiner "A" are below the average value for all participants and most are either close to or below the control limit. By checking the SRM cartridge case in a microscope, the same kind of surface contaminations was found on the firing pin impression (see Fig. 16 right) as was found on the breech face impression of the other SRM cartridge case described above. This contamination had also not been found during the initial inspection and topography measurement at NIST.

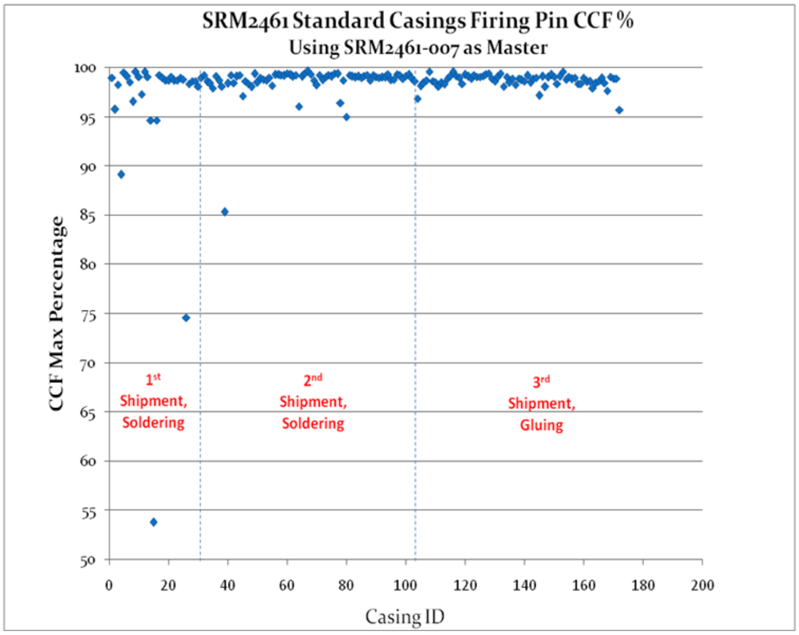

Figure 18. Cross-correlation maximum CCF_{max} tested from the topography measurements of firing pin impressions of 173 SRM cartridge cases. The manufacturing procedure for the first and second shipment had included a soldering process. But a gluing process was used for the third shipment. The topography image of SRM cartridge case 007 is used as a correlation reference.

Contamination had been found initially on some other SRM cartridge cases (but not on the two cartridge cases mentioned above) during the initial surface inspection and topography measurements at NIST. Figure 18 shows the measurement result of CCF_{max} values for firing pin surface of 173 SRM cartridge cases. These SRM cartridge cases were delivered to NIST by three shipments, one each in 2007 (31 cartridge cases), 2008 (71 cartridge cases) and 2009 (71 cartridge cases). Surface contamination was found on some of the SRM cartridge cases from the 2007 and 2008 shipments. The correlation values CCF_{max} for these SRM cartridge cases are below the designed certification of 95%, and these cartridge cases were rejected.

After a discussion with the contractor, it was found that the surface contamination was caused by the soldering process by which the electro-formed nickel SRM cartridge case was fixed onto its brass cylinder holder. It was decided to eliminate the soldering process and switch to a gluing process for the production of the SRM cartridge cases. As a result, none of the 71 cartridge cases of the third shipment made by the new process reveals any surface contamination so far, and their CCF_{max} values are all higher than 95% (see Fig. 18).

To ensure the quality of the SRM cartridge cases and to prevent the reappearance of surface contamination, the project team has decided to replace all 102 SRM cartridge cases shipped in 2007 and 2008 using the soldering process. In March 2010, the fourth shipment of 105 cartridge cases made with the gluing process was delivered to NIST to replace the cartridge cases received from the 2007 and 2008 shipments. These topography measurements at NIST and IBIS correlations at ATF have been completed; these SRM cartridge cases will be certified for sell in 2011.

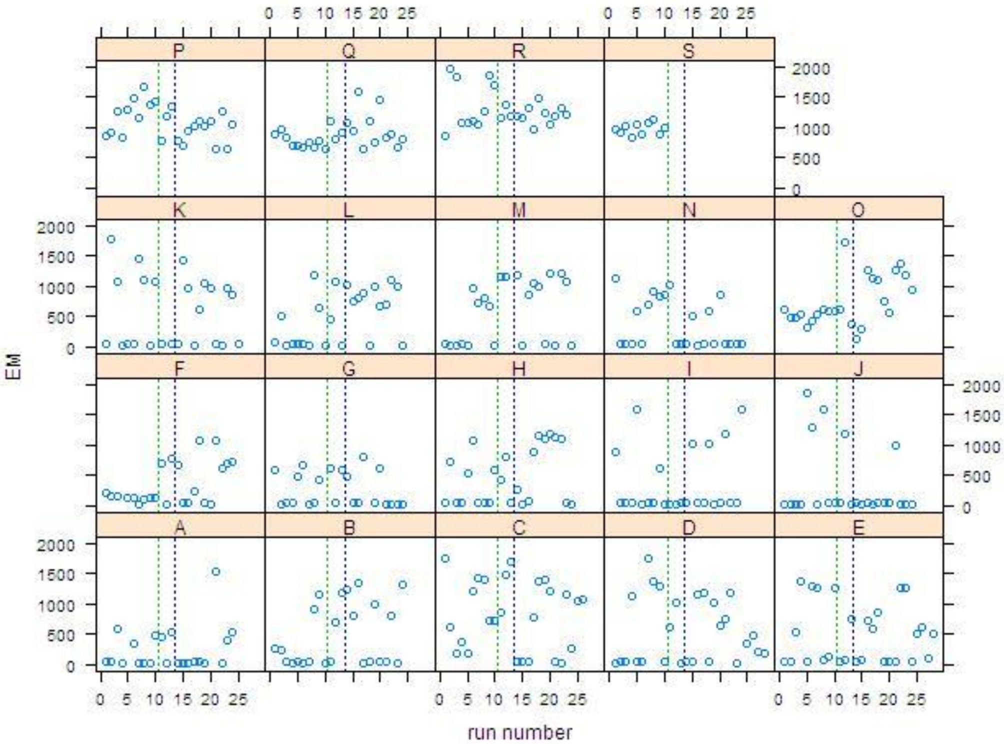

Figure 19. Initial collective correlations for ejector marker (EM) scores of SRM cartridge cases for 19 participants. A quality problem was found in the inter-region correlations for examiners from A to N.

7.3 Quality problems discovered and corrected with the IBIS systems and correlation network

Figure 19 shows the initial set of collective correlation scores for the ejector marks of the SRM cartridge cases for 19 participants. Each participant took 24 correlations in three phases over the course of a year but one examiner, "S," participated in Phase 1 tests only. It can be seen that there are many meaningless correlation scores, which are either close or equal to zero (see examiners from A to N), except for five examiners (O, P, Q, R, S). It was found that all the five examiners are located in the same correlation Region 6 of the NIBIN (there are 13 correlation regions in NIBIN altogether) where the ATF's Golden Images are located. This quality problem was reported to Forensic Technology Inc. (FTI) during the NBIC project. At the NIST/ATF workshop in March 2010, FTI representatives reported that FTI engineers had discovered a fault in the inter-region correlation software that caused errors in some of the correlation scores when ejector marks from different NIBIN regions are correlated. When a manual correlation request was generated against a site in a different region, the paired ejector mark image signatures taken under different lighting condition were occasionally switched because of a database access anomaly. The NBIC tests required a manual correlation against the Golden Image exhibit housed on the Region 6 server at ATF's National Laboratory Center in Ammendale, MD. So the results of correlations of exhibits from outside Region 6 contained inconsistencies. This issue has been resolved throughout NIBIN as of January 2010. As a result, the project team agreed to

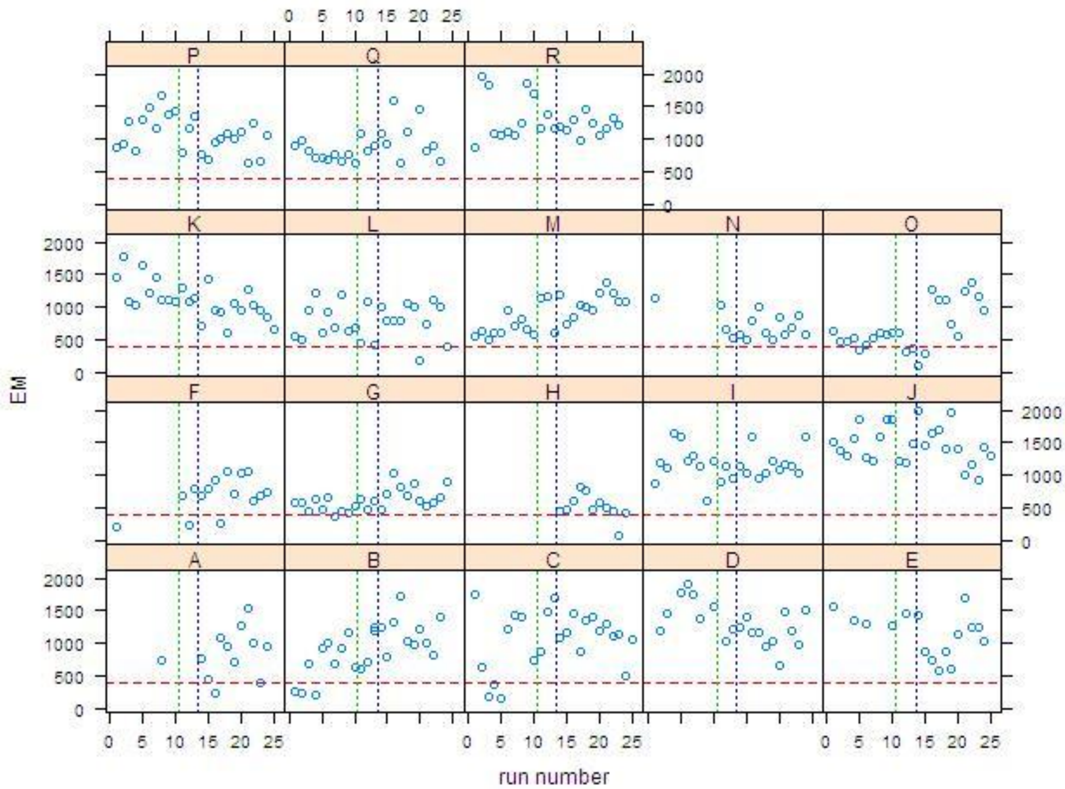

Figure 20. Collective correlations for ejector marker (EM) scores of SRM cartridge cases for 18 participants after the quality problem of inter-region correlation software was corrected.

a re-correlation of the existing cartridge case images with respect to the Golden Image. Figure 20 shows the re-correlation results for 18 examiners who completed the tests of all three phases, from which a control limit of 400 was developed for ejector mark acquisitions (see Table 1). It must be noted that all the control limits developed from the NBIC project (as shown in Table 1) are preliminary and may be modified in the future.

During the re-correlation process, another problem was found with the breech face re-correlations. When the same pair of breech face images was input to the IBIS correlation software for re-correlation, the correlation score can be somewhat different than the score of the first round of correlations. The project team has worked with FTI engineers and solved this problem. It is found that the Golden Image of the breech face was modified on May 29th, 2009. This was an inadvertent modification associated with inspection of the ring boundaries. As a result, when the breech face image captured before May 29, 2009 was re-correlated with the modified Golden Image, some of the correlation scores were modified as well. This problem has been corrected.

8. Summary

The National Ballistics Imaging Comparison (NBIC) project was initialized in 2008 and was aimed at establishing a Nationwide Traceability and Quality System for NIBIN acquisitions and correlations. 19 ballistics examiners from 13 U.S. crime labs participated in this project. They each took 24 acquisitions of NIST SRM Bullets and Cartridge Cases over the course of a year, but one examiner only participated in Phase 1 tests of SRM cartridge case. The acquired images were correlated with Golden Images at the National Laboratory Center of ATF, from which control charts and control limits have been developed. These will be used for maintaining the proposed Traceability and Quality System of NIBIN and for promoting future assessments and accreditations for U.S. ballistics laboratories in accordance with the ISO 17025 Standard.

NIST SRM Standard Bullets and Cartridge Cases function as reference standards for establishing metrological traceability for both the topography measurements at NIST and for the image correlations of NIBIN. For the topography measurements, the measurement traceability is established using the SRM Bullets and Cartridge Cases and NIST proposed parameters D_s and CCF_{max} traceable to the SI unit of length. For the image acquisitions of NIBIN, traceability is supported by correlation of SRM bullet and cartridge case images at local IBIS sites with respect to the Golden Images of the National Laboratory Center of ATF.

NIST SRM Bullets and Cartridge Cases, combined with the use of control charts and control limits, are powerful tools for quality assurance of NIBIN acquisitions and correlations. During the NBIC project, several quality problems related to the operator and acquisition procedure, the IBIS software and correlation network, as well as the SRM cartridge cases themselves, have been successfully identified and have been corrected.

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