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NIST Bullet Signature Measurement System for RM (Reference Material) 8240 Standard Bullets*

ABSTRACT: A bullet signature measurement system based on a stylus instrument was developed at the National Institute of Standards and Technology (NIST) for the signature measurements of NIST RM (Reference Material) 8240 standard bullets. The standard bullets are developed as a reference standard for bullet signature measurements and are aimed to support the recently established National Integrated Ballistics Information Network (NIBIN) by the Bureau of Alcohol, Tobacco and Firearms (ATF) and the Federal Bureau of Investigation (FBI). The RM bullets are designed as both a virtual and a physical bullet signature standard. The virtual standard is a set of six digitized bullet signatures originally profiled from six master bullets fired at ATF and FBI using six different guns. By using the virtual signature standard to control the tool path on a numerically controlled diamond turning machine at NIST, 40 RM bullets were produced. In this paper, a comparison parameter and an algorithm using auto- and cross-correlation functions are described for qualifying the bullet signature differences between the RM bullets and the virtual bullet signature standard. When two compared signatures are exactly the same (point by point), their cross-correlation function (CCF) value will be equal to 100%. The measurement system setup, measurement program, and initial measurement results are discussed. Initial measurement results for the 40 standard bullets, each measured at six land impressions, show that the CCF values for the 240 signature measurements are higher than 95%, with most of them even higher than 99%. These results demonstrate the high reproducibility for both the manufacturing process and the measurement system for the NIST RM 8240 standard bullets.

KEYWORDS: forensic science, ballistics measurement, bullet signature, cross-correlation function, CCF, reference material, RM, standard bullet

Bullets and casings when fired or ejected from guns pick up characteristic signatures, that are unique to the weapon. Striations on the bullet are caused by its passage through the gun barrel. Marks on the casing are caused by impact with the firing pin, breech face, and ejector. By analyzing these signatures, firearm examiners can connect a firearm to criminal acts. In the early 1990s, the IBIS* (Integrated Ballistics Identification System) and the DRUGFIRE* system were established for this purpose in laboratories of the Bureau of Alcohol, Tobacco and Firearms (ATF) and the Federal Bureau of Investigation (FBI), respectively (1–3). Both systems are based on image capture, image analysis, and database techniques. In 1998, the ATF and FBI initiated a joint project to establish the National Integrated Ballistics Information Network (NIBIN) (1–3). In December 2002, after a nearly two-year effort, computer specialists finished installing IBIS workstations into the last of the 233 U.S. crime labs slated to be on the NIBIN (1).

In order to implement a nationwide ballistics information network by sharing data between ballistics laboratories, it is important to establish a measurement standard for traceability, unification, and quality control of ballistics measurements. The RM (Reference Material) 8240 standard bullets are being developed by the National Institute of Standards and Technology (NIST) in collaboration with the ATF. These RM bullets are planned for use in instrument calibration and measurement quality control, and for establishment of measurement traceability to the National Laboratory Center of ATF. In 1998, two prototype standard bullets were manufactured at NIST (4–6). A new parameter and algorithm were proposed for bullet signature measurements (7). A traceability system was also proposed to establish the measurement traceability for bullet signature measurements nationwide (8–11).

Based on the NIST proposed parameter and algorithm, a bullet signature measurement system has now been established at NIST (12). In 2002 and 2003, forty standard bullets were manufactured at NIST (13). All 40 bullets were measured by this system and have shown good results. In the following sections, we introduce the NIST RM 8240 standard bullet project, discuss a new parameter and algorithm for bullet signature measurements, and describe the NIST bullet signature measurement system and some initial measurement results.

NIST RM 8240 Standard Bullets Project

NIST RM 8240 standard bullets are designed as both a virtual and a physical bullet signature standard (6). The virtual standard is a set of six digitized bullet profile signatures. In 2000, NIST received six master bullets from ATF and FBI. These master bullets were fired by six different guns under a standardized shooting procedure. Each master bullet has six land impressions in which there are six unique bullet signatures. By tracing one bullet signature on each master bullet using a stylus instrument, a set of six digitized bullet signatures was established and stored in a NIST computer as a 2-D virtual bullet signature standard. This virtual standard was then used as reference standard for both the production and measurement of the physical standard, the NIST RM 8240 standard bullets. In

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* 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.

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FIG. 1—*Master bullet from ATF National Laboratory Center* (left)*, NIST prototype standard bullet* (center)*, and NIST RM 8240 standard bullet* (right).

January 2002, by using the virtual standard to control the tool path of a numerically controlled diamond turning machine at NIST, 20 RM 8240 standard bullets were produced. Another 20 RM bullets were made in June 2003 (13).

Figure 1 shows a master bullet (left) fired at the ATF's National Laboratory Center, from which one of the bullet signatures was traced at NIST's Surface Calibration Laboratory as the virtual bullet signature standard. The prototype (center) and the RM 8240 standard bullet (right) are also shown.

Bullet Signature Comparisons Using Auto- and Cross-Correlation Functions

It was decided to adapt the auto-correlation function (ACF) and cross-correlation function (CCF) from signal processing theory for bullet signature measurements (7). Because the bullet signatures can be considered as random profiles, their auto-correlation functions decay as the shift distance increases. This statistical property is very useful for bullet signature comparisons to quantify the difference of bullet signatures:

- When two bullet signatures are compared with each other, one of them is taken as a references (see signature A in Fig. 2) and the other is the compared signature B. If these two signatures are exactly the same, $B = A$, then their CCF achieves the maximum value (1.00) when the shift distance is zero.
- If two compared bullet signatures have nearly the same pattern with only small differences on their profiles, as occurs when two bullets are fired from the same gun, they show a strong correlation. Examples of this are signatures A and B in Fig. 3, where $B \approx A$. When the shift distance is zero, their CCF has a maximum value, but not as large as the maximum value of the auto-correlation function of the reference signature ($ACF = 1.00$), because there are small differences between these two signatures.
- If signatures A and B come from bullets fired from different guns, there should be only a small correlation between the two bullet signatures. This is shown in Fig. 4, where $B \neq A$. With the shift distance τ changing, only random variations appear on the CCF curve without a clear correlation peak.

Signature Difference Parameter, D_s, for Bullet Signature Comparisons

Although the CCF can be used for signature comparison, it is not a unique parameter. Based on the definition of the cross-correlation function (7), if two compared signatures have the same shape but different vertical scales, their CCF is still 100% even if they are two different signatures. Therefore, a parameter we call the

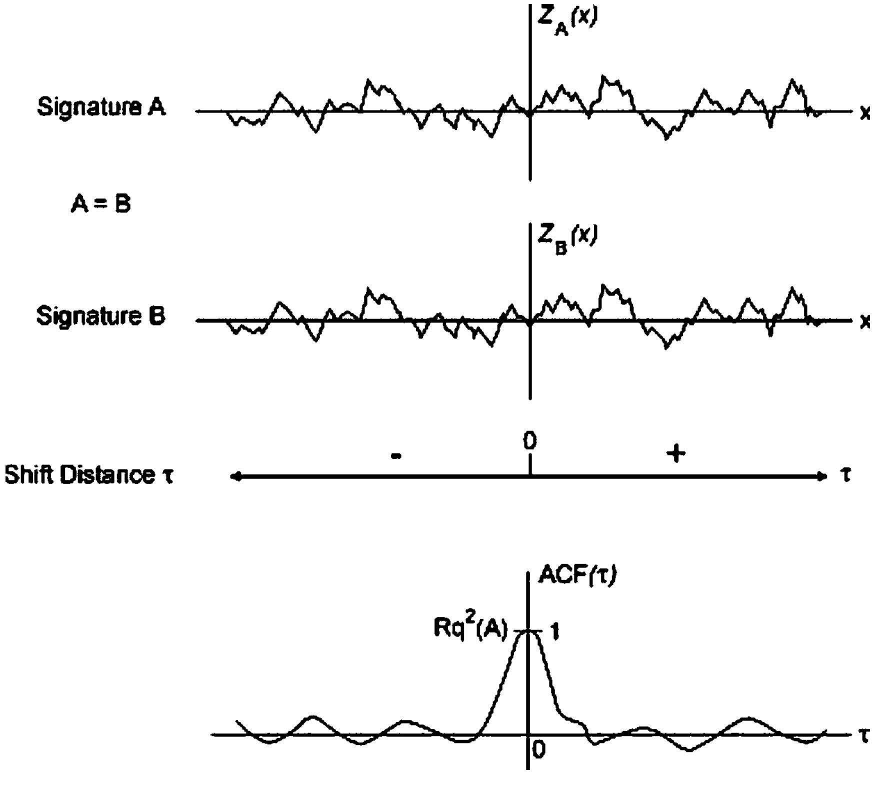

FIG. 2—*Bullet signature comparisons between identical bullet signatures, $B = A$, $ACF = 1$.*

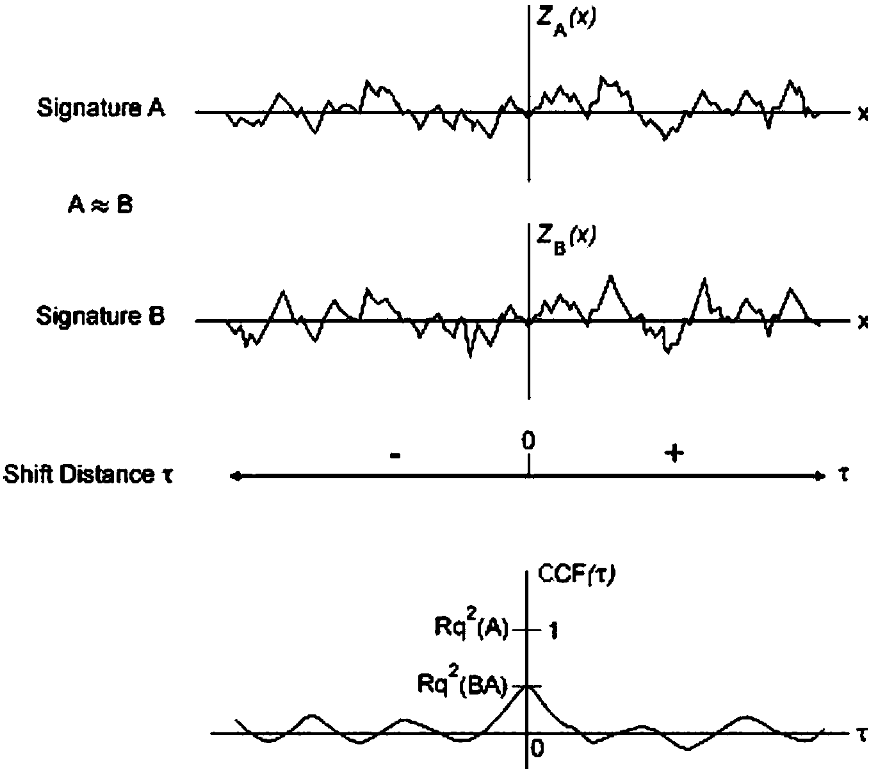

FIG. 3—*Bullet signature comparisons between similar bullet signatures, B ≈ A. A clear correlation peak can be seen on the CCF curve, CCF < 1.*

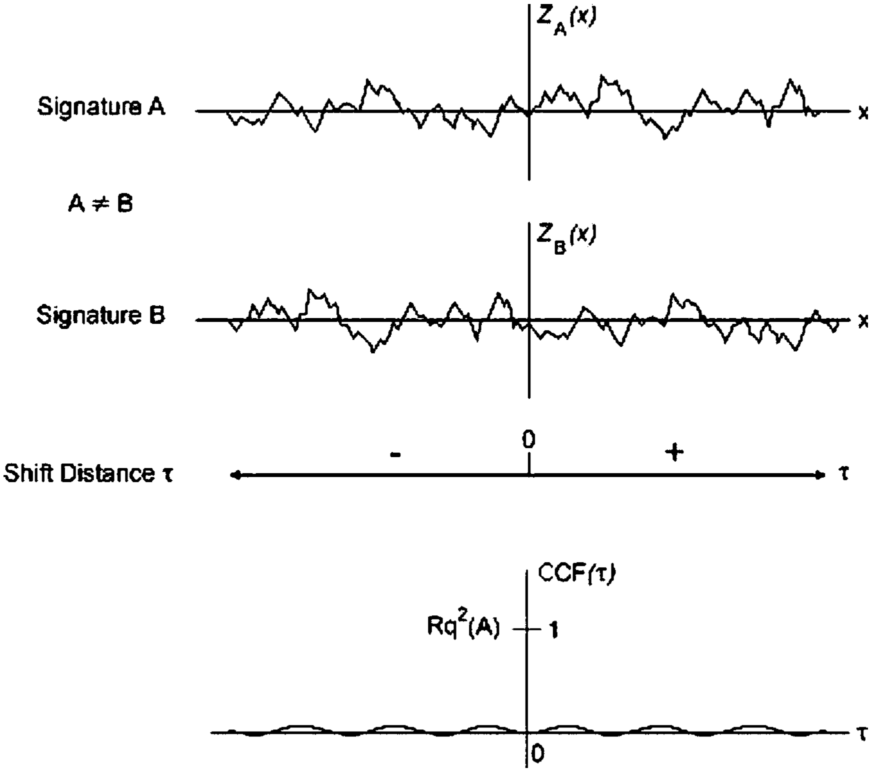

FIG. 4—*Bullet signature comparisons between dissimilar bullet signatures, B ≠ A. No obvious correlation peak can be seen on the CCF curve.*

signature difference D_s was proposed for quantifying bullet signature differences (7). The procedure is as follows:

- At the maximum cross-correlation point between signature B and A (see Fig. 3), construct a new profile Z(B – A) which is equal to the difference of the compared profile signature $Z(B)$ and the reference profile signature $Z(A)$:

$$Z(B - A) = Z(B) - Z(A) \tag{1}$$

- Calculate the Rq (root-mean-square roughness (14)) value for the new profile $Z(\mathrm{B}-\mathrm{A})$, $Rq(\mathrm{B}-\mathrm{A})$.
- Calculate the signature difference D_s of signatures B and A defined as

$$D_s = Rq^2(\mathrm{B}-\mathrm{A})/Rq^2(\mathrm{A}) \qquad (2)$$

where $Rq^2(\mathrm{A})$ is the mean square roughness of the reference signature $Z(\mathrm{A})$, used here as a comparison reference. From Eqs 1 and 2 it can be seen that when two compared profiles are exactly the same (see Fig. 2)

$$Z(\mathrm{B}-\mathrm{A}) = Z(\mathrm{B}) - Z(\mathrm{A}) = 0$$

then

$$Rq^2(\mathrm{B}-\mathrm{A}) = 0$$

and

$$D_s = 0$$

Advantages of Using the Proposed Parameter of Signature Difference D_s

The proposed parameter D_s has several features (7):

- It is easy to understand and use.
- It can be used for quantifying signature differences for both 2-D bullet signatures and 3-D casing signatures.
- Because signature information of all 2-D or 3-D data points is used for comparison, the parameter D_s could have high sensitivity, and can yield high repeatability and reproducibility.
- From Eqs 1 and 2, it can be seen that for the collection of all two-profile comparisons, the minimum profile difference is $D_s = 0$, which occurs when, and only when, these two profiles are exactly the same. That means that when any two compared 2-D or 3-D profiles have a profile difference of $D_s = 0$, these two profiles must be exactly the same (point by point).

NIST Bullet Signature Measurement System

Based on the proposed parameter and algorithm, a bullet signature measurement system was developed at NIST for the measurements of RM 8240 standard bullets. The measurement setup is shown in Fig. 5. A commercial stylus instrument is used for bullet signature measurements. For each measurement, a diamond stylus (item 1 in Fig. 5) traces a land impression of the standard bullet 2. The nominal tip radius of the diamond stylus is 2 μm. The nominal contact force is 0.001 N (about 100 mgf). The traversing speed is 0.5 mm/s. The vertical resolution is 0.01 μm, the horizontal resolution 0.25 μm.

The standard bullet is set on a bullet holder 3 (see Fig. 5), which is mounted on a rotary stage 4. The bullet holder is the same as that used in the IBIS system. This allows the standard bullet to be compatible with the IBIS system. The rotary stage is set on another horizontal rotary stage 5, which is rotated about 5° left around the vertical (Z) axis so that the bullet land with a 5° right twist can be measured perpendicular to the land. Both rotary stage 4 and the horizontal rotary stage 5 are set on an X-Y stage 6. This allows for the adjustment of the X-Y location of the bullet. After the measurement for the first land by scanning the stylus in the x-direction perpendicular to the land impression, bullet 2 is rotated 60° by rotary stage 4 so that the next land is measured. This is repeated

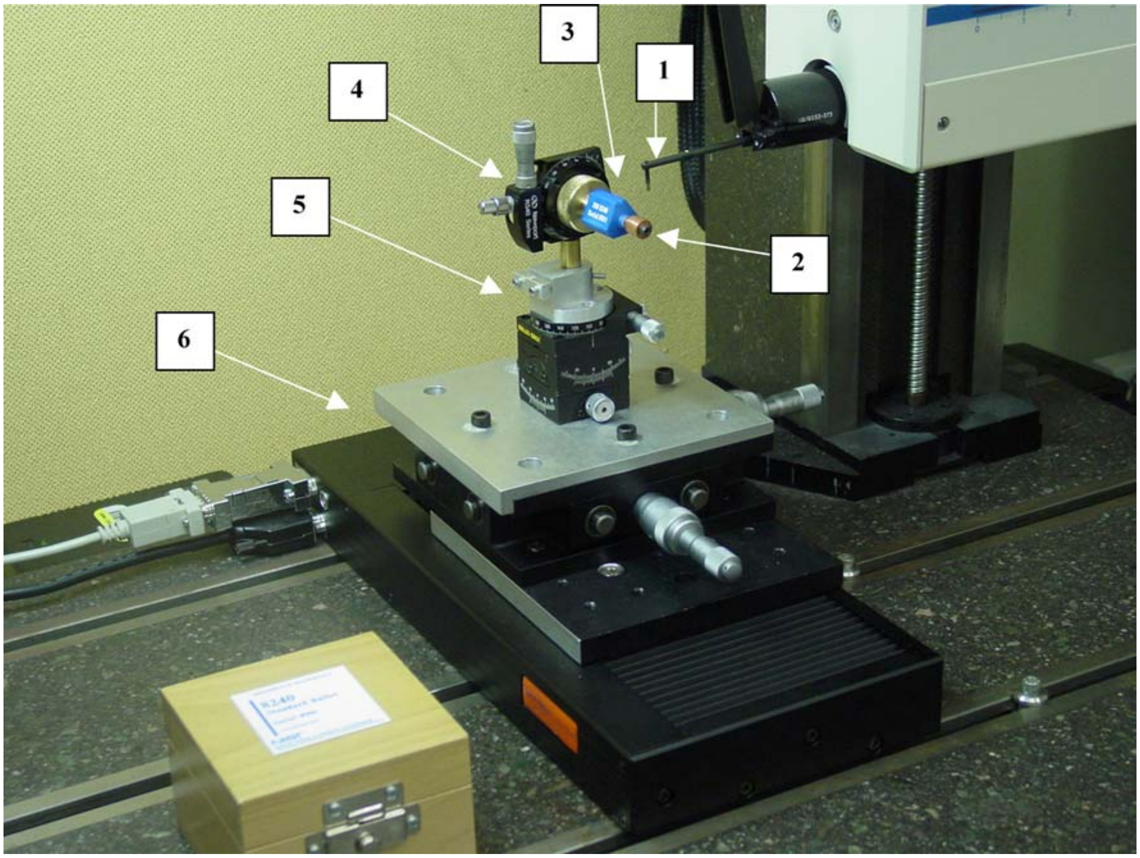

FIG. 5—*Measurement setup for NIST bullet signature measurement system. 1: diamond stylus; 2: standard bullet; 3: bullet holder; 4: rotary stage; 5: horizontal rotary stage; 6: X-Y stage.*

Date: 24/09/2003 11:40:20

Bullet No. 1

Land No. 1

Signature A: C:\bullet\CNC Profile-rev\Atf2r.dat

Signature B: C:\Work\Data\Bullets - Casings\RM 8240 01-20 Data\RM 8240 0

CCF (ACF) : 99.55 %

Shift distance: +0.03375 (mm)

RqA: .467 (um)

RqB: .460 (um)

Rq(B-A): .0447 (um)

Signature difference Ds: .92 %

FIG. 6—*Bullet signature comparison between the land 1 of S/N RM 8240 001 standard bullet (Signature B, as shown on second profile from top) and virtual standard (Signature A, as shown on top). Cross-correlation function CCF = 99.55%; signature difference* $D_s = 0.92\%$.

for all six lands. Finally, the measurement profiles are input into the bullet signature comparison program for analysis.

Bullet Signature Comparison Program

Overview of Comparison Program

The bullet signature comparison program is based on the proposed parameters and algorithm as mentioned above. A screen output of the bullet signature comparison program is shown in Fig. 6. The top profile is the virtual bullet signature standard, or signature A, which is one of the six surface profiles from the bullet signatures of the six master bullets fired at ATF and FBI. The virtual signature standard is used to control the tool path of the numerically controlled diamond turning machine to produce the RM bullets. It is also used as a reference standard for the measurements of the bullet signatures of the RM bullets. The second signature in Fig. 6 shows the measured bullet signature, or signature B, which is a surface profile from the No. 1 land impression of the S/N RM 8240 001 bullet. At the maximum cross-correlation position of the two profiles, a correlation peak shows CCF = 99.55% (see Fig. 6). At this position, a new signature, B – A (see the bottom profile in Fig. 6), is constructed, which is equal to the difference between the two compared signatures. Then the signature difference is calculated by Eq 2, $D_s = 0.92\%$.

Modification of the Bullet Signatures

Both the virtual bullet signature standard (Signature A) and the measured bullet signature (Signature B) are modified bullet signatures. When the stylus of the instrument traces a land impression (see Fig. 5), the traced bullet signature, or the raw profile, includes the shape of the land impression as well as the surface roughness and waviness (14) (see Fig. 7*a*). By windowing the central part of the land impression and removing the curvature, a modified bullet signature is obtained as shown in Fig. 7*b*, which includes both the roughness and waviness (14). The waviness represents the relatively low-frequency profile information, which is considered as being of secondary importance for the bullet signature identification, and is removed before the signature comparison. A high-pass Gaussian filter (14) with 0.25 mm long cutoff length is used for that purpose. Figure 7*c* shows the modified bullet signature after windowing, curvature removal, and Gaussian filter. Both the virtual bullet signature standard (Signature A, see Fig. 6) and the measured RM bullet signature (Signature B) must be modified by the same process before comparisons.

Correction for Unequal Spacing of Horizontal Scales

As the bullet signature is measured on a curved bullet surface, the total range of Z heights in the profiles is significant. The stylus instrument initially acquires the profiles as points equally spaced in X. As with most stylus instruments, however, the stylus actually measures the angle of the stylus tip as it rotates about a pivot point and not the Z height. When the stylus instrument converts these angles into true Z heights, the once equally spaced points become unequally spaced in X. Unequally spaced points are not a problem when manufacturing the bullets, but most profile analysis techniques are significantly easier to implement with equally

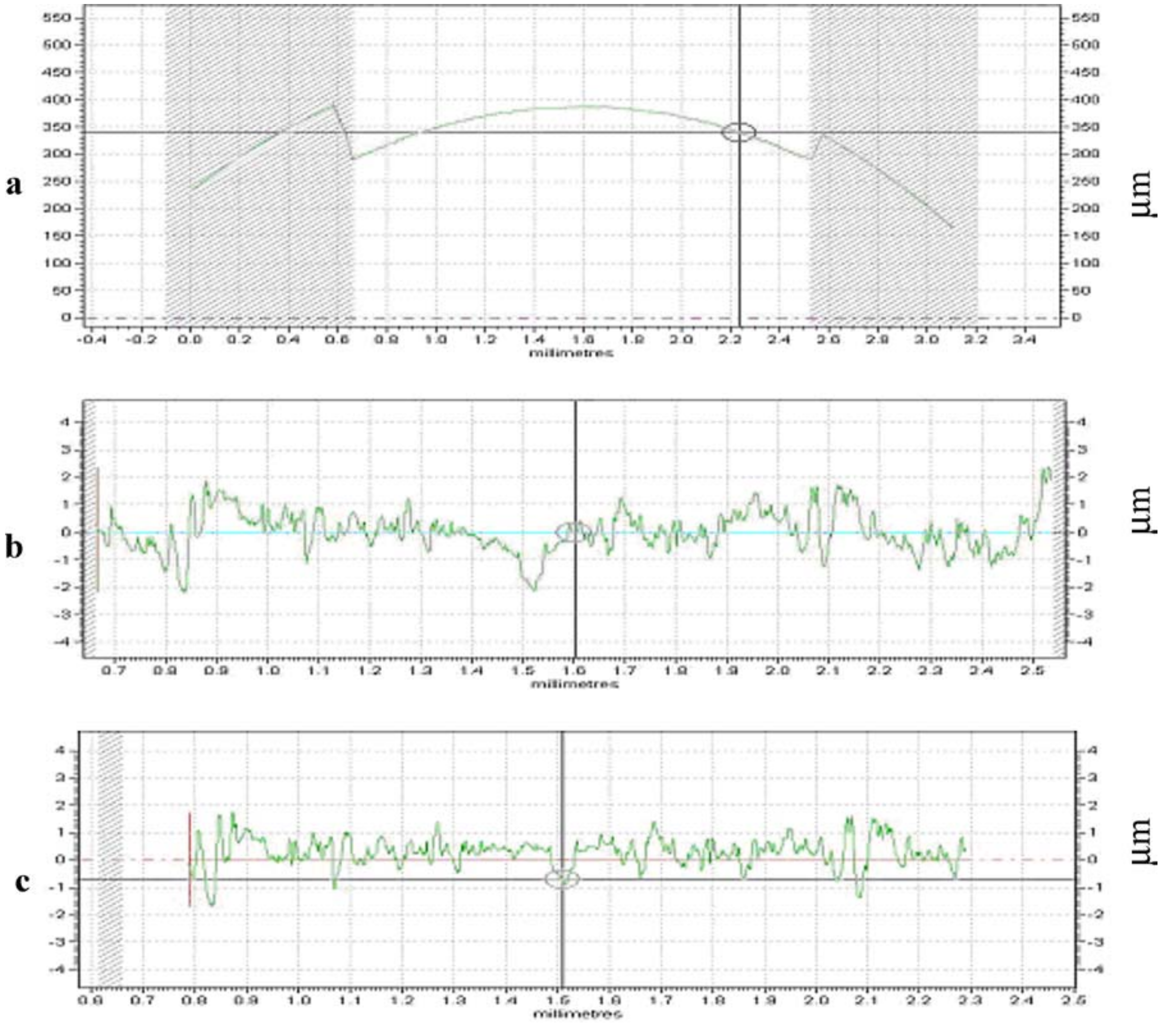

FIG. 7—*Raw profile on No. 1 land impression of S/N RM 8240 001 standard bullet* (a)*; profile after windowing and curvature removed* (b)*; and profile after a 0.25-mm-long cutoff Gaussian filter* (c).

spaced points. Fortunately, cubic spline functions may be used to resample the profile data to make the profiles equally spaced again (13). Both the virtual signature standard (see Fig. 6, Signature A), which is originally traced on the master bullets provided by ATF and FBI, and the compared signature (see Fig. 6, Signature B), which is traced on the RM bullets, must be corrected for unequal spacing of the horizontal scales. Figure 8 shows the standard signature A, which has been corrected, and the compared signature B, which has not. As a result, there is a relative lateral distortion between Signatures A and B, resulting in a large signature difference B − A (see the bottom signature in Fig. 8), $\text{CCF} = 73.67\%$, $D_s = 51.91\%$. When resampling is applied to Signature B (see Fig. 9), Signatures A and B are aligned very well in the lateral direction, and the signature difference B − A is very small (see the bottom profile in Fig. 9), $\text{CCF} = 98.47\%$, $D_s = 3.04\%$.

Data Flow of Standard Signature A and Compared Signature B

Figure 10 illustrates the bullet signature data flow through the measurement program. There are two channels of data flow in the measurement program. The left one shows the data flow of the virtual signature standard, or Signature A, while the right one shows the data flow of the measured signature, or Signature B. Both emanate from the six different master bullets from ATF and FBI. As a result, the radius of curvature for each of the lands is different. The time required to machine the lands on the diamond turning machine is minimized when the radius of those lands are the same as the radius of the standard bullet itself. In order to minimize the machining time, the measured radius was removed from each of the six lands and the designed radius of the standard bullet is added back to each land. By doing this, the virtual bullet signature standard is generated (see Fig. 10).

The virtual signature standard is used as a reference standard for both the production and the measurement of the RM bullets. First, it is used for control of the tool path of the numerically controlled diamond turning machine to produce the physical standard of the RM bullets. Then it is input into the measurement system (see the left channel of the measurement program in Fig. 10) as a reference standard for the signature measurements of RM bullets. In the measurement system the profile of the virtual signature standard is first processed by X-scale resampling to linearize the X-scale, as discussed before. Then a short Gaussian filter (14) with 0.0025 mm short cutoff length is used to remove the high-frequency noise. After curvature removal and application of a 0.25 mm long cutoff Gaussian filter as discussed before, the standard signature A is used as a reference for the measurement of the bullet signature B.

After the diamond turning process, as shown in Fig. 10, the RM bullets are measured by the stylus instrument through the same data

Date: 9/24/2003 1:02:19 PM
Bullet No. 17
Land No. 1
Signature A: C:\Lima\Bullet\RM17\Gussianfilter\ATF02_12ur.dat
Signature B: C:\Lima\Bullet\RM17\Gussianfilter\RM17A_11u.dat
CCF (ACF) : 73.67 %
Shift distance: -0.08025 (mm)
RqA: .464 (um)
RqB: .457 (um)
Rq(B-A): .3342 (um)
Signature difference Ds: 51.91 %

FIG. 8—*Bullet signature comparison before the X-scale correction for Signature B: CCF = 73.67%, D_s = 51.91%.*

processing program to generate a modified profile. The modified profile is input into the measurement program and passes through exactly the same process as the signature A is passed, which includes X resampling, short Gaussian filter, removal of curvature, and long Gaussian filter. Then the measured signature B is compared with the standard signature A.

Measurement Results and Discussion

Repeatability and Reproducibility Tests

Before measurements of bullet signatures of the RM bullets may be considered valid, the measurement repeatability and reproducibility of the measurement system must be tested first. The measurement repeatability is a measure of the short-term random variations of the instrument and the measurement system itself. To assess measure repeatability, it is necessary to minimize other random factors caused by, for example, instrument calibration and measurement setup, and the environment variation. For that reason, the repeatability test was carried out on the same day under the same measurement setup and instrument calibration by repeating ten measurements on the same land impression of the same RM bullet. Using NIST virtual bullets signature standard as reference signature A, the repeatability test results on the No. 1 land of S/N RM 8240 001 bullet (Signature B) are given in Table 1. They have a mean CCF = 99.47% with a standard deviation of 0.06%.

On the other hand, the reproducibility test measures the effects of all the random factors, including those from both the short- and long-term random variations from the instrument and the measurement system, and the day-to-day variations of the measurement setup, instrument calibration, and the environment. Therefore, the reproducibility test was carried out on different days under different measurement setups and instrument calibrations by measuring the same land impression of the same bullet. The reproducibility test results on the No. 1 land of S/N RM 8240 001 bullet are given in Table 2. They have a mean CCF = 99.29% with a standard deviation 0.26%.

It is understandable that the reproducibility tests have smaller mean CCF values (99.26%) and a larger standard deviation (0.26%) when compared with the results of the repeatability tests (CCF = 99.47%, S.D. = 0.06%). This is because the reproducibility tests include all the same sources of error as the repeatability tests and other sources as well.

TABLE 1—*Repeatability tests for NIST bullet signature measurement system.*

RM 8240-001 Land No. 1	CCF %	D_s %	*Rq*(A) μm	*Rq*(B) μm	*Rq*(B − A) μm
1	99.29	1.41	0.467	0.461	0.0555
2	99.49	1.02	0.467	0.462	0.0472
3	99.51	0.99	0.467	0.462	0.0463
4	99.51	0.99	0.467	0.462	0.0464
5	99.51	0.98	0.467	0.463	0.0463
6	99.48	1.03	0.467	0.463	0.0474
7	99.47	1.05	0.467	0.462	0.0478
8	99.47	1.06	0.467	0.462	0.0481
9	99.48	1.03	0.468	0.463	0.0476
10	99.48	1.04	0.467	0.463	0.0476
Mean	99.47	1.06	0.467	0.462	0.0480
S.D.	0.06	0.13	0.000	0.001	0.0027

Date: 9/24/2003 1:06:33 PM
Bullet No. 17
Land No. 1
Signature A: C:\Lima\Bullet\RM17\Gussianfilter\resampled\ATF02_ur.dat
Signature B: C:\Lima\Bullet\RM17\Gussianfilter\resampled\RM17A_11u.dat
CCF (ACF) : 98.47 %
Shift distance: -0.0725 (mm)
RqA: .465 (um)
RqB: .463 (um)
Rq(B-A): .0810 (um)
Signature difference Ds: 3.04 %

FIG. 9—*Same as Fig. 8, after X-scale correction for Signature B: CCF = 98.47%,* D_s *= 3.04%.*

TABLE 2—*Reproducibility tests for NIST bullet signature measurement system.*

RM 8240-001 Land No. 1	Date	CCF %	D_s %	Rq(A) μm	Rq(B) μm	Rq(B − A) μm
1	3/13/2003	99.55	0.92	0.467	0.460	0.0447
2	3/19/2003	99.12	1.76	0.468	0.461	0.0620
3	3/31/2003	99.08	1.83	0.466	0.460	0.0632
4	3/31/2003	98.95	2.10	0.468	0.463	0.0677
5	4/1/1993	99.38	1.25	0.468	0.463	0.0523
6	4/3/2003	99.66	0.69	0.468	0.463	0.0388
7	4/8/2003	99.29	1.41	0.467	0.461	0.0555
Mean		99.29	1.42	0.467	0.462	0.0549
S.D.		0.26	0.51	0.001	0.001	0.0104

TABLE 3—*Measurement results for first set of bullets, S/N RM 8240 001-020, each measured in six lands.*

RM 8240 001-020		CCF %	D_s %	Rq(A) μm	Rq(B) μm	Rq(B − A) μm
Land No. 1	Mean	99.26	1.49	0.467	0.461	0.0548
	S.D.	0.54	1.06	0.001	0.002	0.0162
Land No. 2	Mean	98.83	2.34	0.354	0.353	0.0525
	S.D.	0.59	1.18	0.001	0.002	0.0132
Land No. 3	Mean	99.69	0.62	0.451	0.445	0.0352
	S.D.	0.11	0.21	0.002	0.002	0.0058
Land No. 4	Mean	99.40	1.25	0.407	0.396	0.0448
	S.D.	0.23	0.45	0.001	0.001	0.0080
Land No. 5	Mean	99.73	0.57	0.651	0.640	0.0480
	S.D.	0.14	0.26	0.003	0.004	0.0106
Land No. 6	Mean	97.20	5.53	0.147	0.142	0.0345
	S.D.	0.65	1.25	0.000	0.001	0.0039

Measurements for 40 RM 8240 Standard Bullets

So far 40 RM bullets have been produced at NIST. The first 20 bullets were produced in January 2002 under the same manufacturing setup. The second 20 bullets were produced in June 2003 by a different individual following the same manufacturing procedures as used for the first set of bullets. All 40 bullets have been measured with the NIST bullet signature measurement system. The measurement results for the first set of 20 bullets are given in Table 3 and for the second set in Table 4. Both sets of measurements use the same virtual bullet signature standard as a comparison reference.

Measurement results show that the manufactured bullet signatures are very close to the virtual bullet signature standard. For example, Fig. 11 shows the distribution of CCF values from 240 signature measurements of 40 RM bullets, each measured at six lands. All CCF values are higher than 95%, and most are higher than 99%. Considering that CCF = 100% means the measured bullet signature is exactly the same with the virtual bullet signature standard (point by point), the measurement results have demonstrated high reproducibility for both the bullet signature measurement system and the manufacturing process of the RM bullets. Based on NIST Technical Note 1297 (15), an uncertainty analysis procedure is currently in progress to report the measurement results for both CCF and D_s values with 95% confidence level.

From Tables 3 and 4, it can be seen that most of the mean CCF values are higher than 99%, but the mean CCF values on the No. 6

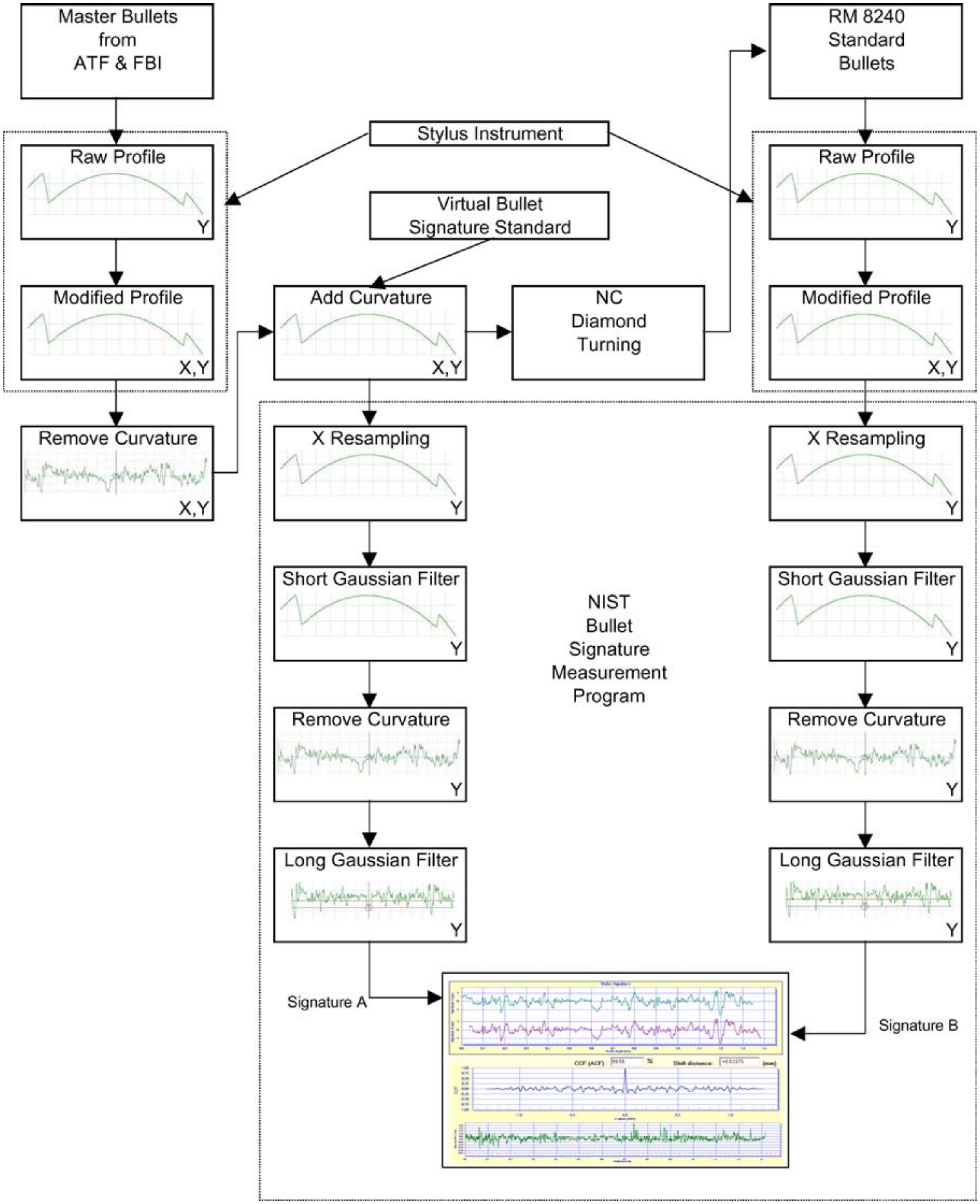

FIG. 10—*Bullet signature data flow through comparison program.*

land shows a significant difference from the others. It is found that the virtual bullet signature of the No. 6 land, which was originally traced on the No. 6 master bullet, is significantly smoother than the other five signatures traced on the other five master bullets. From Tables 3 and 4, it can be seen that the Rq roughness (14) of the No. 6 land is much less than the Rq values of the other five lands. However, the Rq roughness for the signature difference, $Rq(\mathrm{B}-\mathrm{A})$, of the No. 6 land does not show a big difference from the others (also see Tables 3 and 4). This is because $Rq(\mathrm{B}-\mathrm{A})$ is determined mainly by the random variations during the manufacturing and measurement process, which are kept at the same level for the same process. As a result, the relative signature difference $Rq(\mathrm{B}-\mathrm{A})/Rq(\mathrm{A})$ for the No. 6 land is larger than the others, resulting in a smaller CCF value and a larger D_s value (see Eq 2).

Production Repeatability and Reproducibility for RM Bullets

Production repeatability here refers to the similarity of bullet signatures produced at the same time. Production reproducibility

TABLE 4—*Measurement results for second set of bullets, S/N RM 8240 021-040, each measured in six lands.*

RM 8240 021-040		CCF %	D_s %	Rq(A) µm	Rq(B) µm	Rq(B − A) µm
Land No. 1	Mean	99.47	1.07	0.470	0.463	0.0475
	S.D.	0.24	0.47	0.004	0.004	0.0100
Land No. 2	Mean	99.25	1.51	0.348	0.342	0.0419
	S.D.	0.36	0.71	0.001	0.001	0.0093
Land No. 3	Mean	99.66	0.68	0.452	0.450	0.0368
	S.D.	0.12	0.23	0.001	0.001	0.0061
Land No. 4	Mean	99.12	1.80	0.403	0.391	0.0532
	S.D.	0.37	0.71	0.000	0.001	0.0105
Land No. 5	Mean	99.66	0.70	0.642	0.631	0.0520
	S.D.	0.20	0.39	0.001	0.002	0.0128
Land No. 6	Mean	96.72	6.47	0.145	0.141	0.0370
	S.D.	0.78	1.53	0.000	0.001	0.0049

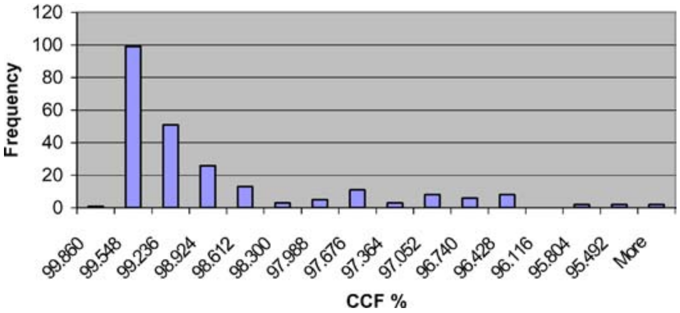

FIG. 11—*CCF distribution for 240 bullet signatures of 40 RM bullets. All CCF values are higher than 95%; most are even higher than 99%. CCF = 100% means that the measured bullet signature is exactly the same as the virtual bullet signature standard (point by point).*

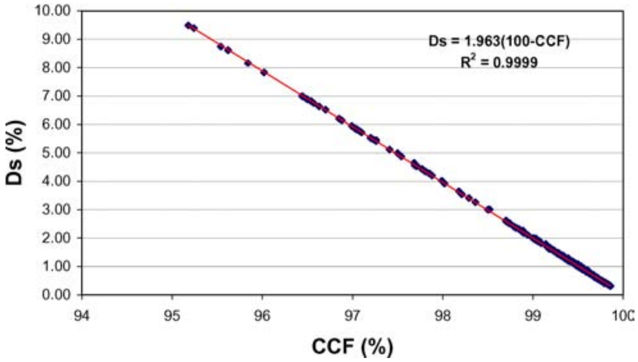

FIG. 12—*Least-squares fitting for statistical relationship between CCF and* D_s *measured on 240 bullet signatures on 40 RM bullets.*

refers to the similarity of all RM bullet signatures produced at two different times.

Table 5 compares signature measurements performed on the same RM bullet and on different RM bullets. The repeatability and reproducibility tests are carried out on the No. 1 land impression of S/N RM 8240 001 bullet. The mean CCF and standard deviation are 99.47% and 0.06% for the measurement repeatability, and 99.29% and 0.26% for the measurement reproducibility. When the No. 1 land impression on different bullets is tested, the mean CCF value and standard deviation are 99.26% and 0.54% for the first set of 20 bullets, and 99.47%, 0.24% for the second set of 20 bullets (see Table 5). It can be seen that the signature variations between bullet and bullet are very close to the repeatability and reproducibility of the measurement system that are tested on the same bullet. This demonstrates that bullet signatures on the 40 standard bullets are manufactured with such a high degree of production repeatability and reproducibility that when these standard bullets are distributed nationwide for checking instrument calibrations, they will virtually play the same function as a single bullet.

Linear Relationship Between Parameters of CCF and D_s

As discussed above, CCF is not a unique parameter for representing bullet signature difference, and therefore the signature difference parameter D_s is derived. However, when the measurement system is well calibrated to measure the 240 signature of 40 bullets, CCF and D_s showed a strong linear correlation (see Fig. 12). We are currently working to develop statistical models to describe that linear relationship.

Summary

Based on auto- and cross-correlation functions, a new parameter and algorithm are proposed for bullet signature measurements for NIST RM 8240 standard bullets. A measurement system based on a stylus instrument is developed at NIST's Surface Calibration Laboratory. Initial test results show that the machined bullet signatures are highly uniform among the 40 RM bullets and are in good agreement with the virtual signature standard. Measurements on 240 bullet signatures of the 40 NIST RM 8240 standard bullets show that the cross-correlation functions (CCF) between the measured bullet signature and the virtual bullet signature standard are higher than 95%; most are even higher than 99%. Considering that CCF = 100% means the measured bullet signature is exactly the same as the virtual bullet signature standard (point by point), the measurement results demonstrate the high reproducibility for both the bullet signature measurement system and the manufacturing process of the RM bullets.

TABLE 5—*Comparison of signature measurements performed on same RM bullet and on different RM bullets.*

	Measurements		Production	
	Repeatability	Reproducibility	Repeatability	Reproducibility
CCF %	Same bullet land Same meas. day Same meas. setup Same calib.	Same bullet land Dif. meas. days Dif. meas. setup Dif. calib.	First 20 bullets made with same setup	Second 20 bullets made and measured by dif. people with the same procedures
Mean	99.47%	99.29%	99.26%	99.47%
S.D.	0.06%	0.26%	0.54%	0.24%

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