Forensic Optical Topography
A Landscape Study

December
2016

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OVERVIEW

The National Institute of Justice's (NIJ's) Forensic Technology Center of Excellence (FTCoE) at RTI International directed this landscape study of optical topography instrument for implementation in forensic practice with input from law enforcement, crime laboratories, research scientists, and practitioners in the criminal justice community.

A landscape study, in concept, is designed to provide a comprehensive list of market participants, their products, and product features to enable better informed decisions by end users. This report provides a landscape view of currently available optical topography systems for firearms identification. It is intended to provide forensic laboratory directors, practitioners, and stakeholders with a survey of commercial systems and a basic introduction to the technology.

Specifically, this report provides decision makers and potential end users with:

- background information on advances in optical topography for forensic practice,
- issues to consider related to optical topography implementation, and
- comparison of the capabilities of available optical topography systems.
- exemplary cases that illustrate successful adoption.

The document also provides a summary of considerations that will impact adoption, procurement, training, and validation.

Public Domain Notice

Disclaimer

Information provided herein is intended to be objective and is based on data collected during primary and secondary research efforts available at the time this report was written. The information provided herein is intended to provide a snapshot of current optical topography systems available to forensic laboratories and a high-level summary of considerations for deployment; it is not intended as an exhaustive product summary. Features or capabilities of additional tools or developers identified outside of this landscape may be compared with these tool features and service offerings to aid in the information-gathering or decision-making processes. Experts, stakeholders, and practitioners offered insight related to the use of optical topography systems.

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Forensic Technology Center of Excellence (FTCoE)

The FTCoE is a collaboration of RTI International and its Forensic Science Education Programs Accreditation Commission (FEPAC) – accredited academic partners: Duquesne University, Virginia Commonwealth University, and the University of North Texas Health Science Center. In addition to supporting NIJ's research and development (R&D) programs, the FTCoE provides testing, evaluation, and technology assistance to forensic laboratories and practitioners in the criminal justice community. NIJ supports the FTCoE to transition forensic science and technology to practice (Award Number 2011-DN-BX-K564).

The FTCoE is led by RTI International, a global research institute dedicated to improving the human condition by turning knowledge into practice. With a staff of more than 4,700 providing research and technical services to governments and businesses in more than 58 countries, RTI brings a global perspective. The FTCoE builds on RTI's expertise in forensic science, innovation, technology application, economics, DNA analytics, statistics, program evaluation, public health, and information science.

Forensic Optical Topography Working Group

We would like to thank the following forensic science community stakeholders and practitioners who offered insight, analysis, and review.

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OBJECTIVES OF THE LANDSCAPE STUDY

The objectives of this landscape study are to:

- Inform the forensic professional concerning the application of optical topography in the crime laboratory;
- Compare available instruments, some of which are not commonly used for forensics;
- Discuss barriers to broader adoption of optical, topography-based solutions;
- Provide practical and technical considerations faced by crime laboratory practitioners who may plan to adopt optical topography in their laboratories; and
- Provide an overview of ongoing developments of the technology and associated standards.

RESEARCH METHODOLOGY

To conduct this landscape study, FTCOE used a process that included the following steps:

- Convene an Optical Topography Working Group that includes firearms examiners, researchers, and industry.
- Research secondary sources, including journal and industry literature for information related to need, successful use, developmental validation, and adoption criteria.
- Discuss the technology's state-of-the-art with subject matter experts, including crime laboratory practitioners, stakeholders, technology developers, academics, and key decision makers.
- Document, summarize, and release key findings to the crime laboratories and forensic community.

OPTICAL TOPOGRAPHY'S RELEVANCE TO FIREARM IDENTIFICATION

The field of firearms identification is undergoing a major change in technology and capability with the introduction of optical topography into forensic laboratory practice. Optical topography provides a three-dimensional (3D) view of the surface of a bullet or cartridge case at resolutions that capture the full range of subclass and individual characteristics. This technology offers an additional method to the comparison microscope for one-to-one firearm evidence comparisons, and may provide an objective measurement of similarity toward a possible source identification. Separately, many laboratories now have access to systems designed for database searches based on topographic data, and some have applied the technique as a method to produce intelligence leads in unsolved cases or as a complement to the comparison microscope. Typically, the instrument permits more rapid and accurate searches of reference collections than traditional microscopy could provide. Combined with the National Integrated Ballistics Information Network (NIBIN)[1] of the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) organization, systems can be used to provide more interjurisdictional links with greater reliability than was previously possible. NIBIN is designed to work with Ultra Electronics Forensic Technology, Inc.'s (Ultra FTI) systems, but other systems produce reliable data for local use. New data standards should permit the use of any optical topographic system in the future within national or international data-sharing frameworks.[2]

[1] https://www.atf.gov/firearms/national-integrated-ballistic-information-network-nibin

[2] https://www.forensiccoe.org/Our-Impact/Focusing-on-Special-Initiatives/Forensic-Optical-Topography/Working-Group-Meeting-Final- Report

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This report details the current state-of-the-art for optical topography in forensic practice, including:

- its relevance to firearms identification,
- technological advances,
- current systems,
- considerations for deployment, and
- case studies.

The report details options that are available to crime laboratories; considerations in the selection and deployment of these sophisticated microscopes; and subsequent approaches to training, validation, and databasing in the laboratory environment. More detailed examination of the specifics of optical topographic technology has been presented elsewhere.

FIREARMS IDENTIFICATION

As observed by Edmond Locard, every contact leaves a trace or exchange of physical material between objects. In some cases, the forensic examiner may find impressions left by the contact between the surfaces of two objects. For example, tools may leave marks on surfaces that they contact. Tool marks may be used to associate a particular surface with a tool or type of tool, if the tool working surface has sufficient individuality and the tool mark is reproducible enough to make comparisons. For over 100 years, forensic examiners have extended this concept to firearm identification because the action of a firearm on the surface of a bullet or cartridge may leave characteristic tool mark impressions.[3] In particular, the firing pin, chamber, and breech face of a firearm may leave marks on a cartridge case, while the rifling, arrangement of spiral grooves in a firearm barrel, will leave impressions and engraving on a bullet.[4] In general, these tool marks exhibit sufficient individuality and reproducibility to permit the firearm examiner to associate bullets or cartridge cases with the gun from which they were fired.

The examiner uses microscopy to identify individual tool mark characteristics, including impressed marks from tools such as firing pins and striated marks from tools such as barrel rifling. Some marks may be class characteristics that are shared by firearms of a certain type and that can be used to narrow the population of possible sources. Other marks may be subclass characteristics that are common across multiple instances of the same type of firearm. These common marks may be created by certain types of manufacturing processes. Finally, some marks represent individual characteristics that distinguish a particular firearm from other firearms of the same type or even of the same production series.

Examiners must analyze each mark to determine its type and suitability for identification. This process is dependent on the examination of class, subclass (if present), and individual characteristics observed under the microscope. The examiner must then evaluate the quality and quantity of the individual characteristics being observed to determine if there is sufficient agreement between the individual characteristics of two tool marks to conclude that they originated, to a practical certainty, from the same source. There are currently two types of criteria that firearm examiners use to determine if "sufficient agreement" exists. The first is known as pattern matching, which is based on an examiner's cognitive ability to recognize when the observed agreement between individual characteristics exceeds the best agreement known, through the examiner's training and experience, to exist between two tool marks known to be

[3] Thompson, R. M. (2010). Firearm identification in the forensic science laboratory. National District Attorneys Association. Retrieved from http://www.ndaa.org/pdf/Firearms_identity_NDAAsm.pdf

[4] For a definition of "rifling," please refer to the Glossary."

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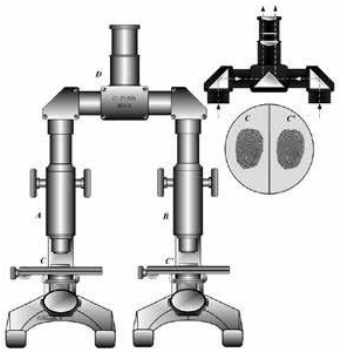
Table 1. AFTE's adopted theory of identification and range of conclusions

Conclusion	Basis	Example
Identification	Individual and class characteristics agree.	The caliber and rifling characteristics (number and direction of twist) of two examined bullets are the same, and sufficient individual agreement is observed with the individual characteristics between corresponding land rifling impressions.
Inconclusive (subcategorized into three accepted levels)	Class characteristics agree but are insufficient for identification or elimination due either to insufficient agreement or disagreement of individual characteristics.	The caliber and rifling characteristics of two examined bullets are the same, but there are not enough matching individual striae in corresponding land rifling impressions to support identification.
Elimination	Class and/or individual characteristics disagree.	The caliber and/or rifling characteristics on two examined bullets are different.
Unsuitable	Marks are not suitable to make judgments about class or individual characteristics because the specimen bears no microscopic marks of value.	Bullets have too much impact or are too damaged for comparison and identification purposes.

from different sources, and is consistent with agreement found between tool marks from the same source. The second criteria used to determine if there is "sufficient agreement", known as quantitative consecutive matching striae (QCMS) theory, is based on a numerical threshold for identification that has been determined through empirical testing.[5] However, the latter technique is only applicable to striated tool marks, such as those found on bullets, and does not apply to impressed marks. The Association of Firearm and Tool Mark Examiners (AFTE) has adopted a theory of identification and range of conclusions that establish the basis for conclusions in firearms examination (see Table 1).

This process depends on the tools and tool marks in question, as well as the capabilities and tools available to the examiner. Most importantly, the examiner must have the skills, training, and experience to examine evidence thoroughly and accurately, and produce conclusions with a sound basis. In addition, the examiner must have access to high-quality microscopy to conduct a detailed analysis of the individual characteristics. The primary tool for examination is the optical comparison microscope, which is basically two compound microscopes linked together by an optical bridge to allow the examiner to simultaneously observe two objects, such as an evidence cartridge case and test-fired cartridge case. Although modern instruments permit these images to be displayed on a computer screen or digital photograph, the firearms examiner performs the essential work by looking through the eyepieces of the comparison microscope in much the same way as was done by Calvin Goddard, the pioneer of the comparison microscope in the forensic laboratory in the 1920s.[6]



https://commons.wikimedia.org/wiki/File:ComparisonMicroscope.png

[5] Biasotti, A., Murdock, J., & Moran, B. (1997). Firearms and toolmark identification (Ch. 35, Vol. 4), in D. L. Faigman, D. K. Kay, M. J. Saks, & E. K. Chen (Eds.), Modern scientific evidence: The law and science of expert testimony (pp 645–723). St. Paul: Thompson-West.

[6] http://www.firearmsid.com/A_historyoffirearmsID.htm

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OVERVIEW OF FIREARM EVIDENCE SEARCH DATABASES

For many years, firearms examiners have used class and individual characteristics on fired cartridge cases and bullets to connect crimes in which the firearm was initially unknown and therefore unavailable for comparison. Computerized image analysis enabled the automation of this process and the construction of databases of firearm evidence in shooting investigations and crime guns starting in the late 1980s. In the late 1990s, NIBIN became the standard tool in the United States for databasing and comparing evidence and crime guns. NIBIN's effectiveness for comparing cartridge cases and clearing firearm- related homicides was demonstrated in the city of Boston.[7] NIBIN is based on the Integrated Ballistic Identification System (IBIS), which historically used plan-view microscopic images to build its reference collection and make comparisons. The comparisons are limited to determining firearm types and identifying possible firearms that may match crime scene evidence. The system does not produce identifications, which still rely on the examiner and comparison microscope.

In 2008, the National Academy of Sciences studied the possibility that a NIBIN-like system could be used to establish a database of all guns manufactured and sold.[8] It concluded that such a database was not feasible because current microscopic and computer analytical methods were insufficient to identify firearms consistently in large databases.

TECHNOLOGY DEVELOPMENTS

Forensic tool mark examiners are the primary users of the comparison microscope, although other microscopic techniques have been developed that may improve an examiner's ability to discern tool mark characteristics. In particular, optical topography may address some of the limitations inherent in traditional approaches, such as depth-of-focus, specular reflection, and lack of 3D data. Some gun manufacturing techniques (e.g., polygonal rifling, computer numerical controlled [CNC] milling, and metal injection molding [MIM]) add to the difficulty of making comparisons in some cases.

The term, "optical topography" includes several technical approaches, including focus variation, confocal microscopy, interferometric-based techniques, and photometric stereo. Systems cost between $100,000 and $500,000, although laboratories may take advantage of the Bureau of Alcohol, Tobacco, Firearms, and Explosives' NIBIN program to defray some or all of the hardware and network costs, subject to funding availability.

In focus variation, the in-focus plane of reflected light is scanned in the z direction (vertical) to provide a complete picture of an object. The image is mathematically reconstructed by combining multiple images—each with a very shallow depth of focus—into a virtual 3D view. Focus variation microscopes accommodate large working distances, which may be convenient for imaging the curved or deformed surface of a bullet and steep edges such as those found in firearms examination. When considering a focus variation instrument, the laboratory should consider vertical resolution carefully because some lower priced instruments may not have the resolution required for tool mark

Caption: focus variation

[7] Linking Crime Guns: The Impact of Ballistics Imaging Technology on the Productivity of the Boston Police Department's Ballistics Unit, J Forensic Sci, July 2004, Vol. 49, No. 4.

[8] National Research Council. (2008). *Ballistic imaging*. D. L. Cork, E. S. Meieran, & C. V. Petrie (Eds). Washington, DC: The National Academies Press. doi: 10.17226/12162

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examination. Alicona and Sensofar LLC have focus variation microscopes for use in the forensic laboratory. These instruments will provide good lateral resolution.

In confocal microscopy, the examiner views an image in which the incident and reflected light from the object are always in focus. Light passes through a pinhole aperture that blocks out-of-focus light. In general, only one point is illuminated at a time, but, in practice, either a laser is scanned using mirrors—a laser scanning confocal microscope—or white light illumination is controlled using an array of pinholes—a spinning (or Nipkow) confocal microscope.
Confocal microscopy is the most common type of optical microscopy in applications outside of firearms identification, at least with respect to the number of system vendors. Carl Zeiss AG, Keyence Corporation, Leica, NanoFocus, Olympus Corporation, Sensofar LLC, and Ultra FTI all make confocal microscopes that could be applied to firearms identification, although the instruments vary with respect to capabilities and ease-of-use for the examiner. In general, confocal microscopes have larger working distances, but this will depend on the objective being used. As in other systems, a confocal microscope using an objective lens with a higher numerical aperture (NA) will have lower working distance and higher maximum measureable slope surface, while an objective lens with a lower NA will have a higher working distance and lower maximum slope surface. For example, the Leica DCM 3D Dual Core Measuring Microscope has a 17 mm vertical scanning range, one of the highest among confocal microscopes. For reference, the Alicona InfiniteFocusSL, a focus variation microscope, can use a special, large-working-distance objective lens to achieve a working distance of 20 mm. Confocal microscopes may be limited with respect to the steepness of the edges that can be successfully imaged in comparison to other optical topography systems. These instruments will provide good lateral resolution dependent on the objective lens and wavelength of the light source and vertical resolution of a few nanometers.

Caption: confocal microscopy

Coherence scanning interferometry (CSI), also called vertical scanning interferometry or scanning white light interferometry, measures changes in interference signal strength as the surface or instrument is scanned in the z direction. Basically, the technique assumes that each point on a surface is a mirror and finds the point by shining coherent light at the surface and looking at the resulting constructive interference patterns. (The interference signal results from combining the light reflected from the surface under examination with light reflected from a smooth reference surface.) Interferometric microscopes have smaller working distances and may not adequately image steep slopes on a surface. Bruker Corporation, Leica, Pyramidal Technologies, Sensofar LLC, Taylor Hobson, and Zygo Corporation produce microscopes that are based on interferometry and may be suitable for forensic applications.

PH-5000 Interferometer microscope: example of coherence scanning interferometry technology

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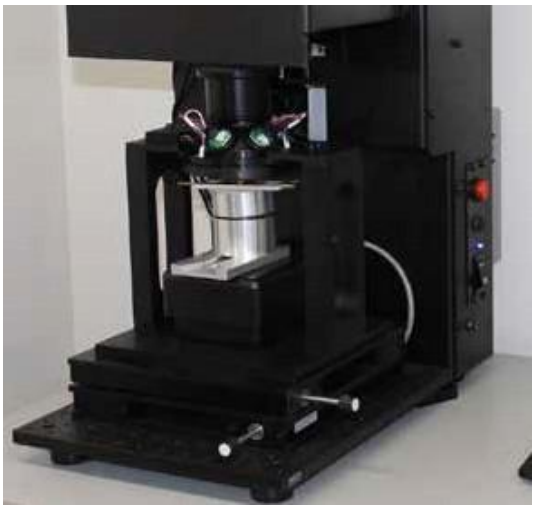
Finally, photometric stereo microscopes are based on the idea that the amount of light reflected from a surface depends on its orientation, so a 3D surface topography can be derived from the light pattern. The technique depends on the uniformity of the surface. In the Cadre Forensics Gelsight instrument, a painted gel is used to make an impression of the cartridge case under examination, and the microscope images the paint, not the case itself. This produces a remarkably accurate topographic representation of the surface under examination. The Cadre Forensics instrument is under development for firearms examination applications and has been funded by the National Institute of Justice's (NIJ) research grant program.[9]

There are other approaches, including scanning electron microscopy (SEM) or stylus profilometry, but, in general, these methods are not used in firearms identification in the crime laboratory. SEM has been used in Europe and the U.S. Fish and Wildlife Service Forensics Laboratory. Stylus profilometry is a contact method that may damage the sample, a significant drawback in the forensic laboratory.



TopMatch-GS 3D Version 2 Scanner: example of photometric stereo technology

INSTRUMENT OVERVIEW

In this landscape report, we present options for the forensic laboratory in selecting optical topography imaging systems. Although we initially contacted a very wide range of vendors to participate with the Forensic Optical Topography Working Group, only a subset chose to do so. We contacted all of the interested vendors to solicit information about their systems for this report.

Table 2 provides a summary of currently available instruments from responding vendors. We surveyed instrument manufacturers concerning the performance of their systems on a wide variety of parameters. The manufacturer chose the model to be included here. Of course, there will be variation among models with respect to operational parameters. Table 2 and the more detailed table presented in Appendix A are based on those industry self-reports. In some cases, manufacturers reported information that is subject to interpretation. All claims should be subject to verification if a laboratory is considering a purchase.

Currently, there are no standardized performance evaluation tests for optical topography instruments for use by firearms examiners. The National Institute of Standards and Technology (NIST)[10] maintains bullet and casing standards, but these do not provide a basis for evaluating the performance of all aspects of these microscopes, such as lateral resolution, maximum measureable slope, and stitching (i.e., the ability to combine multiple images into one view of surface topography). NIST is developing appropriate approaches to these problems. Until then, it may be difficult to compare instrument performance among manufacturers, verify instrument performance, calibrate or address instrument performance, assess quality, and validate a laboratory's ability to perform optical topography reliably.

[9] Law Enforcement's Silent Partner: Forensics Research and Development, Police Chief Volume:81 Dated:October 2014 Pages: 32 to 38

[10] NIST — http://www.nist.gov/forensics/ballisticsdb

Table 2. Brief overview of currently available instruments from responding vendors

Manufacturer	Alicona	Cadre Research Labs	Leica Microsystems	Pyramidal Technologies	ScannBi Technology USA	Sensofar LLC	Ultra FTI	
Model	**InfiniteFocus InfiniteFocus SL (SL)**	**TopMatch-GS 3D**	**Leica DCM8**	**PH-5000 Interferometer**	**Evofinder 4x4**	**S Neox**	**IBIS TRAX-HD3D BULLETTRAX**	**IBIS TRAX-HD3D BRASSTRAX**
Instrument Type								
Confocal			x			x	x	
Interferometry			x	x		x		
Focus variation	x		x		x	x		
Photometric stereo		x						x
3D reconstruction					x			
Data								
Data management	Local data only	TopMatch software includes DB using correlation functionality	Local data only	Advanced search with customizable filtering	Database search using correlation analysis of exhibits and test fires	Local data only	Historical crime-related exhibits and test fires	
Exchange Standards								
X3P	Included	Included	Included	Option	Planned	Option	Planned	
Cartridge Case Image Time (9 mm)								
Full breech face				< 5 min		10–20 secs		5 min
Primer area only	Resolution-dependent	< 2 min		Far less than 5 min	~30 sec	10–20 secs for three fields of view	N/A	
Security								
Security							ISA 27001; NIST SP 800-53	
Estimated Cost (varies based on configuration)								
ATF NIBIN (ATF)	$$ (SL $-$$)	$	$$	$-$$$	$$-$$$	$$	ATF $$	
< $100,000 ($)								
$100,000–500,000 ($$)								
> $500,000 ($$$)								
Users								
Crime Laboratories		Yes, state, local, and federal labs		State of Colima (Mexico)	Several countries in Europe, Brazil, Morocco, and the U.S.	ADFS-Derrick McClarin, FBI	State and local labs, ATF-Atlanta	State & local, ATF, U.S. Customs & Border Patrol, FBI-Quantico
Other		Yes, research labs		Dom Rep (SISNA/LABBS); Huddersfield Uni., UK; EU Odyssey Proj.	Lausanne Technical University	More than 600 systems deployed worldwide	More than 140 units deployed worldwide	More than 220 units deployed

Table information is based on vendor input that is subject to interpretation and verification.

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EFFECTIVE USE OF OPTICAL TOPOGRAPHIC MICROSCOPE

Optical topography can be a powerful complement to existing methods for the firearms examiner, but the particular place of the instrument in the examination work flow should be well established prior to its deployment in the laboratory. The instrument may be used in several ways, including to:

- build and search a reference database to find the source of a bullet or cartridge case from a crime scene;
- serve as a complement to the comparison microscope, especially for difficult comparisons;
- supplement image data taken from the comparison microscope to document a comparison that has been completed;
- clarify the basis on which an examiner has made a particular comparison decision; and
- make comparison decisions.

The laboratory should maintain a protocol that determines when optical topography is to be used and the procedures for each application. Some systems are designed to perform one particular task. For example, Ultra FTI's BRASSTRAX™ system is specifically designed as a reference database tool for cartridge cases.

In the future, optical topography may be used to provide a quantitative match probability for comparisons, but further research is required to put this concept into practice.
Additionally, because these instruments are measuring devices, calibration and performance checks are required to obtain accurate surface acquisitions. Traceable surface standards for such calibrations may not be familiar to examiners new to this technology. They would require additional training for accurate use.

Theoretically, optical topography systems may complement or even replace comparison microscopes in the future. Comparison microscopy is limited with respect to the number of perspectives that can be clearly viewed by the examiner, while computer-based image analysis enables rapid review of almost any orientation of a bullet or casing, thus facilitating a "virtual reality" view of the surface. Although the comparison microscope has been proven in the forensics community for nearly a century, the extent to which limitations of human visual perception and visuospatial cognition may affect examinations is unknown. In contrast, optical topography permits a completely independent review of the exact same data by multiple examiners and the presentation of the basis of identification decisions in detailed images. Further, optical topographic data can be quantitatively evaluated to produce a probabilistic interpretation of identification decisions, although research is still needed to enable such an advance.
Current analytical techniques may provide an imperfect measure of error rates, and algorithms do not necessarily capture all of the information contained in complex striated or impressed tool marks.[11]

Current automated systems permit more efficient comparison decisions that may be useful to produce leads in a "forensic intelligence" framework. In these programs, the intent is to provide investigators with leads and linkages among crime scenes. It must be understood that the evidence that produces the leads must ultimately be subject to analysis using traditional comparison microscopy before use in trial proceedings.

There are some concerns that optical topographic systems may introduce unknown artifacts into image data that could skew interpretation. At this time, examiners should expect to rely on the

[11] Petraco, N. D. D., Chan, H., De Forest, P. R., Diaczuk, P., Gambino, C., Hamby, J., ...Shenkin, P. (2012, July). *Application of machine learning to toolmarks: Statistically based methods for impression pattern comparisons*. U.S. Department of Justice.

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comparison microscope for several reasons. First, the comparison microscope has been in use worldwide for many decades, so there is a good understanding of its capabilities and limitations within the forensics community as well as the broader police and legal communities. Also, there are well-established training regimes to produce an expert tool mark examiner who relies on the comparison microscope, but there is nothing comparable for optical topography methods. Finally, examiners and scientists do not yet have a systematic understanding of the artifacts, outliers, dropouts, or other imperfections in topographic images that may lead to erroneous identification decisions. For example, optical topographic instruments may vary with respect to how well they stitch together images to create a complete view of a surface's topography or with respect to their ability to accurately collect data from steep slopes on a sample's surface.

Some laboratories have used optical topography systems to build reference collections and make "cold" hits between firearms and evidence collected in shooting investigations. Two instruments, the IBIS® TRAX-HD3D™ (based on the BRASSTRAX imaging system) and the ScannBi "Evofinder," have software that facilitates this function. The former system is tied to NIBIN and available through that program or directly from the vendor. Evofinder has been installed in a few sites in the United States but has a larger presence in European crime laboratories. In general, laboratories have found that optical topography-based systems are superior to prior- generation image microscopy systems (e.g., so-called "heritage IBIS" systems) with respect to the likelihood that an accurate match is made in a database search and that the accurate match ranks highly among the list of possible matches from a search.[12,13] Further information about optical topography's use as a tool for firearm evidence collection construction is provided below.[14,15]

OPERATIONAL CONSIDERATIONS

Confocal microscopy and similar systems have existed for decades primarily in surface measurement and medical diagnostics, but current systems surpass older confocal microscopes with respect to ease of use and the extent to which they are adapted to firearms identification. Unlike older systems, the majority of current optical topography systems do not require special environments or optical tables to limit vibration and obtain useful images. Most vendors specify an office-like environment. In some research and operational facilities, the systems have been deployed on optical tables in basement laboratories with environmental controls. Since such requirements could add to the logistical and financial burden, the potential user should consult with the vendor concerning specific installation and environmental requirements.

Training is limited to that provided by manufacturers. Some vendors provide substantial training upon installation in the operation of the instrument, and the majority will provide enough training to permit the use of the instrument in database searches. If the laboratory intends to use optical topography in casework as a complement to comparison microscopy, it is important to understand that little to no specialized training currently exists to support that type of practice.

[12] The reference ballistic imaging database revisited, Jan De Ceuster, Sylvain Dujardin, Forensic Science International, 248 (2015) 82-87.

[13] Reconsidering the Ballistic Imaging of Crime Bullets in Gun Law Enforcement Operations, Anthony Braga and Glenn Pierce, Forensic Science Policy & Management: An International Journal, 2:3, 105-117.

[14] Vorburger, T. V., Yen, J. H., Bachrach, B., Renegar, T. B., Ma, L., Rhee, H-G.,…Foreman, C. D. (2007, May 1). Surface topography analysis for a feasibility assessment of a national ballistics imaging database. Gaithersburg, MD: NIST.

[15] Chu, W., Song, J., Vorburger, T., Yen, J., Ballou, S., & Bachrach, B. (2010, March 1). Pilot study of automated bullet signature identification based on topography measurements and correlations. Journal of Forensic Science, 55(2), 341–347. doi: 10.1111/j.1556-4029.2009.01276.x.

Of course, the same principles of traditional examination apply to the analysis of topographic images. An appropriate validation study should be conducted prior to use in casework to determine baseline capacity, laboratory accuracy, and examiner proficiency.

A typical validation regime would include examining test-fired bullets from the laboratory's firearms collection and from independent laboratories, such as the Brundage P85 Barrel Test, which has been used to examine the performance of the BRASSTRAX HD3D system and other optical topographic systems.[16] The NIST Standard Bullets and Casings program provides standard reference materials that can be used to validate the collection of topographic data in an independent laboratory. Standard Reference Material (SRM) 2460—the standard bullet—and Standard Reference Material SRM 2461—the standard cartridge case—have been developed and tested to ensure that each replica is an accurate duplicate. NIST has taken topographic images of ejector marks, firing pin impressions, breech face impressions, and bullet land impressions. It has also developed a cross-correlation function approach that can be used to measure the extent to which a particular topographic image is similar to its standards. SRMs have been used for many years to validate NIBIN acquisitions. In the case of optical topography, such validation is even more important because the new technology requires the examiner to establish appropriate confidence in the data that is produced from the instrument.[17]

By its nature, topographic analysis is highly computational and data-intensive. Some data compression is employed. For example, Ultra FTI's BRASSTRAX system stores data in JPEG 2000 and can accommodate the data it produces within its server. The Bureau of Alcohol, Tobacco, Firearms, and Explosives' (ATF) NIBIN network has the potential to be used to share information with other agencies or as an information resource within an individual laboratory for any user of the BRASSTRAX system that conforms to ATF policy requirements. Other system types cannot access the NIBIN system at this time due to security, network architecture, and compatibility reasons.

Most manufacturers have committed to adopting a common data interchange standard, the X3P format for 3D surface profiles developed by the International Organization for Standardization (ISO) and adopted by the Open Forensic Metrology Consortium (OpenFMC). The OpenFMC website will serve as a repository for tools and resources for those who use X3P for ballistics databases.[18] The NIST Ballistics Toolmark Research Database (NBTRD) uses the X3P format and collects optical topography data from a wide variety of research studies and instruments.[19] Although NIST collects data for its database using the NanoFocus instrument on which BULLETTRAX is based, it includes data from a wide variety of other instruments, including the Cadre Forensics system.[20] The X3P format is much more data-intensive than JPEG 2000, which is used by the commercial systems under NIBIN. Both formats are considered to be lossless compression file formats. The goal of OpenFMC is to standardize one file format for interoperability. In that case, it will not matter what the instrument stores locally as long as it can convert into X3P when moving the files around. Instruments must also be able to import X3P. Currently, for practical purposes, crime laboratories may prefer to be able to use both X3P and JPEG 2000 files.

[16] Hamby, J. E., Brundage, D. J., & Thorpe, J. W. (2009). The identification of bullets fired from 10 consecutively rifled 9 mm Ruger pistol barrels: A research project involving 507 participants from 20 countries. *AFTE Journal, 41*(2), 99–110.

[17] Zheng, X. A. (2009, January 13). Standard bullets and casings. NIST. Retrieved from https://www.nist.gov/pml/engineering-physics-division/surface-and-nanostructure-metrology/standard-bullets-and-casings

[18] Open Forensic Metrology Consortium (OpenFMC). http://www.openfmc.org/

[19] NBTRD. Retrieved from https://tsapps.nist.gov/NRBTD

[20] Weller, T. J., Zheng, A., Thompson, R., & Tulleners, F. (2012, July). Confocal microscopy analysis of breech face marks on fired cartridge cases from 10 consecutively manufactured pistol slides. *Journal of Forensic Science, 57*(4), 912–917.

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CONSIDERATIONS IN THE SELECTION OF OPTICAL TOPOGRAPHIC MICROSCOPES

Thus far, only a limited number of laboratories have procured optical topographic microscopes, and even fewer have applied them to actual casework. NIST has studied optical topography extensively for application to firearms identification. It has established a foundation for collection and data analysis that is based on the fundamental advantage of optical topography: the ability to provide detailed topography images of surfaces. The components of surface topography include roughness, waviness, surface irregularity, and flaws or imperfections. Topographic microscopy can measure roughness directly, independent of illumination and shadowing effects, but with some limitations. The standards for each consideration are laid out in detail in ISO Draft International Standard 25178-6,[21] which includes several individual documents for different types of topographic instruments. It is not necessary for a user to be able to apply the ISO document independently, but a vendor of a topographic microscope should be able to reference the performance of a particular systems against parameters in the ISO standard, including those in Table 3.

Table 3. ISO standard parameters and questions for measurement

Parameter	Definition	Typical question
Instrument type	Type of optical topography instrument	Is it focus variation, confocal, interferometry, or photometric stereo?
Other instrument aspects	Subtype and constraints	What is the magnification of the types of objective lenses that are available?
Sample mount		Does the system require special mounting or media (e.g., water immersion or the use of a gel)?
Forensic application		Has the system been designed for reference collection databases, cold hit searches, and/or as a complement to comparison microscopy in casework?
Reference databasing	Database search capability	Can the system collect and search a reference collection?
Spatial (lateral) resolution	Smallest lateral 3D structure that can be resolved	What is the smallest lateral 3D feature that the microscope can measure?
Lateral range	Largest lateral measurement range the instrument can measure	What is the maximum lateral measurement range?
Bandwidth limits	Spatial resolution and longest measureable spatial wavelength	What is the range between the smallest and largest features?
Vertical resolution	Smallest height variations that can be assessed with the instrument	What is the smallest step that will be detected?
Vertical range	Largest height variation that can be assessed	What is the tallest feature this instrument can measure?
Dynamic range		
Working distance	The distance between the microscope objective and the sample	How close does the objective come to the surface? Can images of complex geometries be collected without making contact with the sample?
Vertical scanning resolution	Linearity and reproducibility of the scanning stage	Does the scanning stage limit my ability to reliably measure vertical steps?

[21] ISO 25178-6:2010 — Geometrical product specifications (GPS) — Surface texture: Areal — Part 6: Classification of methods for measuring surface texture (http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=42896)

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Table 3. ISO standard parameters and questions for measurement *(continued)*

Parameter	Definition	Typical question
Pixel size	The lateral size of one pixel of the imaging array on a surface	What is the smallest feature that can be imaged (generally higher than spatial resolution)?
Maximum slope	The steepest slope that can be reliably imaged	What are the highest surface slopes that this instrument can image without dropouts or outliers (objective-NA-dependent)?
Typical measurement time	Seconds to capture a full field of view	How long does it take to capture a single measurement?
Typical data collection time	Minutes to capture a sample of bullet land, firing pin, and breech face	How long does it take to capture a complete image, including mounting and setting up the bullet or cartridge case?
Facility requirements	Temperature, humidity control, power, and stability	Does the instrument need to be placed in a dry environment or on an optical table/in a basement laboratory?

There are tradeoffs for any instrument with respect to these parameters. For example, focus variation instruments have very good vertical range (i.e., they can measure steeply sloped surfaces). On the other hand, they may not attain the vertical resolution of other instruments.

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USE CASES

This section provides examples of successful implementation of optical topography technology to illustrate benefits and key adoption issues. The use cases offer insight on different ways that the technology has been an effective tool within law enforcement and a crime laboratory. Key impacts and lessons learned are highlighted.

ORANGE COUNTY, CALIFORNIA

Orange County California

Contributor

Tara Heye, Senior Forensic Scientist, Orange County Crime Laboratory

User Profile

Orange County, California has a population of 3 million people, making it the sixth most populous county in the United States. Its ballistics unit employs five examiners. It employed NIBIN Heritage for 12 years and generated approximately 100 hits, of which two were confirmed hits outside of Orange County. It stopped entering bullets into NIBIN in 2008 because it had not achieved any hits from that work, which had poor image quality. After losing its NIBIN system in 2013, Orange County established the Orange County Ballistic Unit Local Law Enforcement 3D Technology (OCBULL3T) system using Evofinder.[22] Evofinder is a focus variation system that reconstructs 3D topography from multiple 2D images. This approach is sometimes called "2D+D." OCBULL3T includes bullets and cartridge cases from evidence and test fires from 2013 to the present, covering 1,260 cases, 1,300 cartridge cases, and 1,650 bullets. Orange County has generated 56 confirmed total hits, including 43 cartridge case cold hits and 13 bullet hits, including 3 from pistols and 4 from revolvers. Two of the pistol hits were based only on bullets.

Key Impacts and Lessons Learned

1. The number of hits has increased dramatically from 5 in the first 2 years with NIBIN Heritage to 50 with Evofinder (OCBULL3T).
2. OCBULL3T success has produced an increase in firearms work request submissions. The current backlog is ~600 cases (an approximately 10-fold increase).
3. The increase in hits and firearms submissions was difficult to foresee; crime lab management is actively working on increasing trained staff to respond to the increase.
4. The dramatic increase in hits appears to be the result of correlation using the 3D reconstruction data sets provided by Evofinder.

Validation and Implementation

Orange County conducted a validation of the Evofinder system using currently available methods, including test-fired bullets from consecutively rifled barrels (based on the Brundage 10 Barrel Test), and both bullets and cartridge cases generated from its firearms collection. The entire test-fired data set included 76 items, including at least 2 test fires from each firearm. As stated previously in this report, there is no accepted method to validate optical topography instruments for forensic comparison purposes because of the lack of performance measurement standards. In Orange County's

[22] 2D+D. (2016). Evofinder. Retrieved from http://evofinder.com/technology/2dd/

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examination of consecutively rifled barrels from the Brundage study, staff did not observe an instance in which an unrelated bullet ranked higher than duplicate or "sister" images. For virtual microscopy validation, the Orange County Crime Lab selected firearms that produce test fires that are difficult to identify using comparison microscopy. Staff analyzed test fires using comparison microscopy and the Evofinder system, and used a scanning electron microscope as a "ground truth" validation of individual impressions, such as striae. Overall, 92% of breech face and firing pin correlations ranked very high—either first or second—in the match list, although the database was limited. Interestingly, the Evofinder search produced accurate matches even in cases when an examiner using a comparison microscope could not make an identification.

Orange County has applied the Evofinder to casework in both cartridge cases and bullets as a complement to comparison microscopy, although staff have found that optical topographic image data is superior. At this time, they rule out any conclusion based on the Evofinder if the match cannot be made using the comparison microscope. In this case, even a clear Evofinder match would be ruled "inconclusive." In reporting such instances, staff state that the images "suggest an identification." In other words, the comparison microscope is still the standard by which the laboratory makes forensic comparisons.

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NEW JERSEY STATE POLICE

Contributors

The New Jersey State Police (NJSP) has long used NIBIN to link firearms to crime scenes. Nonetheless, NJSP sees high rates of gun crime, especially along the Route 21 corridor. In the past, it took an average of 10 months for a crime gun to make it into NIBIN. In some cases, it took up to 2 years. Given that the "time to crime"—the amount of time from legitimate sale to the use of a gun in crime—is often shorter than the 2 year timeframe, it became imperative to improve the use of ballistics evidence to get any investigative value.

In accordance with a state statute and under the leadership of NJSP's Superintendent, Colonel Rick Fuentes, New Jersey's 800 law enforcement agencies took a new approach. Administrative and policy choke points were identified and new processes established to facilitate the rapid turnaround of evidence. Now, police agencies expeditiously submit all crime guns for inclusion into NIBIN. The evidence is prioritized and uploaded into NIBIN quickly.

Key Impacts and Lessons Learned

1. Optical topography and advanced data analysis enable the rapid turnaround of case hits to enable investigative leads and crime scene linkages.
2. The BRASSTRAX system and ATF network provide a seamless capability for finding hits across jurisdictional boundaries.
3. Executive leadership can enable more efficient use of firearms identification data through the development of processes that prioritize evidence and eliminate policy choke points.

NJSP's process reforms were enabled by the technological revolution of optical topography. Older, "heritage" NIBIN systems were based on 2D images of cartridge cases and bullets, but newer systems now obtain high-resolution, 3D data. The difference in image quality produces an astounding difference in the ability to identify an unknown firearm in a reference database quickly and accurately. The Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF) has deployed data "concentrators" to ingest this data across the country, with the goal of enabling rapid database searching across jurisdictional boundaries and development of early casework leads from ballistic evidence.

The NJSP Real-time Crime Center uses ballistic evidence in combination with other types of information about suspects, trends, and other forensic intelligence. Staff gathered over 1,000 hits in Newark—an astounding number that changes the entire dynamic of the investigation of violent crime.

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STATE OF THE MARKET

Although several manufacturers have developed optical topography instruments that may be useful in firearm identification, the vast majority of systems deployed in crime laboratories are BrassTrax systems from Ultra FTI. These instruments are compatible with the ATF's NIBIN program, thus permitting information sharing and leveraging of ATF investments in network architecture and systems. ATF supports the purchase and maintenance of the Ultra FTI instruments in some cases, and will support the connection of the Ultra FTI instruments to NIBIN for any laboratories that purchase the systems on their own. Ultra FTI provides instruments only to laboratories that participate in NIBIN.

Currently, ATF does not permit instruments from other manufacturers to access NIBIN. Theoretically, any data produced by other instruments could be output into the standard JPEG 2000 image compression format and uploaded into NIBIN. In practice, that does not occur. Ultra FTI instruments are currently the only instruments that meet the rigorous data security requirements of ATF's NIBIN network.

There is very little data concerning the relative performance of competing systems with respect to image fidelity, efficiency of their database searching algorithms, or other parameters of operational interest. This report recommends that such studies be performed in the context of improving understanding of the fundamental performance of optical topography as a tool for the firearms examiner.

FUTURE OF OPTICAL TOPOGRAPHY IN FIREARM IDENTIFICATION

Optical topography presents a major opportunity to improve the practice of firearm identification in a manner that is similar in impact to DNA technology for human identification. As of this writing, the adoption of optical topography in firearm identification is in its early stages. Thus far, forensic science laboratories have adopted optical topography primarily as an upgrade to their existing systems for database searching.

Others are using the technology to augment their examinations from comparison microscopy. Few laboratories are using the full range of the systems' capabilities. It is difficult to foresee the changes that may arise from further development of the technology and more widespread use.

To date, NIJ has funded extensive work in the development of systems and improved understanding of the topographic metrology of ballistic evidence.[23] The Forensic Optical Topography Working Group examined the state of optical topography and developed several recommendations to address adoption issues in forensic practice. Several of the recommendations focus on research and development of key issues. Other recommendations address shortfalls in training and practice.

- **Improve data sets and the understanding of similarities and differences among firearms,** particularly with respect to consecutively manufactured firearms, mark persistence, and firearms that present identification challenges. NIST and the Federal Bureau of Investigation (FBI) have pursued this research jointly to build the NIST Ballistics Toolmark Research Database. The work complements the view that optical topography may elucidate issues related to difficult match comparisons that are not easily amenable

[23] For examples of extensive funding, please see https://www.ncjrs.gov/pdffiles1/nij/grants/232136.pdf, https://www.ncjrs.gov/pdffiles1/nij/grants/248962.pdf, and https://www.ncjrs.gov/pdffiles1/nij/grants/248639.pdf.

to traditional comparison microscopy. More fundamentally, characterization of the NBTRD could contribute to the scientific basis for firearms identification. This process may also contribute to the development of validation and operating procedures.

- **Establish validation, methods, best practices, certification, and training for firearms examiners using optical topography in practice. Firearms examiners receive extensive formal and informal training to use the comparison microscope and complementary methods to make comparisons in current practice.** AFTE has established programs to promulgate accepted methods and train and certify examiners. Thus, the field is organized around a very effective set of practices and technology. No comparable foundation exists to establish and promulgate methods related to the application of optical topography, except the training provided by instrument manufacturers in the operation of their systems. The NIST Organization of Scientific Area Committee's (OSAC) Firearms and Tool Marks Subcommittee has begun to establish validation, methods, and training to support optical topography. Additional support will be needed to turn these methods into guidance and training for the field.
- **Examine factors that improve database searching using optical topography.** As stated previously, there are several ways in which a laboratory could apply this new technology in practice. Currently, laboratories use it as a tool to improve database searches as a simple substitute for less capable microscopes. Studies indicate that database searches are greatly improved when using optical topography,[24] but there is limited evidence with regard to related factors, such as firearm type, search algorithm, operational constraints, or instrument type. For example, some instruments use search algorithms that are designed to take advantage of topographic data and may present an opportunity to improve the speed and reliability of searches. Studies should include controlled sets of firearms, operational evaluations to examine implications in practice, and consideration of various algorithmic approaches to improve the efficiency of searches. Anecdotally, practitioners report that interjurisdictional hits are enabled by the use of topographic data. Research is needed to confirm this assertion and determine factors that enable effective interjurisdictional searching.
- **Improve the understanding of the impact of the application of optical topography in the laboratory.** Evidence prioritization and improved process flow could enable broader use to improve the investigation of gun crime, as in New Jersey. Further, rapid presumptive identification could be leveraged to produce cold hits early in investigations, an approach that leverages ATF's substantial investment in the national data concentrator infrastructure. This is only possible because of the improvement in image quality and visualization in current systems such as BRASSTRAX HD3D. Finally, the new systems may improve the ability of examiners to review difficult comparisons as a complement to the comparison microscope. Ultimately, this may lead to broader use of optical topography in the examination and comparison process itself. Operational evaluations in firearms laboratories are needed to understand the effectiveness and impact of these novel operational approaches so that they can be promulgated across the criminal justice community with research-based best practices. Operational evaluations should include multiple platforms, including systems emerging from

[24] Jan De Cuester and Sylvain Dujardin, The reference ballistic imaging database revisited, Forensic Science International, 248 (2015) 82-87.

interlaboratory comparisons, data exchange research and development, depending on the operational readiness of the systems to meet practitioner requirements.

- **Improve interoperability of instruments and databases across laboratories.** Several instruments have the capability to collect detailed and accurate data for use in ballistic comparisons. That said, interoperability depends on several factors, including standards, data security, and related issues. In particular, the X3P data interchange standard could enable operational cooperation among law enforcement agencies and data interchange, if it becomes a standard feature of all optical topography systems. NIST, in collaboration with government laboratories and researchers, is in the process of an interlaboratory study on interoperability currently. Initial results are expected in mid-2017.

Forensic scientists have become more aware of the need for rigorous evaluation and validation prior to the use of a new method or technology, in part because of the overarching review of forensic practice by the National Academy of Sciences.[25] Further research, development, and evaluation can provide a foundation that should permit firearms examiners to take advantage of the promise of optical topography and avoid pitfalls from the use of invalidated or poorly understood methods.

[25] National Research Council. 2009. Strengthening Forensic Science in the United States: A Path Forward. Washington, DC: The National Academies Press. doi:10.17226/12589.

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GLOSSARY OF COMMONLY USED WORDS AND PHRASES

This glossary was built using various resources, with the following three references adding significant value.

AFTE (2013). *Association of Firearm and Tool Mark Examiners glossary* (6th ed.). Version 6.120414.

Thompson, R. M. (2010). *Firearm identification in the forensic science laboratory.* National District Attorneys Association. Retrieved from http://www.ndaa.org/pdf/Firearms_identity_NDAAsm.pdf

Vorburger, T. V., Song, J., & Petraco, N. (2015, December 17). Topography measurements and applications in ballistics and tool mark identifications. *Surface Topography: Metrology and Properties, 4*(1).

Action: The working mechanism of a firearm.

Automatic—A firearm design that feeds cartridges, fires, extracts, and ejects cartridge cases as long as the trigger is fully depressed and there are cartridges in the feed system. Also called "full auto" and "machine gun."

Bolt—A firearm mechanism in which the breech closure

1. is in line with the bore at all times;
2. manually reciprocates to load, unload, and cock; and
3. is locked in place by breech bolt lugs and engages abutments usually in the receiver. There are two principal types of bolt actions: the turn rotating bolt and the straight pull.

Lever—A design wherein the breech mechanism is cycled by an external lever, generally configured below the receiver.

Revolver—A firearm, usually a handgun, with a cylinder having several chambers so arranged as to rotate around an axis and be discharged successively by the same firing mechanism.

Semiautomatic—A repeating firearm requiring a separate pull of the trigger for each shot fired, and which uses the energy of discharge to perform a portion of the operating or firing cycle (usually the loading portion).

Slide—An action that features a movable forearm which is manually actuated in a motion parallel to the barrel by the shooter. Forearm motion is transferred to a breech bolt assembly that performs all of the functions of the firing cycle assigned to it by the design.

AFTE: Association of Firearm and Tool Mark Examiners, the international professional organization for practitioners of firearm and/or tool mark identification, dedicated to the exchange of information, methods, and best practices, and the furtherance of research since its creation in 1969.

Breech face: The part of the breechblock or breech bolt that is against the head of the cartridge case or shotshell during firing.

Bullet: A nonspherical projectile for use in a rifled barrel.

Cartridge: A single unit of ammunition comprising the case, primer, and propellant with one or more projectiles. Also applies to a shotshell.

Cartridge, center fire: Any cartridge that has its primer central to the axis in the head of the case.

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Cartridge, rim fire: A flange-headed cartridge containing the priming mixture inside the rim cavity.

Cartridge case: The container for all other components of a cartridge.

Chamber: The rear part of the barrel bore that has been formed to accept a specific cartridge. Revolver cylinders are multi-chambered.

Chamber marks: Individual microscopic marks placed on a cartridge case by the chamber wall as a result of any or all of the following: chambering, expansion during firing, or extraction.

Class characteristics: Measurable features of a specimen that indicate a restricted group source. They result from design factors and are therefore determined prior to manufacture.

Coherence scanning interferometric microscope: An optical microscope that produces a topographic image from the interference between light reflected from the surface under study and light reflected from a reference surface.

Comparison microscope: Two microscopes tied together by an optical bridge to allow an examiner to simultaneously observe two objects, such as a questioned cartridge case from a crime scene and one from a test-fired cartridge case from a submitted firearm, side by side in the same field of view. Although modern instruments permit these images to be displayed on a computer screen or photograph, the essential work is done by the expert firearms examiner peering through the eyepieces of the comparison microscope.

Confocal microscope: An optical microscope that uses a pinhole to eliminate out-of-focus light from an image and permits the reconstruction of a topographic, three-dimensional (3D) view of an object by combining images from multiple focal planes. Types of confocal microscopes include laser scanning confocal microscopy, disk scanning confocal microscopy (including Nipkow disk scanning), and programmable array microscopy.

Ejector: A portion of a firearm's mechanism that ejects or expels cartridges or cartridge cases from a firearm.

Extractor: A mechanism for withdrawing the cartridge or cartridge case from the chamber.

FTCOE (http://www.forensiccoe.org/): A collaborative partnership providing testing, evaluation, and technology assistance to forensic laboratories and practitioners in the criminal justice community. This partnership is led by RTI International (http://www.rti.org/), and funded by the National Institute of Justice.

Firearm: An assembly of a barrel and action from which a projectile is propelled by products of combustion.

Firing pin: The part of a firearm mechanism that strikes the primer of a cartridge to ignite the powder charge inside the cartridge. Sometimes called "hammer nose" or "striker."

Focus variation: An optical microscope that reconstructs a topographic (3D) view of a surface from the sharpest, best-focus features in a series of surface scan images that are sequentially obtained from different vertical positions of an object.

Impression: Contour variations on the surface of an object caused by a combination of force and motion where the motion is approximately perpendicular to the plane being marked. These marks can contain "class" and/or "individual characteristics."

Individual characteristics: Marks produced by the random imperfections or irregularities of tool surfaces. These random imperfections or irregularities are produced incidental to manufacture and/or caused by use, corrosion, or damage. They are unique to that tool and distinguish it from all other tools.

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IBIS: Integrated Ballistics Identification System, a workstation on the National Integrated Ballistic Information Network (NIBIN).

JPEG 2000: An image compression standard and coding system. The Joint Photographic Experts Group committee created it in 2000 with the intention of superseding the original, discrete cosine transform–based JPEG standard (created in 1992) with a newly designed, wavelet-based method.

Land: The raised portion between the grooves in a rifled bore.

Magazine: A container for cartridges that has a spring and follower to feed those cartridges into the chamber of a firearm. The magazine may be detachable or an integral part of the firearm.

Metal injection molding (MIM): A general term for processes in which complex metal shapes are produced from powder using methods borrowed from plastic injection molding.

NIBIN (https://www.atf.gov/firearms/national-integrated-ballistic-information-network-nibin): National Integrated Ballistic Identification Network, the national system managed by the Bureau of Alcohol, Tobacco, Firearms, and Explosives to permit interjurisdictional sharing and searching of firearms identification data.

NIST (http://www.nist.gov/forensics/ballisticsdb): National Institute of Standards and Technology

Optical topography: The collection of quantitative, three-dimensional surface topography images using optical microscopy.

Photometric stereo: An optical microscope that produces a surface topography image from the shadow patterns of surfaces illuminated by multiple light sources. For samples such as bullets or cartridge cases, the technique requires that a gel be used to "lift" the impression from the object for examination.

Polygonal rifling: Firearm barrel rifling in which "wavy" or rounded polygonal shapes are used instead of square-cut lands and grooves.

Range of conclusions possible when comparing tool marks: The examiner is encouraged to report the objective observations that support the findings of tool mark examinations. The examiner should be conservative when reporting the significance of these observations.

Elimination—Significant disagreement of discernable class characteristics and/or individual characteristics.

Identification—Agreement of a combination of individual characteristics and all discernible class characteristics where the extent of agreement exceeds that which can occur in the comparison of tool marks made by different tools, and is consistent with the agreement demonstrated by tool marks known to have been produced by the same tool.

Inconclusive—Three categories, as follows:

A. Some agreement of individual characteristics and all discernible class characteristics, but insufficient for an identification.

B. Agreement of all discernible class characteristics without agreement or disagreement of individual characteristics due to an absence, insufficiency, or lack of reproducibility.

C. Agreement of all discernable class characteristics and disagreement of individual characteristics, but insufficient for an elimination.

Unsuitable—Unsuitable for examination.

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Rifling: Helical grooves in the bore of a firearm barrel designed to impart rotary motion to a projectile during firing for the purpose of stabilizing it in flight.

Rifling methods: Broach, gang—A tool having a series of cutting edges of slightly increasing height used to cut the spiral grooves in a barrel. All grooves are cut with a single pass of the broach. A gang broach without a rifling profile on its cutters may also be used to achieve a desired bore size in a barrel prior to rifling.

Broach, single—A nonadjustable rifling cutter that cuts all of the grooves simultaneously and is used in a series of increasing dimensions until the desired groove depth is achieved.

Button—A hardened metal plug with a rifled cross-section configuration. It is pushed or pulled through a drilled and reamed barrel blank so as to cold form the spiral grooves to the desired depth and twist. When the carbide button was first introduced, it was described as a "swaging process" or "swaged rifling."

Hook—A cutting tool that has a hook shape and only cuts one groove at a time.

Scrape—A cutting tool that cuts two opposing grooves at a time.

Swage—An internal mandrel with rifling configuration that forms rifling in the barrel by means of external hammering. Also known as "hammer forging."

Shotgun: A smooth bore shoulder firearm designed to fire shotshells containing multiple pellets or sometimes a single projectile.

SRM: Standard reference material

Striations: Contour variations, generally microscopic, on the surface of an object caused by a combination of force and motion where the motion is approximately parallel to the plane being marked. These marks can contain "class," "subclass," and/or "individual characteristics."

Stitching: The process of combining multiple, overlapping images to produce a single view; used in optical topography systems to combine many images into a single view of a surface's topography.

Striker: A rod-like firing pin or a separate component that impinges on the firing pin.

Subclass characteristics

Discernible surface features of an object that are more restrictive than "class characteristics" in that they

1. are produced incidental to manufacture;
2. are significant in that they relate to a smaller group source (a subset of the class to which they belong); and
3. can arise from a source that changes over time. Examples include bunter marks (which make the stamped impressions on cartridge cases) and extrusion marks on a pipe.

Caution should be exercised in distinguishing subclass characteristics from "individual characteristics."

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Theory of identification as it relates to tool marks:

1. The theory of identification as it pertains to the comparison of tool marks enables opinions of common origin to be made when the unique surface contours of two tool marks are in "sufficient agreement."
2. This "sufficient agreement" is related to the significant duplication of random tool marks as evidenced by the correspondence of a pattern or combination of patterns of surface contours. Significance is determined by the comparative examination of two or more sets of surface contour patterns comprising individual peaks, ridges, and furrows. Specifically, the relative height or depth, width, curvature, and spatial relationship of the individual peaks, ridges, and furrows within one set of surface contours are defined and compared to the corresponding features in the second set of surface contours. Agreement is significant when it exceeds the best agreement demonstrated between tool marks known to have been produced by different tools, and is consistent with agreement demonstrated by tool marks known to have been produced by the same tool. The statement that "sufficient agreement" exists between two tool marks means that the agreement is of a quantity and quality that the likelihood another tool could have made the mark is so remote as to be considered a practical impossibility.
3. Currently, the interpretation of individualization/identification is subjective in nature, founded on scientific principles, and based on the examiner's training and experience.

Tool: An object used to gain mechanical advantage. Also thought of as the harder of two objects that, when brought into contact with each other, results in the softer one being marked.

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DETAILED PRODUCT SPECIFICATIONS

Table 4. Currently available instruments from responding vendors

	Alicona	Cadre Research Labs	Leica Microsystems	Pyramidal Technologies	ScannBi Technology USA	Sensofar LLC	Ultra FTI	
Model	**InfiniteFocus** **InfiniteFocus SL (SL)**	**TopMatch-GS 3D**	**Leica DCM8**	**PH-5000 Interferometer (fifth-generation instrument)**	**Evofinder 4x4**	**S Neox**	**IBIS TRAX- HD3D BULLETTRAX**	**IBIS TRAX-HD3D BRASSTRAX**
General Instrument Specifications								
Instrument type	Focus variation	Photometric stereo	Instrument incorporates three technologies: confocal, interferometry, and focus variation	White light interfero-metry	Combined focus variation and 3D reconstruct-ion	Confocal, interfero-metry, and focus variation in one system	Confocal	Nonlinear photometric stereo sensor
Availability	Commercial, research	Commercial, research	Commercial, research	Commercial	Commercial	Commercial	ATF, commercial	
Mounting	Air/None	Custom mount holds case against custom gel pad	Air/Dry	Application-specific holder for bullets including rotating motion; application-specific (multiple) holders for cartridge cases with a capacity for a maximum of six items per holder; no preparation required	Springing clip	Samples are measured by standard Nikon microscope objectives, including one water immersion objective if required (not typically used for forensics)	Specialized universal bullet or cartridge case holder	
Type of light source	LED, coaxial and ring light (SL LED, ring light)	LED	Quad LEDs (red, green, blue, and white)	High-power LED, MTBF > 100,000 hours	LED matrix	Multiple LED (white, red, blue, and green)	LED lighting system	LEDs for 3D images and halogen lamps for 2D images
Software for display and analysis	Alicona software can exported to the following: STL, AL3D, G3D, Open GPS, CVS, QDAS, SUR, and X3P	TopMatch	Leica Map (Mountain Maps) and Leica Scan	Advanced Ballistics Analysis System (ALIAS)	2D/3D pictures, Mountain Maps, surface profiling, overlapping, and correlation analysis	SensoScan, SensoMatch, and SensoMap (version of Mountain Maps)	IBIS MATCH-POINT	
Facility requirements	100–240 VAC, 1,000 W, 50–60 Hz, 18–28 C, 1 C/hour 45% +- 5	No special requirements; scanner requires standard 120 V power outlet	115 V power, 10 A, active or passive vibration suppression	Power supply 110–230 V AC; office environment	110–240 V, 40 W; desktop-variant; standard requirements for laboratory	Power; vibration isolation typically included	Office environment	

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Data Management								
Database search		Yes, the TopMatch software does implement a database that can be searched	Windows File Explorer	Yes, advanced search capabilities with customizable filtering	Correlation analysis for preselected (formalized) areas of objects' surfaces (e.g., primary traces lands, grooves, firing pin, breech face, and ejector mark)	Local data only	Yes, historical crime-related exhibits and test fires	
Data storage capacity	750 GB	20,000 scans (base), unlimited with expansion	~5 MB per data set	Unix operating system capable of addressing up to 32 petabytes of data storage	On demand, 1 TB; 40,000 objects	Depends on local hard drive and server availability	Scalable, unlimited; JPEG 2000 lossless compression	
Statistics available for data dropouts		No dropouts with photometric stereo		Internal to system with user control over threshold		Yes	Available	
Data collection time	1.7 million points/ second	Less than 2 mins per case	1 min	Cartridge cases: < 5 mins (unoptimized); bullets: < 3 mins (unoptimized); 3D data collection for each	~2 mins for both object types (bullet and cartridge)	Approximately 10–15 mins per bullet for a bullet with 6 lands	10 mins for a pristine 9 mm bullet (land and groove areas)	5 mins for a breech face and firing pin on a centerfire cartridge case
Network compatible	Yes	Yes	Yes	Yes	Yes	Yes	Yes, automated search across regional and international networks of instruments	
Data exchange standards	Now, standard	Yes, we are a founding member of OpenFMC; we fully support X3P now	X3P, .dat, .csv	Open data formats with existing support for PLY (ASCII format), PLY (binary format), CSV and TIFF; because ALIAS is an open architecture, if a client wants support for X3P, they will have it	Now, self-developed; X3P soon, as a standard	X3P currently supported through Mountain Maps; in development for SensoFar software	XML export and X3P in the future	
Background correction		Automatic baseline correction can be applied	Yes, vignetting correction		No	Yes, proprietary objective calibrations	Yes, shape, waviness, and texture are acquired; shape and waviness are removed for correlation	5 mins for a breech face and firing pin on a centerfire cartridge case

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Measurements and standards								
Calibration	Traceable to PTB by using an Alicona calibration tool	Calibration uses a known ball grid array (calibration takes just a few minutes); sinusoidal reference standards are used for determining lateral and depth resolution; yes, system can scan the NIST standard casing	Calibrated with NIST-traceable etched step height standard	3D precision reference specimens according to ISO 5436-1 and ISO 25178; calibration certificates available by UKAS-accredited calibration laboratory	Routine calibration against 1 mm etalon standard; accuracy check based on reference standard cylinder, diameter 8 mm	Objectives are calibrated for field flatness and aberration using optical flat; systems are typically verified for z accuracy with NIST-traceable step height standards	Calibration done by the supplier of the 3D sensor: NanoFocus	Self-calibration every 50 acquisitions with the use of a special target inside the acquisition unit
Spatial resolution	Limited by illumination type ~400 microns (SL 640 microns)	Typical lateral resolution: 1.4 microns per pixel (system can scan up to 0.9 microns per pixel)	140 microns	2 x 2 microns	Theoretically ~1 microns	Dependent on technology and objective; highest resolution is 150 microns lateral (half pitch)	3 pixels wide: ~10 microns	3 pixels wide: ~15 microns for breech face images and ~10 microns for firing pin, ejector mark, and rim fire images
Best vertical resolution	10 microns (SL 20 microns)	Typical depth resolution of 1 micron (assessed using reference standard)	0.1 micron [as reported, may not be specific to firearm toolmarks]	100 microns	Theoretically ~1 micron	Dependent on technology and objective; interferometry resolution is better than 1 micron	0.2 micron	Approximately 1 micron
Smallest vertical slice interval				68 microns	~ 0.1 micron (least significant digit)	Dependent on technology and objective; PSI vertical slice with optional Piezo stage is about 1 microns	Fixed value of 2 microns	
Lateral range		N/A		Full-size cartridge case or bullet		Images can be stitched to cover large areas; depending on stage size, up to 300 x 300 microns	Object limited only	Wavelength of approximately 10 microns (i.e., 2 times the FOV for breech face images)

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	Alicona	Cadre Research Labs	Leica Microsystems	Pyramidal Technologies	ScannBi Technology USA	Sensofar LLC	Ultra FTI	
Measurements and standards								
Vertical measurement range for a single image	Up to 23 microns (SL Up to 26 microns)	N/A	Working; distance-dependent	4 microns	Several microns	Dependent on technology and objective; ranges from 300 microns for high NA objectives to 17 microns for low NA objectives	2 microns	~250 microns; limited by the microscope depth of field
In-process surface follower technology	Yes	N/A	N/A	Height and tilt are automatically detected, and measurement range is automatically adjusted		Yes	Yes, automatic surface following for pristine and deformed bullets as well as fragments (including "V" shaped)	N/A
Varied surfaces	Yes	Works with any surface, including glass or mirror; it is also possible to scan live tissue (e.g., fingerprints)	Thick/Thin film measurement	White light interfero-metry is robust against surface properties; it measures transparent, metallic, diffusive, and highly reflective surfaces	Metal surfaces of bullets and cartridges, and plastic surfaces (castings)	Yes, from mirror surface to very rough	Yes	
Dynamic range of camera		N/A	N/A		> 48 dB		8 bits	12 bits
Working distance	Objective-lens-dependent	N/A	13 (5x)–0.2 mm (150x)	3.8 mm	41 mm	Dependent on technology and objective; ranges from 300 microns for high NA objectives to 17 mm for low NA objectives; super long working distance objectives are available with working distance up to 37 mm	1 cm	9 cm

	Alicona	Cadre Research Labs	Leica Microsystems	Pyramidal Technologies	ScannBi Technology USA	Sensofar LLC	Ultra FTI	
Measurements and standards								
Measurable range of caliber	All	22 short to 7.62 x 39 mm (additional calibers can be accommodated with adapters)	40 mm		Up to 20 mm	Virtually unlimited	Calibers from 0.17–0.700, and an effective diameter from 4–20 mm	Calibers from 0.17–0.50 and from .410 bore to 8-gauge for shot shells, and an effective diameter from 2–27 mm
Motorized scanning (x,y,z)	Yes, motorized rotation and tilt optional (SL Yes, motorized rotation optional)	N/A	Yes (x,y,z)	Yes	Yes	Yes (x,y,z)	Yes, automated acquisition: x, y, z (focus), tilt, rotation, lighting	Yes, automated acquisition, y, z (focus), zoom, rotation, lighting
Reliability of measure-ments (based on mechanical stage movement)	N/A	Reproducibility, repeatability, precision assessed by recently completed study; publication to be submitted in 2016	< 1 micron	XYZ stages have optical encoders with 100 nm resolution	The system x-y scanning stage is fully self-designed; theoretically ~ 1 micron	X-Y scanning reproducibility is in the range of (x,y) scanning	Measurements are not dependent on the mechanical stages reproducibility	N/A, all ROIs are captured on a single camera's FOV
Number of camera pixels	1,840 x 1,840 (SL 2,000 x 2,000)	Current: 18 million; next version likely 50 million	1,360 x 1,024	Typical measurement of cartridge case comprises 25 megapixels (stitched)	At the moment, 510 x 492; soon 2,048 x 1,536	1,360 x 1,024	512 x 512 total pixels contained in the outputted bullet image is extended with image stitching	960 x 960
Maximum slope	87°	Theoretical: Up to 90°	85° (with 0.95 NA objective)	80° for technical surfaces with residual roughness	Up to ~ 90° (reported theoretical)	71° for confocal with 0.95 NA objective, slopes up to 86° can be measured with focus variation and with rough surfaces	17°	> 30°

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Measurements and standards								
Field of view with 20x objective	0.81x.81mm(SL1 x1mm)	N/A, using our 3x objective single image field of view is ~35 mm2	877 x 660 microns	580 x 556 microns	N/A, the system objective 2x, field of view 2.1x 1.7 mm	877 x 660 microns	1.6 mm x limited by stitching (10x objective); a full circumference of the bullet can be done	3.2 x 3.2 mm (firing pin, ejector, and rim fire) with 1.5x zoom objective and 4.8 x 4.8 mm for breech face with 1.0x zoom objective
Measurement point density	Depending on objective, best : 0.09 micron (SL Depending on objective, best: 0.2 micron)	Typical: 1.4 micron/ pixel; maximum 0.9 micron/pixel	N/A	2 x 2 micron	280 points/mm	Depends on technology and objective	N/A	
Conformance with standards for roughness measurement	Yes	System will comply with NIST OSAC standards once published; these standards are still being created and will build from the cited ISO and ASME documents	ISO 4287, ISO 13565, ISO 12085, ISO 12780, ISO 12181, ASME B46.1, MBN 31 007-12, VDA 2007	Yes		Yes	N/A	
Conformance with standards for surface measurement	Yes	System will comply with NIST OSAC standards once published; these standards are still being created and will build from the cited ISO and ASME documents	ISO 4287, ISO 13565, ISO 12085, ISO 12780, ISO 12181, ASME B46.1, MBN 31 007-12, VDA 2007	Yes		Yes	N/A	

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Measurements and standards								
Form measurement	Yes	3D surface height map	Can filter between roughness and form on both 2D and 3D profiles	Instrument produces high-resolution 3D topology; 2D profiles can be derived computationally from 3D topologies	3D Mountain Maps for cartridges: depth drop, angle, and distance between 2 points; cross-section is available	2D, 3D, and profile; software provides a wide variety of methods to process surfaces, including form removal, and ISO filters	Shape and waviness are distinguished using a spatial frequency cutoff maximizing correlation performances	
Conformance with ISO 17025	No	System will comply with NIST OSAC standards once published; these standards are still being created and will build from the cited ISO and ASME documents	No			Yes	N/A	
Color imaging	Yes	N/A	Yes	Yes, with secondary 2D camera	No	Yes	No	
Illumination	Coaxial and ring light (24 segments) (SL Ring light (24 segments))	Photometric stereo ring light configuration	LED	High-power LED, MTBF > 100,000 hours for 3D measurements; white LED for 2D color imaging	Diffusive LED light, four ring segments	Four LED light sources (red, green, blue, and white)	Coaxial–confocal	Annular light, side lights for 2D; LEDs for 3D
Measurement time for a 9 mm cartridge case primer area	Resolution-dependent	Less than 2 mins	TBD	< 5 mins for entire cartridge case, not just primer area, which will be far less	~0.5 min	10–20 secs	N/A	5 mins for a breech face and firing pin on a center fire cartridge case
Measurement time for a 9 mm bullet	Resolution-dependent	N/A	TBD	< 3 mins	~1.5 mins	10–20 s for 3 fields of view over one land	10 mins for a pristine 9 mm bullet (land and groove areas)	N/A

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Measurements and standards							
Security		System will comply with NIST OSAC standards once published; these standards are still being created and will build from the cited ISO and ASME documents	No			Not at present	Yes, ISO 27001 and NIST SP 800-53
Training, Costs, and Current Users							
Is training offered?	Yes	Yes, firearms examiners and technicians have been successfully trained	Yes, Leica-certified trainer	Yes, have trained operators with no background, beginner, intermediary, and advanced	Yes. computer experience and ballistics grounds	Yes, minimal background required	Yes, no specific background required
Technical support provided?	Yes, all methods and different service contracts available	Yes, phone, e-mail, and Web	Installation and training provided with purchase; online, telephone, and Internet training and support available per request	Yes, five support plans (bronze, silver, gold, and platinum) up to 24/7/365 support options with phone, e-mail, and Web contact to fit any client mission criticality requirements; 2-year default warranty	Yes, full range support	Yes, typical installation includes two days on site, with follow-on training available	1-year warranty and complete safeguard coverage for state and locals; NIBIN customer support and program management
Estimated cost < $100,000	(SL)	x		x			
$100,000–$500,000	x		x	x	x	x	x
> $500,000				x	x		
Other				Suite of products for forensic ballistics and firearms registration	Depends on configuration		Free as part of the ATF NIBIN program

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Training, Costs, and Current Users								
Confirmed use: State and local crime lab		Yes, state and local labs	N/A	State of Colima (Mexico) Crime Lab	United States, Germany,Brazil, Greece, and France	ADFS—Derrick McClarin (now at FBI Labs)	Three units deployed in state and local labs	Approximately 180 units deployed in state and local labs
Federal crime lab		Yes, federal labs	N/A		Germany, France, Switzerland, Belgium, Finland, Brazil, Uruguay, United States, and Morocco	FBI labs	One unit deployed in the ATF Atlanta Lab	Approximately 10 units deployed in the three ATF labs, 1 at U.S.Customs and Border Protection, and 1 in the FBI Quantico Lab
Other		Yes, research labs	N/A	National security initiative by Presidential Decree in the Dominican Republic (SISNA/ LABBS) falling under the Minister of the Interior and Police; used for research at the Centre for Precision Technologies at Huddersfield University, United Kingdom, under the authority of Professor Liam Blunt; participation in the	Lausanne Technical University	Over 600 systems installed around the world for a variety of applications, from anthropology to micro-electronics	More than 140 units deployed in the rest of the world	Morethan 220 units deployed in the rest of the world
For further information	http:// www.alicona.com/	http://www. cadreforensics.com/	http://www.leica-microsystems.com/ home/	http://www. pyramidaltechnologies.com/	http://evofinder.com/	http://www.sensofar.com/	http://www.ultra- forensic technology.com/	

All data is based on vendor input that is subject to interpretation and verification.

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