August 2022

2022 Update: 3D Imaging Technologies and Virtual Comparison Microscopy for Firearms Examination, A Landscape Study

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Acknowledgments

The Forensic Technology Center of Excellence (FTCoE) would like to acknowledge the following industry and forensic professionals for their advice and input to this report:

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Suggested Citation

Shute, Rebecca, Gabby DiEmma, and Nicole Jones, "2022 Update: 3D Imaging Technologies and Virtual Comparison Microscopy for Firearms, A Landscape Study." Research Triangle Park, NC: RTI International.

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1. Report Overview

The National Institute of Justice's (NIJ) Forensic Technology Center of Excellence (FTCoE), led by RTI International, provides resources that promote the use of technologies in the forensic community. This report updates a 2016 landscape study[1] meant to inform the forensic community of the emerging application of 3D imaging technology to firearms identification in the crime laboratory. Since the original report, the firearms examiner community has evaluated this technology in the crime laboratory and considered how this may be implemented into their workflows. Optical topography, or three-dimensional (3D) imaging technologies, may provide value to numerous applications within the impression and pattern evidence community, but this report focuses specifically on the application of 3D toolmark technologies and virtual comparison microscopy (VCM) to cartridge case and bullet examination. Although yet to be fully integrated into many agencies, some state, local, and federal agencies, including the Federal Bureau of Investigation (FBI), are actively using these instruments in their casework. This update is meant to summarize collective thinking around how 3D imaging technologies may be deployed in firearms and toolmarks units, how the technology has developed to meet the needs of the examiners, and gaps that may limit its adoption.

The firearms identification discipline is based on the premise that firearms contain numerous parts that act as tools, leaving marks on the bullet and cartridge surface during loading and firing (more context can be found in the original landscape study). These marks may include class and subclass characteristics or reproducible marks that may support a same-source conclusion for ammunition fired from the same firearm, as described in the Association of Firearm and Tool Mark Examiners (AFTE) theory of identification.[2] Traditionally, these markings and impressions can be visualized and compared with known test-fired bullets and cartridges via light comparison microscopy (LCM), a traditional optical microscopy where the specimens are placed on two separate stages and viewed side-by-side in the optical path under variable lighting conditions and orientations. Two-dimensional (2D) images of the bullets and cartridges can be entered into databases like the National Integrated Ballistic Information Network (NIBIN) to compare evidence across jurisdictions, identify potential linkages between cases, and produce actionable crime gun intelligence.

Optical topography 3D imaging systems, or simply 3D imaging technologies, are metrology techniques that directly measure the surface topographical features of the bullet or cartridge with more accuracy than traditional 2D LCM. This allows examiners to view a faithful representation of the firearm and toolmark evidence virtually, which (1) mitigates lighting and reflectivity variation common in traditional LCM and (2) introduces measurement metrology, thereby decreasing the subjectivity of the comparison. The use of 3D imaging and metrology allows for more comprehensive databasing efforts and has the potential to incorporate algorithms that provide weight of evidence and statistical support to examiners' conclusion statements by incorporating the national Reference Population Database of Firearms and Toolmarks (RPDFT).

The original landscape report discussed several use cases, including relevant crime laboratory and crime gun statistics for agencies that were in the process of validating and implementing 3D imaging technologies in their workflows at the original time of publication. The report discussed the state of the market in 2016, including NIBIN requirements and potential future directions for 3D imaging in firearm identification. The authors identified several areas for improvement, including improving datasets for known match and known non-match bullets and cartridges, establishing and validating best practices and training for 3D imaging in practice, investigating applications for database searching and laboratory impacts, and improving the interoperability of instruments and databases across laboratories by using a uniform, vendor-neutral language such as the X3P (XML 3D surface Profile) format. The authors also compiled a glossary of relevant terminology for reference.

This 2022 update discusses the advancements in 3D imaging for firearms identification that have been rapidly developing in the years following the 2016 landscape study. Specifically, it describes VCM and its applications in more detail along with how the field has addressed concerns cited in the original landscape study regarding areas of improvement.

2. Virtual Comparison Microscopy

Firearm examiners analyze evidence by identifying tool marks on cartridge cases and bullets that may be characteristic of the firearm used at a crime scene. Traditionally, these examiners have used LCM to locate and evaluate these marks and to determine if there is sufficient agreement between the evidence and a known reference (bullet or casing) to suggest that the marks were produced by the same firearm. Optical topographic methods record a 3D representation of an object of interest at a high resolution and has emerged as an alternative method of visualizing the surface of a cartridge case or bullet. Optical topography encompasses a number of 3D imaging techniques, including focus variation, confocal microscopy, interferometric techniques, and photometric stereo. 3D imaging instruments used for firearm and toolmark analysis are more commonly referred to as 3D toolmark technologies, abbreviated as 3D2T.

The application of this advanced 3D imaging technology for forensic use has led to the development of VCM for firearms examination. Future technology-enabled applications include the use of 3D imaging for database matching purposes.

VCM was first described by Senin *et al.* (in a 2006 paper published in the *Journal of Forensic Sciences*) as a two-part system consisting of an image acquisition component and an image analysis component.[3] The image acquisition component involves the use of 3D imaging technology to produce the 3D image that can then be used for comparison.[3] Overall, VCM describes a visualization tool that enables the examiner to compare 3D digital images built from optical topographic scans of two or more bullets or cartridge cases.

Instead of working with a conventional light microscope, VCM enables examiners to conduct the comparison using high-resolution 3D representations of the bullet or cartridge case on a computer screen, whether or not the evidence is physically present. If the 3D images are acquired on properly calibrated instruments, then reliable comparisons can be made even if they were acquired at different sites or on different manufacturer's instruments. The images can be enhanced and reoriented (i.e., by changing lighting, contrast or rotation of the image) to help examiners locate features to compare.

Furthermore, given that the optical topographic data are digital, algorithms can be developed and used to objectively compare different scan datasets and to apply statistical comparisons. Such datasets can be used to build a database of bullet or cartridge case scans as a way to mine potential associations from historical data from previous casework. Although algorithms can be used to suggest associations, it is ultimately the firearms and toolmarks examiner who concludes whether there is a potential association and is responsible for explaining why and to what degree of certainty.

To use 3D imaging technology for database searching, the software compares an image across a database for potential close associations, and provides a quantitative score based on the degree of similarity. Database comparisons may be used to triage a large number of cartridges for potential associations, followed by a trained firearms examiner performing a direct comparison of the images.

Crime laboratories are starting to explore the use of VCM in place of or alongside of LCM for firearms examination. Experts agree that VCM provides multiple benefits that compare with or that even improve upon traditional methods. This report outlines the applications and benefits of VCM in the following sections.

2.1 Improved Image Quality

VCM can improve quality of image comparison, addressing some of the typical challenges examiners experience when using traditional light microscopy methods. Within VCM, the examiner can reliably alter the lighting from a "virtual light source" and adjust the orientation and viewing angle. This can help prevent instances where lighting bias may suggest differences or similarities between samples that do not exist. Because the high reflectivity of firearms evidence can make distinguishing marks in LCM challenging, VCM instrument vendors have addressed this challenge by incorporating lighting adjustment features within the VCM software or through measurement methods that help show the detail of toolmarks without interference from the high metal surface reflectivity. For example, Cadre Forensics uses GelSight, a reusable elastomeric sensor with uniform surface reflectivity that conforms to the surface topography.[4]

The VCM allows the examiner to easily rotate and zoom in and out of a 3D image viewed on a computer screen. The examiner does not need to constantly adjust the focal depth of the microscope, lighting, and orientation to examine firing pin and impression marks, as is required with LCM. The ability to easily zoom and isolate regions of the scan is especially important to avoid visual distractions and facilitate pattern recognition and comparison. Additionally, some VCM software allows examiners to save and re-load settings so they can return to the same comparison without having to re-orient and illuminate the sample. Using these features, examiners can focus their time and efforts on evaluating toolmark features rather than adjusting the physical samples in preparation for the comparison.

2.2 Easier Implementation with Help from Validation Studies

The number of validation studies has increased in recent years, and their findings indicate that VCM performance is comparable with traditional LCM.[5-8] For example, the FBI posted a Validation Summary of VCM using Cadre's TopMatch-GS 3D system that included comprehensive testing procedures, results, and conclusions.[8] The document concluded that "following traditional comparison methods integrated with digital reproductions of toolmarks, the validation method (plan) demonstrated that 3D toolmark comparison for common source determination using VCM is as accurate and in some cases better than traditional LCM."[8] Similarly, the Royal Canadian Mounted Police (RCMP) had examiners test expended cartridge cases with VCM via Cadre's TopMatch system and traditional LCM analysis and then statistically analyzed the data.[6] The results of this study, published in November 2021, noted that VCM produced a higher sensitivity and specificity rate than LCM, and positive identifications were made more frequently with VCM than LCM. This study concluded that the VCM software used in the study "is an appropriate and valid technique for conducting comparisons of expended cartridge cases and can be implemented into routine casework for that purpose."[6]

A comprehensive review of firearm examination studies was presented at the 2022 Firearm and Toolmarks Policy and Practice Forum, sponsored by NIJ and hosted by the FTCoE, and can be found in the published event proceedings.[9] Topics included validation studies, error rate studies, and white and black box studies, among others.

In addition, the Technical Working Group for 3D Toolmark Technologies (TWG3D2T) has compiled validation studies and is currently collecting a database of images that can be used as validation datasets, which will reside on the working group website (https://twg3d2t.org/). In addition, the NIJ Forensic Laboratory Needs Technology Working Group has developed a white paper outlining implementation strategies for 3D imaging of firearms and toolmarks, which includes validation considerations.[10]

Vendors, in addition to laboratories, have developed validation and other studies to understand VCM performance. The NIJ supported numerous Cadre Forensics research projects related to VCM, including the following:

- Assessing Class Consistency and Common Source Using 3D Virtual Comparison Microscopy in Firearm Forensics (2020-DQ-BX-0028)
- Expanding the Scope and Efficiency of 3D Surface Topography Analysis in Firearm Forensics (2019-DU-BX-0012)
- Evaluation of 3D Virtual Comparison Microscopy for Firearm Forensics within the Crime Lab (2018-DU-BX-0216)
- Firearm Forensics Black-Box Studies for Examiners and Algorithms using Measured 3D Surface Topographies (2017-IJ-CX-0024)
- Advanced Scan Matching, Scalable Search, and Visualization Tools for the Analysis of 3D Scans of Cartridge Casings in Firearm Forensics (2016-DN-BX-0182)
- Applied Research, Development, and Method Validation of Toolmark Imaging, Virtual Casing Comparison, and In-Lab Verification for Firearms Forensics (2015-DN-BX-K032)
- Applied Research, Development, and Method Validation for a Statistically Based Comparison of Tool Marks using GelSight-Based 3D Imaging and Novel Comparison Algorithms for Firearm Forensics (2014-DN-BX-K012)

2.3 Improvements in Workflow and Efficiency

VCM offers workflow and efficiency improvements over LCM—VCM software offers creative features that improve collaboration and expedite analysis. With VCM, evidence does not need to be physically transferred for it to be analyzed, and examiners can perform their analyses remotely by capturing a 3D image of the evidence that can be archived and digitally compared. They do not have to be physically in the laboratory, and they are not tied to the comparison microscope for extended periods. Examiners can access the software from a standalone computer without network access or through the network via a Virtual Private Network (VPN). This can enable easier collaboration across jurisdictions, facilitate assistance from outside agencies to alleviate caseload challenges, and allow a larger pool of candidates who can perform independent third-party verifications, which may lead to more objective quality reviews. By capturing the full 3D images of the evidence, examiners can also revisit cases as needed, even when the physical cartridge casing is not in their possession.

Because scanning a bullet or cartridge casing and comparing the 3D images are two separate tasks, they can be decoupled. A technician can be trained to scan the evidence, allowing the examiner more time to focus on critical examination and interpretation tasks. Additionally, examiners may have less eye strain using VCM and may be able to work for longer hours in a more ergonomically friendly position by relying on large screens for analysis rather than the small lenses in a microscope.

Most 3D imaging technology vendors with VCM software offer the ISO XML 3-D Surface Profile (X3P) data format, described in the International Organization for Standardization (ISO) Standard 225178-72, for saving images. X3P is an open data format that allows examiners to share and view scans from different instruments, in accordance with both ISO 25178 and ISO 25178-72. For example, an agency that uses an Alicona instrument can exchange images with an agency that uses a Sensofar instrument. The common file format allows agencies to choose the best instrument to fit their laboratory's needs, regardless of which instruments have already been implemented in other agencies. Avoiding incompatibility between systems may ease concerns over the cost and time required to implement and use the new technology in casework. The Open Forensic Metrology Consortium (OpenFMC) is currently developing an extension to the X3P data format to address metadata issues specific to forensic toolmark analysis.

Some manufacturers of VCM technologies also offer features that allow the examiner to annotate images with notes and markup features that they felt helped them determine an association or areas of great difference. This may be useful for independent review, examiner training, and evidence presentation in court; for court specifically, these features can help examiners recall the comparison before for court testimony by allowing them to see their notes embedded in the images instead of shuffling between documents. Highlighted regions and annotations may also help jurors comprehend the evidence by drawing their eye to the features and regions that led the examiner to their conclusion. Altogether, these features, which are available from multiple vendors, can streamline the examination process and optimize the workflow.

2.4 Improved Accuracy and Reliability Through Comparison Algorithms

Some vendors may incorporate comparison algorithms into their VCM software, although these algorithms may differ across vendors. Although few agencies have incorporated these comparison algorithm capabilities into their workflows, they may help address the accuracy and reliability challenges in a comparative discipline, a key challenge outlined in the 2009 National Academy of Sciences report, "Strengthening Forensic Science in the United States: A Path Forward." This could be an additional objective tool for assessing the statistical weight of the comparison rather than relying on the examiner's subjective conclusion alone. Objective comparison algorithms could improve the accuracy and reliability of firearm and toolmark examination because it can identify areas of similarity between two pieces of evidence or give a numerical score of the similarity to highlight areas of interest for further attention by an examiner.

2.4.1 Reference Population Database of Firearms and Toolmarks

Forensic disciplines, such as firearms examination, must consider the weight of evidence and how this can accurately be conveyed to the triers of fact. However, determining the statistical weight of evidence or scoring in impression disciplines is not simple because it requires large, representative datasets. To fill this gap, the National Institute of Standards and Technology (NIST) is collaborating with the FBI and the Netherlands Forensic Institute to develop the RPDFT.

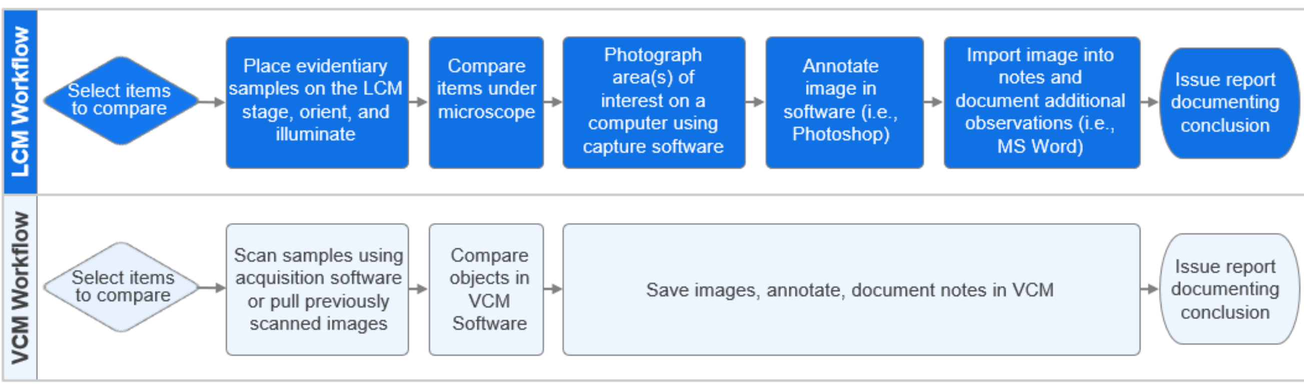
The RPDFT contains a reference dataset of known match and known non-match comparisons that can produce statistical distributions that then allow examiners to determine the statistical weight of evidence. This database allows statistical conclusions to be drawn about the evidentiary strength of a same-source conclusion. The RPDFT framework provides examiners with a mechanism to submit their result and the metadata (e.g., make, model, and caliber of a cartridge casing or bullet) and request a weight of evidence, which is a measure of the amount of evidence that supports or refutes the hypothesis that there is an association based on the reference population. For example, the examiner will enter the hierarchical metadata for the firearm: manufacturer; model; manufacturing methods for the breech face, firing pin, and barrel; and number of land engraved areas. For the bullet, the examiner will enter the manufacturer, model, caliber, primer and cartridge case material, bullet weight, twist, and surface material. The more metadata the examiner can enter about the evidence, the better the population fit and the more accurate the calculation of the weight of evidence will be; however, if the size of the reference population is too small, there are less metadata regarding the class characteristics in which case the RPDFT algorithm moves up in the hierarchy to include more samples and scores. However, this can lead to a loss of specificity.[9]

The user interface also allows the examiner to focus on a specific region of interest on the item that is being examined. The system builds a relevant reference population using the class characteristics—once the examiner enters the metadata, the database will calculate the likelihood ratio for the known match and known non-match based on the class characteristics entered. This gives the examiner core objective evidence upon which to base their conclusions. The FBI is currently conducting a pilot test to validate the likelihood ratio calculations using old case work and in parallel with current case work and proficiency test sets. This validation study is scheduled to be completed in 2022. Once validated, a portal will be built to allow forensic laboratories to access the RPDFT database for use on their casework.

3. Use Cases for VCM

Although VCM has had limited adoption to date, many crime laboratories are piloting or exploring integration of the technology into the traditional firearms examiner workflow. Applying 3D imaging technology will not remove the firearms examiner from the equation; rather, it may change their role, saving more time for focusing on comparisons and offloading routine tasks to technicians.

Exhibit 1. Comparison of LCM vs. VCM Workflows



A cross-section of 3D imaging technology users reported the following:

- VCM as an alternative or supplement to LCM serves as another tool in the toolbox. When appropriate, VCM is used in place of LCM based on examiner preference, collaboration needed for a case, demand for remote work, or need for independent verification. All analysis is performed by the examiner and quality reviewer.
- VCM, with matching algorithms, is used as a triage step for the initial case entry into NIBIN. Each cartridge submitted to the laboratory may be analyzed using 3D imaging with objective matching algorithms to identify which cartridge case might be the best representative sample for further examiner analysis.
- VCM, with matching algorithms, may be used to identify a potential association and verification for casework—the algorithm will outline potential areas of interest for the examiner who will then review and verify the details in these regions of interest to aid in their conclusion.
- VCM, with matching algorithms, may be used with a reference database of topographic image data for in-jurisdiction identification of potential associations. When an expended cartridge is scanned, the image is compared against a database of known or unknown cases to determine whether there may be links. Then, examiners analyze these images to conclude whether there is sufficient agreement between them. This principle operates similar to that of the NIBIN but is limited to the 3D scans collected by the laboratory.

- VCM may be used for training and blind verification. When trainees are given immediate feedback, they can identify features that are causing confusion and learn through experience. Annotation heatmaps can be used to inform future education, training, and standards with respect to the most probative areas of interest to focus on for comparison (e.g., the surfaces that help make accurate source determinations and produce the least false positives and negatives). The ability to add notes and annotations as separate layers allows two separate individuals to conduct the comparison analysis on the scans without seeing the other examiner's notes and conclusions. The reviewer performing the verification does not have to be within the same laboratory or jurisdiction because they can work with the digital files remotely.
- VCM can be used to standardize and optimize the production of sample materials for proficiency tests, validations, and white and black box studies. Proficiency tests evaluate examiners continued ability to perform an examination correctly, but each examiner receives a slightly different test because of the nature of firearms evidence. However, using 3D scans and VCM, all examiners would receive the same test with the same level of difficulty. Traditionally, large-scale validation, error rate, and white and black box studies are limited in sample size and scope by the amount of test fires, known associations, and known non-associations they can produce and distribute. This issue could also be mitigated by using 3D scans and VCM that require coordinating the distribution of digital files opposed to the physical items associated with large test sets.
- VCM can be used to reanalyze archived scans and compare them with new samples or with more advanced instrumentation or algorithms. Databasing these scans can allow examiners to access archived samples without physically handling the samples, which could likely provide more timely intelligence and investigative leads in the future through data sharing between agencies.

Incorporating this technology into existing firearm analysis workflows will depend on end user buy-in, financial affordability and maintenance of this technology (especially in centralized lab systems), validation efforts, and successful use of the technology in court.

4. Advancements in Vendor Technology

Although the core tenets of 3D imaging technology have not changed over the past 6 years, improvements to VCM software and hardware have driven adoption of these instruments in a forensic setting. Across vendors, 3D imaging instruments have incrementally improved in image acquisition times, algorithm matching capabilities, graphics quality, and image enhancement qualities. Strides have been made in improving the user experience for firearm examiners. These advancements include those discussed here.

4.1 User-Centric Software Products

User-centric software products that offer annotation and interoperability features enable virtual comparison and collaboration. Vendors have developed robust VCM software platforms to analyze the scan data, with annotation capabilities and shareability across different vendor users using the X3P data file format. These products are created specifically for the needs of firearms examiners and include considerations like simplifying reporting into the laboratory's information management system. Vendors also offer free user interfaces that allow collaborators or other criminal justice community stakeholders to view this evidence if needed.

Although the previously mentioned RPDFT population database has its own scoring algorithms, vendors are encouraged to collaborate to produce vendor-specific statistical distributions from the RPDFT reference datasets. Therefore, the development of software products with more forensically relevant features may further facilitate implementation efforts because it will be easier to incorporate vendor-specific algorithms into resources such as the RPDFT.

4.2 Hardware Products Evolving for Laboratory Needs

Along with software programs, companies are modifying their hardware so that training on and using these complex instruments is simpler. Sensofar, for example, plans to offer a four-axis version of their instrument, which will be more cost-effective than the five-axis model currently available.

Some companies are considering mobile or even handheld systems that may be easily deployed to a crime scene, which may enable further changes in agency workflows. These would be ruggedized systems that could be used to help determine how many firearms may be present at a scene or to inform investigators if multiple shooters are involved. In future scenarios where agencies have developed a reference database of scanned cartridges, these handheld devices may be used as presumptive screens to identify investigative leads.

For example, Cadre has developed a handheld system that can run in the field. Although the instrument offers lower resolution than its tabletop counterpart, it leverages the same TopMatch software and GelSight technology and can immediately upload images to the network via a mobile hotspot and Cadre Nexus connectivity. Ultra FT's Integrated Ballistic Identification System (IBIS) and Quantum 3D instruments can be implemented in a mobile analysis van or trailer and have been deployed to incidents such as mass shooting scenes.

Manufacturers have developed other triage systems that can scan evidence in the field or upon entry into the crime laboratory. These systems may employ 2D or 3D imaging and can improve the overall firearms workflow by determining the number of firearms present at a crime scene and which bullets or casings to prioritize for NIBIN entry. Leeds Micro has developed the Evofinder® Automated Ballistics Identification System to capture 2D and 3D images of firearms evidence that can be uploaded to a digital database of bullets and cartridge cases for future comparison. Evidence IQ's triaging software system, named Ballistics IQ, provides crime gun intelligence by scanning cartridge cases, determining number and type of firearm, and identifying possible case linkages. These systems produce preliminary results for triage and timely actionable intelligence and must be confirmed through either traditional LCM comparisons or VCM.

4.3 Automation Capabilities

Automation capabilities can improve process efficiency and may reduce overall analysis time. Cadre Forensics, for example, has built a scanning tray for its TopMatch system that enables 15 cartridges to be analyzed serially, even if the caliber differs. This tray significantly reduces time for analysis by eliminating the unloading and reloading process for each cartridge.

5. Considerations for Implementing VCM

VCM is emerging as a 3D imaging application that may improve the objectivity, workflows, and collaborative abilities of firearm examiners. Like any forensic technology, successful VCM implementation depends on several factors. Laboratories should consider the following takeaways when choosing and integrating 3D imaging technology into their workflows.

5.1 Plan for Costs of VCM Implementation Beyond the System Cost

Although some vendors have developed tools specifically for firearms examination applications, VCM is not an "out-of-the-box" solution. Laboratories should consider hardware, software, examiner training, maintenance costs, and the resources needed for validation. In larger laboratories or laboratory systems where multiple laboratories are operating under shared standard operating procedures, such as satellite offices of a state-based system, each laboratory should have the same equipment. This equipment can be quite expensive and may cost $50,000 or more per instrument. Laboratories should consider alternative funding mechanisms, such as grant funding, cooperative agreements with vendors, or leasing options to obtain these instruments.

5.2 Instill Confidence in the Technology Through Training and Validation

Early studies of VCM using 3D imaging technology indicate that the approach is comparable with traditional LCM workflows, but there is a learning curve associated with the use of this technology. Optical topography instruments capture detail at a high resolution, arguably more resolution than an examiner would experience using LCM. With the click of a mouse, examiners can easily manipulate the virtual light source and see significant detail. This requires examiners to adjust the way they conduct their analyses, which some may find difficult. Laboratories implementing VCM should re-train users to be comfortable with making conclusions following analysis via VCM, which may take more front-end time and effort and may entail use of test sets and analyses using both LCM and VCM so that examiners do not take too conservative of an approach for identifying toolmarks as they gain confidence and proficiency in their use of VCM. Conservative approaches may lead examiners to report evidence as inconclusive when an association or exclusion could have been made based on the feature details.

Historically, examiners have been taught that all comparisons should be made using the physical items instead of pictures of the toolmarks in question; however, the fidelity and resolution of VCM has challenged this mindset. In most cases, the VCM images may have greater detail than traditional LCM, which can lead to cognitive overload. When this technology was implemented at the Phoenix Police Department Crime Laboratory, they noted that this caused their examiners to be initially more conservative in their conclusions until they became more confident in their ability to recognize the patterns in the 3D virtual format.[9]

Internal validation is a critical consideration for implementing an instrument in a laboratory. Laboratories should internally validate the technology to ensure that these new protocols are comparable or superior to current methods. For accredited laboratories, ISO 17025 requires validation of an instrument prior to use in casework. Laboratories should refer to previous validation studies from vendors and agencies for study design; both the FBI's Firearms and Toolmarks Unit and the TWG3D2T have developed guidance documents for validation studies. Furthermore, laboratories should consider consulting a statistician to help them understand and interpret the results and communicate the value of 3D imaging technology to laboratory leadership.

5.3 Consider the Value of Ballistics-Focused and General 3D Imaging Systems

Over the past 10 years, 3D imaging technology vendors have introduced and improved hardware and software systems developed specifically for firearms analysis. 3D imaging, however, may be able to play a significant role in related disciplines in the near future, such as toolmark analysis of a forced lock. These systems were built to decrease the training and operating time needed for VCM, so laboratories may want to consider the tradeoff of operation and training time for a system that can be expanded to other toolmark analysis tasks.

5.4 Understand Capabilities and Limitations of Available 3D Imaging Systems

Selecting an appropriate system can be a complicated process because none are one-size-fits-all options. The firearm examiners consulted for this study identified key needs for an imaging system, including the ability to capture the following:

- Cartridge case heads (firing pin and breech face impressions)
- Cartridge case sides (for chamber marks)
- Bullets

Ideally, users would like an imaging system that can scan all three types of evidence, with the ability to annotate scans in the comparison software. Matching algorithms, although not currently used in casework, may play a key role soon in helping examiners make data-informed conclusions. **Exhibit 2** provides a brief update of key VCM features across vendors. Because no vendor offers all features, laboratories must strategically choose a system or systems that address their needs. A more complete list of features of each 3D Imaging system is provided in **Exhibit 3.**

Exhibit 2. Key VCM features across vendors

Vendor	Instrument	Cartridge Case Head–Firing Pin and Breech Face	Cartridge Case–Sides	Bullet Scanning	VCM Software	Annotation Capabilities	Matching Algorithms
Alicona	SL	Yes	Yes	Yes	No	No	No
Alicona	G5	Yes	Yes	Yes	No	No	No
Cadre Research Labs	TopMatch-GS 3D	Yes	Yes	Yes	Yes	Yes	Yes
Leica Microscopes	DCM8	No	No	No	No	No	No
Laboratory Imaging	Balscan	Yes	Yes	Yes	Yes	Yes	Yes
Leeds	Evofinder® 4x4	Yes	Yes	Yes	Yes	Yes	Yes
Sensofar	S Neox	Yes	Yes	Yes	Yes	Yes	Yes
Ultra Electronics Forensic Technology (FT)	Quantum 3D, S1 Model	No	Yes	Yes	Yes	No	Yes

5.5 Consider How Implementation of 3D Imaging May Affect NIBIN Workflows

Many laboratories participate in the Bureau of Alcohol, Tobacco, and Firearms (ATF)'s NIBIN, an interstate network meant to improve information sharing of firearms evidence across jurisdictions. Using Ultra FT's IBIS BRASSTRAX and BULLETTRAX products, which use proprietary algorithms to help them delineate regions of interest and quickly find the best associations, participating laboratories enter images of cartridge cases into the IBIS database. NIBIN then searches its images for those that are similar.

Use of 3D imaging in firearms examination may complement, but not replace, NIBIN workflows with VCM. Although BRASSTRAX and BULLETTRAX systems identify possible associations, they do not confirm them; VCM can be the confirmatory next step. 3D scanned images of cartridge cases are not accepted by NIBIN because the system relies on 2D images and is not interoperable.

An area of potential overlap between NIBIN and the evolving 3D imaging technology is database matching, where laboratories develop internal databases of 3D scans that could help identify potential hits to unsolved crimes. Given the widespread and established nature of NIBIN for 2D images, the development of an internal 3D database may not add value for agencies already using NIBIN. However, given the nature of crime to cross jurisdictional lines, it can hinder data sharing across agencies when one county is using an internal 3D database while the next county is using NIBIN. In these instances, linkages between guns used during crimes may be missed because the evidence is separately contained in two non-interoperable databases.

Nevertheless, 3D imaging systems can be used both for evidence triage and to select the best bullets or casings to enter into NIBIN. Although they are currently disparate systems, the use of 3D imaging can inform examiners on which samples to prioritize for NIBIN entry, potentially leading to more timely, probative intelligence and investigative leads.

5.6 Consider Available Resources for Choosing and Implementing 3D Imaging Into Your Workflow

3D imaging for forensic firearms is an active area of research, and laboratories can rely on numerous resources to help them make informed decisions, including the following:

- The Technical Working Group for 3D Toolmark Technologies (TWG3D2T)
- Forensic Optical Topography Working Group Report
- FBI – Firearms and Toolmarks Unit
- Firearm and Toolmarks Policy and Practice Forum – Archival of Event and Proceedings Publication
- Annual NIJ Forensic Research & Development (R&D) Symposium
- Original: A Landscape Study of Forensic Optical Topography
- FLN-TWG – Implementation Strategies: 3D Imaging for Firearms and Toolmarks

Once a laboratory selects a system, its implementation will require training and validation. The TWG3D2T offers 3D training sets that can be used to familiarize examiners with viewing 3D data to gain confidence before using their new system in casework. The FLN-TWG published a report on Implementation Strategies: 3D Imaging for Firearms and Toolmarks to assist agencies in their adoption plan and implementation efforts.

6. The Future of VCM as a 3D Imaging Technology Application

VCM, enabled by 3D imaging technology, has the potential to become an accepted standard for microscopy in firearms identification and beyond. VCM can facilitate remote collaboration. The matching algorithms under development provide objective, quantitative results that may be highly valued in the legal system once they have been fully validated for use in casework. The development of field instruments, autosampling trays, and examiner-focused software programs will ultimately improve the experience of examiners with this new technology. Firearms examiners will always be an important part of the discipline, though their roles and responsibilities may change over time as the technology evolves. It is likely to take a number of transitional years before 3D imaging and VCM will be consistently used in casework across the discipline, because there are still wide gaps in implementation and use for 3D VCM and database matching.

Exhibit 3. Optical Topography Instrumentation and Specifications

Company	Alicona	Cadre Research Labs	Leica Microsystems	Laboratory Imaging s.r.o.	Leeds	Sensofar	Ultra Electronics Forensic Technology Quantum 3D Microscope, S1 Model	
Model	**InfiniteFocus SL and G5 Plus**	**TopMatch-GS 3D**	**Leica DCM8**	**Balscan**	**Evofinder® 4x4**	**S Neox**	**IBIS BULLETTRAX**	**IBIS BRASSTRAX**
Instrument type	Focus variation	Photometric stereo	Instrument incorporates three technologies: confocal, interferometry, and focus variation	Focus variation, photometric stereo	Combined focus variation and photometric stereo	Confocal, interferometry, and focus variation in one system	Nonlinear photometric stereo sensor	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; 15 cartridge case holder tray allows batch scanning	Air/Dry	Bullet holders and universal cartridge case holder	Detachable universal cassette for bullets and cartridge cases	Universal bullet or cartridge case holder	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)	LED	LED	Multiple LED (white, red, blue, and green)	LED lighting system	LED lighting system
Software for display and analysis	Alicona software can exported to the following: STL, AL3D, G3D, Open GPS, CVS, QDAS, SUR, and X3P	TopMatch (includes remote viewer software allowing examiners to view scans from their desktop windows computer)	Leica Map (Mountain Maps) and Leica Scan	LUCIA BalScan	Evidence FINDER	SensoVIEW, SensoCOMP, SensoMatch, and SensoMap (version of Mountain Maps)	IBIS MATCHPOINT	
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	No special requirements, standard 100–240 VAC power outlet	Standard laboratory requirements	Power; vibration isolation typically included	Office environment	

Company	Alicona	Cadre Research Labs	Leica Microsystems	Laboratory Imaging s.r.o.	Leeds	Sensofar	Ultra Electronics Forensic Technology	
Data Management								
Database search	Can search within a local database	Yes, the TopMatch software does implement a database that can be searched; Remote database (with search) via Cadre Nexus	Windows File Explorer	Yes, correlation search based on marks (firing pin, breech face, ejector marks, land and groove impressions)	Yes Bullets can be searched by primary (slippage), land, and groove traces. Cartridge cases can be searched by firing pin, breech face, and ejector marks	Windows File Explorer	Yes, historical crime-related exhibits and test fires	
Data storage capacity	Current Control Servers have 2 TB storage	6000 GB; 50,000 scans (base), unlimited with expansion	Depends on local hard drive and server availability	1 TB (20,000 images), expandable	Unlimited Storage requires approx. 1 TB per 40,000 objects	Depends on local hard drive and server availability	Scalable, unlimited; JPEG 2000 lossless compression	
Statistics available for data dropouts	Yes	No dropouts with photometric stereo	Leica MAP		Yes	Yes	No dropouts with photometric stereo	
Data collection time	1.7 million points/ second	Less than 1 min per primer at 1.8 micron/px sampling	1 min	Bullets ~ 3–8 mins CC bottom ~ 1 min CC surface ~ 9 min	Less than 2 mins for both object types (bullet and cartridge)	Approximately 6–16 min. per bullet for a bullet with 6 lands	10 mins for a pristine 9 mm bullet (land and groove areas)	5 mins for breech face and firing pin on a center fire 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; have added X3P since 2016	Yes, founding member of OpenFMC; fully support X3P	DAT, CSV	X3P	X3P and proprietary format	X3P supported	X3P, JPG, PNG	
Background correction	Yes, optionally to the user, but not as a default	Automatic baseline correction can be applied	Yes, vignetting and objective aberrations calibrations	Automatic corrections during scanning, corrections for correlation	Yes	Yes, proprietary objective calibrations	Yes, shape, waviness, and texture are acquired; shape and waviness are removed for correlation	No

Company	Alicona	Cadre Research Labs	Leica Microsystems	Laboratory Imaging s.r.o	Leeds	Sensofar	Ultra Electronics Forensic Technology	
Measurements and standards								
Calibration	Traceable to Physikalisch-Technishe Bundesanstalt (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	Field flatness is corrected for all available objectives as well as objectives aberration within FOV; systems are always verified for z accuracy and repeatability with NIST-traceable step height standards	Automatic calibration	Factory calibration only; can be checked periodically with reference standard	Objectives are calibrated for field flatness and aberration using optical flat; systems are typically verified for z accuracy with NIST-traceable step height standards	Self-calibration every 50 acquisitions (configurable) with the use of a special target inside the acquisition unit	Self-calibration every 50 acquisitions (configurable) with the use of a special target inside the acquisition unit
Spatial resolution	Limited by illumination type ~400 nanometers (SL 640 nanometers)	Typical lateral resolution: 1.8 microns per pixel (system can scan up to 0.9 microns per pixel)	Best spatial resolution is 150 microns (half pitch criteria)	3.08 µm/px	3.5 µm	Dependent on technology and objective; highest resolution is 0.15 microns lateral (half pitch); typical resolutions are 0.7 microns for bullets and 1.44 microns for cartridge cases	2.975 µm/pixel	Primer (Breech Face): 4.84 µm/px Firing Pin and Ejector: 3.25 µm/px
Best vertical resolution	10 nanometers (SL 20 nanometers)	Typical depth resolution of 1 µm (assessed using reference standard)	Best vertical resolution 0.1 µm	Microns (result of photometric stereo interpolation)	Theoretically ~1 µm	Dependent on technology and objective; interferometry resolution is better than 1 micron	0.2 µm	Approximately 1 µm
Smallest vertical slice interval	Same as vertical resolution	NR	Best achieved with Potential Scatter Interferometry (PSI) technology and Heidenhain sensor (close to 1 µm)	NR	NR	Dependent on technology and objective; PSI vertical slice with optional Piezo stage is about 1 nm	N/A	N/A

Company	Alicona	Cadre Research Labs	Leica Microsystems	Laboratory Imaging s.r.o	Leeds	Sensofar	Ultra Electronics Forensic Technology	
Lateral range	50 × 50 mm for SL, 100 × 100 mm or 200 × 200 mm for G5	N/A	2D and 3D stitching available up to big dimensions (biggest XY stage is H112 with 300 × 300 mm range)	50 × 50 mm	25 × 25mm	Images can be stitched to cover large areas; depending on stage size, up to 300 × 300 mm	2.86 mm width, unlimited height	4.65 mm × 4.65 mm
Measurements and standards								
Vertical measurement range for a single image	Objective dependent; max Z-axis range for G5 is 100 mm, SL is 25 mm	N/A	Depends on tech used and obj. From 10 µm to few <40 mm when using low NA	Theoretical maximum: 50 mm; typically <10 mm	Subject to be clarified in detail	Dependent on technology and objective; ranges from 150 microns for high NA objectives to 37 mm for low NA objectives	Undefined	Undefined
In-process surface follower technology	Yes	N/A	Yes	Yes	Yes	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)	From very smooth/polished to very rough surfaces. Thick/Thin film measurement	Yes, optimal for non-translucent surfaces (metal, castings)	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	N/A	12db	>48 dB		57 dB	57 dB
Working distance	Objective lens–dependent Max of 37.5 mm with 10× HX and min of 4.5 for 100×	N/A	13 (5×)–0.2 mm (150×)	88 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	9 cm	9 cm

Company	Alicona	Cadre Research Labs	Leica Microsystems	Laboratory Imaging s.r.o.	Leeds	Sensofar	Ultra Electronics Forensic Technology	
Measurements and standards								
Measurable range of caliber	All	22 short to 7.62 × 39 mm (additional calibers can be accommodated with adapters)	40 mm	All (up to 50 × 50 mm)	Up to 20 mm	Virtually unlimited	Calibers from 0.17–0.700 mm, and an effective diameter from 4–20 mm	Calibers from 0.17–0.50 mm 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	X-Y scanning reproducibility is in the range of (x,y) scanning	XYZ stages repeatability 0.1 microns	High reliability is defined by self-designed optics and mechanical platform	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 × 1,840 (SL 2,000 × 2,000) for a single measurement, up to 500 million for a stitched dataset	Current: 12 million	1,360 × 1,024	1920 × 1440	510 × 492; 2,048 × 1,536 (under development)	2,442 × 2,048	1,920 × 1,200	1,920 × 1,200
Maximum slope	87°	Theoretical: Up to 90°	85° (with 0.95 NA objective)	Theoretical < 90°	Up to ~90º (reported theoretical)	71° for confocal with 0.95 NA objective, slopes up to 86° can be measured with focus variation and with rough surfaces	20°–25° on rough surfaces with nominal FOV size	25°–35° on rough surfaces with nominal FOV size

Company	Alicona	Cadre Research Labs	Leica Microsystems	Laboratory Imaging s.r.o	Leeds	Sensofar	Ultra Electronics Forensic Technology	
Measurements and standards								
Field of view with 20× objective	0.81 × .81 mm (SL 1 × 1 mm)	N/A, using our 3× objective single image field of view is ~35 mm^2	877 × 660 microns	N/A, objective is 1.48×, FOV 5.7 × 4.3 mm	2.1 ×1.7 mm for objective 2×	877 × 660 microns	2.9 mm × limited by stitching (10× objective); a full circumference of the bullet can be done	3.1 × 3.1 mm (firing pin, ejector, and rim fire) with 1.5× zoom objective and 4.8 × 4.8 mm for breech face with 1.0× zoom objective
Measurement point density	Depending on objective, best : 0.09 µm (SL Depending on objective, best: 0.2 µm)	Typical: 1.8 µm/ pixel; maximum 0.9 µm/pixel	Depends on technology and objective	8400 PPI	280 points/mm	Depends on technology and objective	2.975 µm/pixel	Primer (Breech Face): 4.84 µm/px Firing Pin and Ejector: 3.25 µm/px
Conformance with standards for roughness measurement	Yes, ISO and American Society of Mechanical Engineers (ASME)	System will comply with NIST proposed OSAC standards by an SDO (e.g., ASTM); 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	Not tested	N/A	Yes	N/A	
Conformance with standards for surface measurement	Yes, ISO and ASME	System will comply with NIST OSAC proposed standards by an SDO (e.g., ASTM); 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	Not tested	N/A	Yes	System will comply with NIST proposed OSAC standards once published by an SDO such as ASTM	

Company	Alicona	Cadre Research Labs	Leica Microsystems	Laboratory Imaging s.r.o	Leeds	Sensofar	Ultra Electronics Forensic Technology	
Measurements and standards								
Form measurement	Yes, 2D and 3D Profiles and Contour; surface processing including filtering and form removal are also provided	3D surface height map	Can filter between roughness and form on both 2D and 3D profiles according to ISO standards	3D surface profile overlaid with texture; 3D profile measurements available	2D, 2D+D, 3D, profile, and color hear map	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 proposed OSAC standards by an SDO (e.g., ASTM); these standards are still being created and will build from the cited ISO and ASME documents	No	No	N/A	Yes	Yes	
Color imaging	Yes	N/A	Yes	No (alternative color camera available upon request)	No	Yes	No	
Illumination	Coaxial and ring light (24 segments) (SL Ring light [24 segments])	Photometric stereo ring light configuration	Four LED light sources (red, green, blue, and white)	8-segment LED ring light, 2-segment LED side light	Diffusive LED light, four ring segments	Four LED light sources (red, green, blue, and white)	LEDs for 3D	Annular light, side lights for 2D; LEDs for 3D
Measurement time for a 9 mm cartridge case primer area	Resolution-dependent	Less than 1 min (using 15 cartridge case holder tray)	TBD	50 secs for complete 9 mm cartridge case bottom	~0.5 min	2 min	N/A	4 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	3D surface profile overlaid with texture; 3D profile measurements available 3:30 mins for 5.8 mm wide 360° stripe of whole bullet	~1.5 mins	6 min for a pristine 9 mm bullet (land areas)	10 mins for a pristine 9 mm bullet (land and groove areas)	N/A

Company	Alicona	Cadre Research Labs	Leica Microsystems	Laboratory Imaging s.r.o.	Leeds	Sensofar	Ultra Electronics Forensic Technology	
Measurements and standards								
Security	No	System will comply with NIST proposed OSAC standards by an SDO (e.g., ASTM); these standards are still being created and will build from the cited ISO and ASME documents	No	No	N/A	No	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	Yes, computer experience and ballistics grounds	Yes, minimal background required	Yes, wide selection of training courses, on site and via eLearning; no specific background required	
Technical support provided?	Yes, all methods and different service contracts available	Yes, phone, email, and web	Installation and training provided with purchase; online, telephone, and internet training and support available per request	Yes, 2 years warranty, 3 years of software updates and support included	Yes, full range support	Yes, typical installation includes 2 days on site, with follow-on training available	1-year warranty included and extended SafeGuard warranty coverage; customized support packages available for national programs; 24/7 worldwide remote and on-site support	
Estimated cost <$100,000		X		X				
Estimated Cost $100,000–$500,000	x (Both SL and G5)	x (2020 pricing: System 118k; Delivery, Setup, First Year Support: 11k)	X		X	X	X	X
Estimated Cost >$500,000					X			
Other		$129k all in price; Peer-reviewed validated VCM tools; batch scanning tray; remote viewer			Depends on configuration			

Company	Alicona	Cadre Research Labs	Leica Microsystems	Laboratory Imaging s.r.o.	Leeds	Sensofar	Ultra Electronics Forensic Technology	
Training, Costs, and Current Users								
Confirmed use: State and local crime laboratory	Yes, local laboratories	Yes, state and local laboratories	N/A		Yes, United States, Germany, Brazil, Greece, and France	Yes (United States, Check Republic and China)	2 units deployed in state and local laboratories	Approx. 220 units deployed in state and local laboratories
Federal crime laboratory	Yes, several laboratories worldwide	Yes, federal laboratories	N/A	Yes	Germany, France, Switzerland, Belgium, Finland, Brazil, Uruguay, United States, and Morocco	FBI labs	3 units deployed in ATF labs	Approx. 45 units deployed in ATF labs, U.S. Customs and Border Protection, and FBI Lab
Other	Research laboratories worldwide	Yes, research laboratories	N/A	NR	More than 60 laboratories in more than 22 countries	Over 800 systems installed around the world for a variety of applications, from anthropology to micro-electronics, including 5 units at universities doing research of 3D technologies for firearms identification	Approx. 200 units deployed worldwide	Approx. 550 units deployed worldwide
For more information	https://www.alicona.com/	https://www. cadreforensics.com/	https://www.leica-microsystems.com/home/	https://www.forensic.cz/	https://www.leedsforensics.com/	https://www.sensofar.com/	https://www.ultra-forensictechnology.com/	

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

Abbreviations: The American Society of Mechanical Engineers (ASME); Field of View (FOV); High Index (HX); I International Organization for Standardization (ISO); Light Emitting Diodes (LED); Not Applicable (NA); Not Reported (NR); Numerical Aperture (NA); Standards Development Organization (SDO).

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The FTCoE, led by RTI International, is supported through a Cooperative Agreement from the National Institute of Justice (2016-MU-BX-K110), Office of Justice Programs, U.S. Department of Justice. Neither the U.S. Department of Justice nor any of its components operate, control, are responsible for, or necessarily endorse, this landscape study.

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. Any perceived value judgments may be based on the merits of software features and developer services as they apply to and benefit the law enforcement and forensic communities. The information provided herein is intended to provide a snapshot of current 3D optical topography technologies; it is not intended as an exhaustive summary. Features or capabilities of additional products identified outside of this landscape may be compared with these instrument features and service offerings to aid in the information-gathering or decision-making processes. The opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect those of the Department of Justice.