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Analysis of Contactless Fingerprint Minutia Deviations

(Version 1.1)

April 13, 2015

DOJ Office of Justice Programs
National Institute of Justice
Sensor, Surveillance, and Biometric Technologies (SSBT) Center of Excellence (CoE)

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EXECUTIVE SUMMARY

The effect of minutia deviations on match performance due to contact scanning is a topic that needs to be investigated to better understand the interoperability, performance, and viability of contactless fingerprint scanners. In 2012, the National Institute of Justice (NIJ) Sensor, Surveillance, and Biometric Technologies (SSBT) Center of Excellence (CoE) undertook a biometric collection of fingerprint data from traditional scanners and next generation contactless devices – Contactless Fingerprint Collection, Round 1 (CFPv1).[1] This data was the first of its kind across the two classes of scanners using the same subject population. To build upon that work and facilitate investigations by other researchers, the CoE has developed a tool for characterizing contact and contactless fingerprint minutia data, used that tool to analyze minutia deviations between probe and gallery datasets, and conducted biometric experiments to investigate the effect of minutia deviations on match performance.

Minutia Deviation Tool (MDT)

To explore the minutia deviations in the datasets and their effect on match performance, the SSBT CoE developed a custom software tool – the Minutia Deviation Tool (MDT). The MDT is a prototype software utility that aids a user in designating equivalent minutia pairs across two fingerprint biometric images and calculating the pair's minutia spatial deviations. The tool also allows for those mated minutiae to be filtered based on deviation or position criteria to produce Electronic Biometric Transmission Specification (EBTS) files with a subset of minutia markings.

Data

The fingerprint data used by this evaluation consisted of finger images collected in the CFPv1 West Virginia University (WVU) biometric collection and then processed to produce Latent Friction Ridge Features Search (LFFS) EBTS files that had been reviewed by a Certified Latent Print Examiner (CLPE). Data processing and analysis was limited to the right index rolled (or rolled-equivalent) fingerprints collected from ~500 subjects using three devices. The resulting data consisted of three datasets (3) for each of four (4) devices. Each dataset contains 468 images or EBTS files for the same subject finger for 100% N:N compatibility.

- Devices
  - Cross Match Guardian R2 (CMR2) rolled prints
  - Cross Match SEEK II (SEEK) rolled prints
  - Touchless Biometric Systems 3D Enroll (TBS) two dimensional (2D) grayscale rolled-equivalent prints
  - FlashScan 3D Single Finger D1 Scanner (FS3D) 2D grayscale rolled-equivalent prints
- Dataset Types
  - Original Images
  - Original LFFS Files
  - Markup LFFS Files

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To facilitate an investigation of minutia deviations, the Markup LFFS files were input into the MDT to create another dataset. To calculate minutia deviations, LFFS files from the same subject collected across different devices were opened in an MDT session. The minutiae were examined manually; using the surrounding fingerprint image features as context identical minutiae in each LFFS file were mated into pairs. This created a log of all common minutiae across the two devices. Then, to facilitate deviation calculations, an image landmark approximately in the center of the captured print image was chosen to serve as the common center point in each image. The minutia pairing process was performed on **130 subjects** across three devices – CMR2 vs. SEEK and CMR2 vs. TBS.

Experiments

Three sets of experiments were performed to explore and understand the contact and contactless fingerprint data and their paired minutia deviations.

1. The full datasets from the three stages of the CLPE vetting process were used to perform matching runs using the Neurotechnology MegaMatcher (MM) 4.5 algorithm. These experiments provided insight into the vetting process and established a foundational match performance for deviation filtered matching.
2. The full deviation logs from paired MDT sessions were exported and used to investigate the nature and context of the minutiae in those sets.
3. The MDT sessions were filtered by distance deviation to create two datasets and then used as probe data in matching runs using MM. Companion datasets with an equal number of random minutiae were used as controls. These experiments were to explore the effect of deviation on matching performance.

Conclusions

In general, several key observations/conclusions were identified as a result of this analysis effort:

- The MDT allowed for categorizing, visualizing, and filtering minutiae to produce biometric data for analysis and match performance evaluation (see Section 3.1.1 Minutia Deviation Tool).
    - **Conclusion:** MDT is a useful and unique biometrics analysis tool that should be maintained and distributed to the biometrics research community.

- The process used to prepare the LFFS datasets, while necessary, introduced rounding errors when converting minutiae details from MM to Extended Feature Set (EFS) Quick Search Profile 2 (QSP2). The resulting biometric matching resulted in the images performing better than Original LFFS (LFFS0), but improving when using Markup LFFS (LFFS1) vetted files (see Section 5.1.1 Comparison of TMR at Rank 1). In addition, the similarity score distributions collapsed to lowered values using LFFS files as compared to image datasets (see Section 5.1.3 Comparison of Similarity Scores).
    - **Conclusion:** Extraction algorithms should use industry standard profiles for defining minutiae to avoid rounding errors.
    - **Conclusion:** Raw images remain the best probe types for submissions and necessary for high priority applications (e.g., counterterrorism, criminal justice),

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but templates may be acceptable for medium-low priority applications (e.g., identity verification, access control).
  - **Conclusion:** The narrower similarity score distributions of LFFS files have implications for setting False Accept Rate (FAR) / False Rejection Rate (FRR) acceptance thresholds.

- Although the SEEK and TBS fingerprint images were collected using different technologies, the overall distributions of deviation magnitudes were the same (see Section 5.2.1 Magnitude Distribution of Deviations).
  - **Conclusion:** The unwrapping technique used by TBS was implemented well such that it closely mimics a contact-based rolled print capture and/or the minutia deviations from pressure deformation are not significant. This topic is deserving of additional research.

- The distributions of minutiae positions are centered on X≈0, Y≈500, R≈830 (see Section 5.2.2 Spatial Distribution of Minutiae) for all three device datasets (CMR2, SEEK, TBS).
  - **Conclusion:** The X position mean is due to the movement direction of the rolled print capture process and the unwrapping technique. The Y position mean is likely due to a decrease in feature resolution (and therefore fewer identified minutiae) at the curvature of the finger tip. This characteristic could be leveraged to improve matching algorithm speed.

- There is a linear correlation between radial distance from the image center and the magnitude of the minutiae deviation (see Section 5.2.3 Minutia Spatial Position vs. Deviation). The plots for both SEEK and TBS are identical. In comparison, there is a linear relationship between Y position and minutia deviation, but the correlation is opposite between TBS and SEEK.
  - **Conclusion:** The linear behavior suggests a uniform scaling factor between CMR2 and the comparison images. The Y position vs. deviation differences could be related to the TBS unwrapping technique. This topic is deserving of additional research.

- There is a direct, but weak correlation between similarity score and minutiae deviations for both SEEK and TBS datasets (see Section 5.2.4 Similarity Score). The average similarity score decreases with increasing deviation.
  - **Conclusion:** This is a reasonable and expected result. The less in register a set of minutiae are between probe and gallery image, the less similar the images are to the matcher.
  - **Conclusion:** There is significant variation (i.e., noise) in the data. Combined with the weak dependency, this suggests that minutia deviations are not the primary factor for the MM algorithm when determining similarity during biometric matching processes.

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- The average minutia deviation does affect the National Institute of Standards & Technology (NIST) Fingerprint Image Quality (NFIQ) score, but the correlation is different for SEEK and TBS datasets (see Section 5.2.5 NFIQ Score). The CMR2-TBS NFIQ scores increase with increasing minutia deviations, but the CMR2-SEEK scores decrease.
    - **Conclusion:** It is possible that the CLPE vetting process allowed a greater degree of error in the position and direction of minutiae when examining TBS images due to their atypical overall appearance. Alternatively, the TBS and SEEK images possess different quality discrepancies that affect the calculation of the NFIQ score to differing degrees.

- Datasets with lower average minutia deviations did not inherently produce better matching performance than those with higher average deviations. The deviation filtered dataset matching runs resulted in *63up* out performing *63up random* for both SEEK and TBS (see Section

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- 5.3 Matching Runs – Deviation Filtered Datasets).
    - **Conclusion:** Minutia deviations are not the primary factor for the MM algorithm when determining similarity during biometric matching processes.
    - **Conclusion:** A qualitative examination of images with minutia marks suggests that the clustering of minutiae or the effective network of nearest neighbors may play a larger role in the MM algorithm in determining similarity during biometric matching processes.
    - **Conclusion:** For contactless systems, the fidelity of the image is likely more important for match performance than the accuracy of the unwrapping transformation applied to the contactless representation of the fingerprint.

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1.0 INTRODUCTION

In 2012, the NIJ SSBT CoE undertook a biometric collection of fingerprint data from traditional scanners and next generation contactless devices – Contactless Fingerprint Collection, Round 1 (CFPv1). This data was the first of its kind across the two classes of scanners using the same subject population. The data was used to evaluate the match performance and interoperability of contactless versus contact fingerprint data. These results were published in a 2014 report – *Evaluation of Contact versus Contactless Fingerprint Data*.[1] However, this previous work did not explore the more detailed aspects of the captured fingerprints, such as the minutia markings, the deviations in spatial position of like minutia across probe and gallery fingerprint images, and the resulting effect on biometric matching.

The effect of minutia deviations on match performance due to contact scanning is a topic that needs to be investigated to better understand the interoperability, performance, and viability of contactless fingerprint scanners. To build upon that work and facilitate investigations by other researchers, the CoE has developed a tool for characterizing contact and contactless fingerprint minutia data, used that tool to analyze minutia deviations between probe and gallery datasets, and conducted biometric experiments to investigate the effect of minutia deviations on match performance.

1.1 About the SSBT CoE

The NIJ SSBT CoE is a center within the NLECTC System.[2] The Center provides scientific and technical support to NIJ's R&D efforts. The Center also provides technology assistance, information, and support to criminal justice agencies. The Center supports the sensor and surveillance portfolio and biometrics portfolio. The CoEs are the authoritative resource within the NLECTC System for both practitioners and developers in their technology area(s) of focus. The primary role of the CoEs is to assist in the transition of law enforcement technology from the laboratory into practice by first adopters.

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2.0 BACKGROUND

2.1 Data Source: WVU Fingerprint Collection and Minutia Companion

This report utilized two datasets for its evaluations – a WVU fingerprint collection and a companion minutia EBTS dataset. The data used in this report's evaluations originated from a fingerprint dataset collected by WVU under an earlier SSBT CoE initiative. For WVU IRB and data request purposes, the collection, protocol, and dataset are formally titled "ManTech Innovations Fingerprint Study." The dataset is available for use by third-party research organizations by submitting an email request to wvubiometricdata@mail.wvu.edu. The full report detailing the WVU fingerprint collection is publically available.[3] Fingerprint data was collected from 500 unique subjects in a controlled, sterile environment during the time period of April – July 2012 on the following devices:

- Rolled-ink fingerprint cards – Digitized at 500 pixels per inch (ppi) and 1000 ppi
- Legacy Fingerprint Devices:
    a. Cross Match Guardian R2 (CMR2) – Rolled and plain fingers
    b. i3 DigID Mini – Rolled and plain fingers
    c. L1 TouchPrint 5300 – Rolled and plain fingers
    d. SEEK II – Rolled and plain fingers
- Contactless Fingerprint Devices
    a. Touchless Biometric Systems (TBS) 3D Enroll Device – Individual fingers
    b. FlashScan 3D Single Finger D1 Scanner – Individual fingers
    c. FlashScan 3D 4-Finger Slap D4 Scanner – Plain fingers

The second part of the evaluation data was a companion dataset to the WVU primary fingerprint dataset called – "ManTech Innovations Fingerprint Study: Minutia Markup Dataset."[4] The dataset contains LFFS EBTS files and the collected grayscale image files. The LFFS files were vetted by a CLPE to remove incorrect or false minutia. Original and CLPE processed versions of the files, as well as the corresponding original image files, are contained in the dataset for testing and comparison purposes. This companion dataset can also be requested for use by third-parties by contacting WVU at wvubiometricdata@mail.wvu.edu. The EBTS files have the following features:

- Conformance to ANSI/NIST-ITL 1-2011.
- Type-9 minutia records encoded in the FBI EFS QSP2 standard with data in Field Block 9.300-9.399.
- Type-13 latent image record, in accordance to ANSI/NIST-ITL 1-2011.
- Fingerprint image possessing 500 ppi resolution in field 13.999.
- Minutiae markings produced by the Neurotechnology MM 4.5 feature extractor.

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2.2 Evaluation of Contactless vs. Contact Fingerprint Data

In 2012, the SSBT CoE undertook a biometric collection of fingerprint data from traditional scanners and next generation contactless devices. This effort is referred to as CFPv1 (contactless fingerprint project version 1). This data was the first of its kind across the two classes of scanners using the same subject population. The data was used to evaluate the match performance and interoperability of contactless versus contact fingerprint data. These results were published in a 2014 report – *Evaluation of Contact versus Contactless Fingerprint Data* (https://www.ncjrs.gov/pdffiles1/nij/grants/245146.pdf).[1] A summary of those evaluation results and conclusions is included here for reference.

NOTE: The lack of available 3D matchers and varying collection methodologies and data formats used among 3D collection devices required the evaluation to focus on a format common to all devices: the 2D legacy fingerprint image. Due to the limitations of 3D images converted to 2D images, the quality or efficacy of the 3D contactless fingerprint devices in capturing topological fingerprint details was not investigated.

Twenty matching runs were performed on the rolled and rolled-equivalent fingerprint data collected from devices and card-scans using the Neurotechnology MM Suite fingerprint algorithm (version 4.2) software. The various matching efforts are organized into the following categories:

- Galleries were matched against themselves to establish ground truth performance
- Legacy fingerprint (LFP) datasets were matched against LFP galleries
- Contactless fingerprint (CFP) datasets were matched against LFP galleries
- CFP dataset were matched against CFP galleries
- Select LFP datasets were matched against a CFP gallery

NOTE: Raw 3D images generated from optical structured light (i.e. FlashScan Single and D4) and other methods are not directly compatible with existing fingerprint matching algorithms. As a result, all analysis discussed in this report does not utilize this 3D fingerprint data directly, rather the analysis is performed on images obtained from each 3D system's transformation of the scanned data into 2D grayscale images that are intended by their vendors to be matchable against existing fingerprint databases.

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Matching results were analyzed and compared based on True Accept Rate (TAR) and NFIQ score. A summary of matching results is included here:

Table 1: CFPv1 Matching Runs Results

MATCHING RUNS	True Match at Rank 1 (Based on Matched Pairs)	False Match at Rank 1 (Based on Matched Pairs)
Gallery Runs		
GR1- Cross Match R2 Set 1 vs. Set 1	100%	0%
GR2- Cross Match R2 Set 2 vs. Set 2	100%	0%
GR3- Card Scan 500 dpi vs. 500 dpi	100%	0%
GR4- FlashScan Single vs. Single	100%	0%
GR5- TBS (HT1) vs. TBS (HT1)	100%	0%
2D LFP Runs		
LFPR1- I3 vs. G1	92.66%	7.34%
LFPR2- L1 vs. G1	96.58%	3.42%
LFPR3- Card Scan 500 dpi vs. G1	91.34%	8.66%
LFPR4- Cross Match SEEK vs. G1	97.80%	2.20%
CFP to LFP Runs		
CFPR1- FlashScan Single vs. G1	71.40%	28.60%
CFPR2- FlashScan D4 vs. G1	17.05%	82.95%
CFPR3- TBS (HT1) vs. G1	91.15%	8.85%
CFPR4- TBS (HT2) vs. G1	85.67%	14.33%
CFPR5- TBS (HT6) vs. G1	86.42%	13.58%
CFP to CFP Runs		
CFPR6- FlashScan D4 vs. G4	11.80%	88.20%
CFPR7- TBS (HT1) vs. G4	65.75%	34.25%
CFPR8- TBS (HT2) vs. G4	56.53%	43.47%
Additional GR5 Runs		
AR1- FlashScan Single vs. G5	65.64%	34.36%
AR2- Cross Match R2 Set 1 vs. G5	90.73%	9.27%
AR3- Cross Match SEEK vs. G5	91.20%	8.80%

In general, seven key observations/conclusions were identified as a result of this evaluation effort:

- This effort is the first quantitative demonstration by a third party that fingerprints collected under ideal conditions from LFP and CFP devices can be matched against each other in a statistically meaningful way.
    - Conclusion: The experimental methodology employed (data collection and analysis) can be used to determine a comparative match performance among LFP and CFP using 2D projections.

- Matching CFP legacy-equivalent images to LFP images provides less match performance than LFP images to LFP images.
    - Conclusion: More work is needed to improve the quality of captured images or the quality of 2D legacy-equivalent conversions. Additional research

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opportunities may exist in developing or modifying fingerprint matching algorithms that are less sensitive to skin elasticity.

- Matching CFP legacy-equivalent images between the various contactless devices provided very poor results as compared to currently available technologies.
    - Conclusion: Additional research may be necessary to provide better CFP to LFP conversion algorithm accuracy.

- The ink and paper collection provided lower similarity scores from the fingerprint matcher and had poorer NFIQ scores. We assume from this finding that ink and paper fingerprinting requires more skill and experience than collecting on live scan devices. Additionally, live scan fingerprint collection devices generally provide immediate quality feedback and the opportunity to recollect a poor fingerprint.
    - Conclusion: Rolled-ink tenprint cards may not be the "gold standard" ground-truth gallery for biometric testing or research

- The Cross Match SEEK II performed better than expected as a livescan collection device, as compared to the other legacy CFP systems. The reason for expectations of lower match performance was due to the smaller platen surface area.
    - Conclusion: SEEK may be suitable for field enrollments, and is more than adequate for field queries.

- The FlashScan D4 performed very poorly. The device had several failures during collection efforts and required vendor support. Also, due to the failures this device had the fewest number of collection subjects.
    - Conclusion: Data from prototypes can be significantly poorer than commercial systems using similar capture approaches, and therefore the purpose/objective of data collections should be taken into account when considering the inclusion of prototypes.

- The images collected by the TBS 3D Enroll are mirrored along the vertical axis, causing an inability to match against standard datasets. The Test Team corrected the images locally prior to testing. Images in the WVU dataset remain unchanged.
    - Conclusion: Devices developed for civilian access control applications, or for foreign markets, may not follow standard Appendix F requirements. Research, Development, Test, and Evaluation (RDT&E) must be aware of potential issues.

As one of the first research efforts to investigate the match performance and interoperability of contact and contactless fingerprint data, this work has made important first steps. However, there are many related areas or follow-on tasks that could be pursued. The dataset collection and foundational analysis should aid enterprise and research endeavors to improve biometric and identity management knowledge and capabilities.

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3.0 TEST ENVIRONMENT & APPROACH

3.1 System Test Environment

The lab evaluation environment consisted of the resources needed to evaluate the fingerprint images collected from the devices in the WVU dataset. The hardware environment for the evaluation consisted of a Windows 7 (64 bit) operating system executing on a Dell Precision T7500 64-bit with a dual quad core processor. It has 12 Gigabytes (GB) of system RAM, a 256 GB solid state drive, and two 1 Terabyte (TB) hard drives configured as a RAID 1 drive. The image datasets were temporarily hosted on the computers during matching run processing, but are permanently stored on an encrypted external hard drive for archival and security purposes. These computers hosted the Neurotechnology's MM algorithm and gallery manager.

The algorithm selected to verify and evaluate the performance of the matching was Neurotechnology MM version 4.5. The MM was utilized in the CFPv1 evaluations previously conducted; it was also selected based on its low cost, product maturity, performance, and experience integrating it into many products.

3.1.1 Minutia Deviation Tool

To explore the minutia deviations in the datasets and their effect on match performance, the SSBT CoE developed a custom software tool – the Minutia Deviation Tool (MDT). MDT is described in detail in its Software Design Description (SDD) report.[5] The MDT is a prototype software utility that aids a user in designating equivalent minutia pairs across two fingerprint biometric images and calculating the pair's minutia spatial deviations. This tool was used in these evaluations to calculation minutia deviations between traditional contact-based gallery and probe images (LFP and CFP) from the same subject. The tool also allows for those mated minutiae to be filtered based on deviation or position criteria to produce EBTS files with a subset of minutia markings. A summary of the tool and its key features relevant to this report's evaluations are included here for reference. The specific operation of the tool is not covered here, but can be found in the SDD.[5]

MDT allows a user to open two LFFS files or a pair of images with common separated value text files and presents them side-by-side to compare and analyze the minutia markings. Figure 1 shows two images from the same subject collected by the CMR2 and SEEK scanners. The vetted minutia sets are overlaid on the images. The user determines which minutia marks on each image are from the same fingerprint feature and then mates them. The deviation log and EBTS files can be filtered and exported using filter parameters specified by the user for follow-on analysis. These filter options include relative deviations between minutiae, absolute deviations between minutiae corrected for a common center point, or position coordinates.

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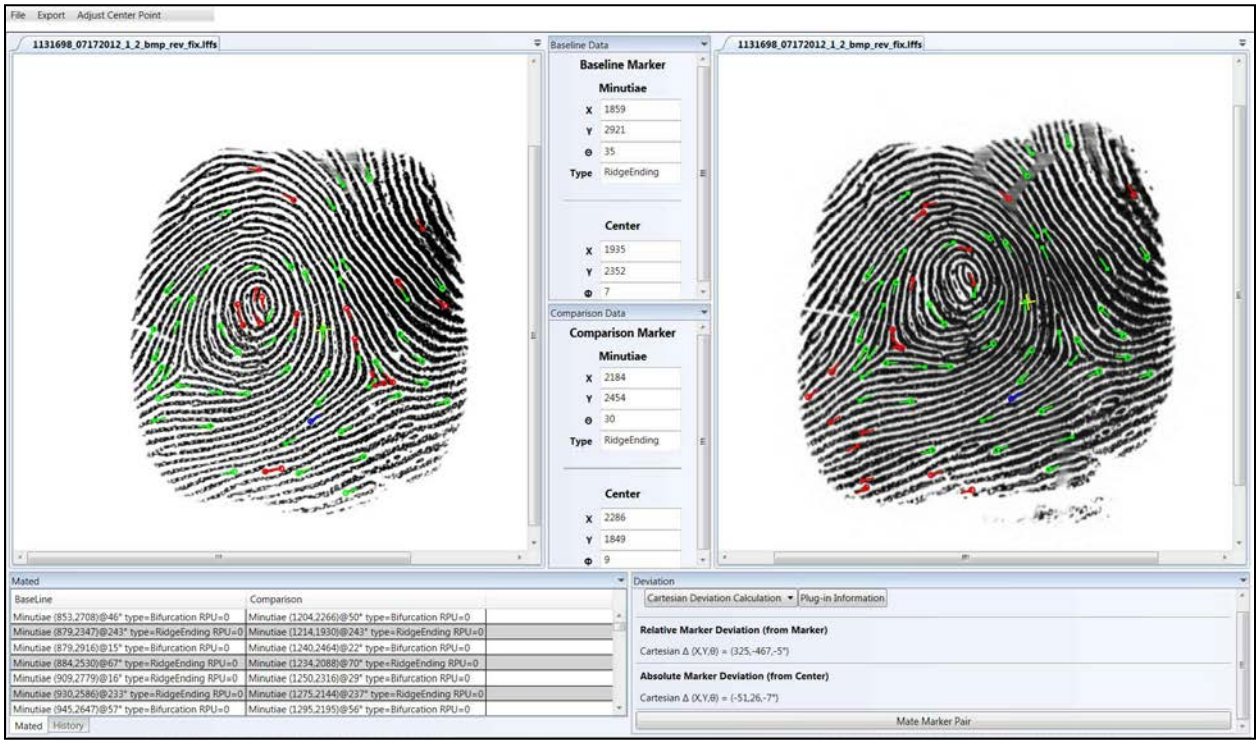

Figure 1: Example MDT Session

Two images from the same subject, but different scanners, are shown together. Minutia marks (red) can be selected (blue) to determine deviations and mated (green) to save the results to a log.

For research and analysis purposes, MDT allows the paired minutia markings from both images to be filtered based on deviation or positional criteria. Figure 2 shows the deviation filter window with the various parameters available to a user (using the Cartesian Deviation Calculation module). This MDT feature allows a user to explore the effect of varying deviations on the match performance of fingerprint EBTS datasets. Once filtered, only minutia pairs that meet the criteria are exported as a deviation log or EBTS file. The filtered (or unfiltered) minutia sets can then be analyzed or used for input into a matcher. The groups of filter parameters in this module are as follows:

- Relative Deviations – The difference in raw position coordinates and minutia angle between the comparison minutia and baseline minutia.
- Absolute Deviations – The difference in position and angle between comparison and baseline minutia corrected for a common designated center point location and rotation. The variable *D* is the deviation distance between the two marks.
- Position Band – Spatial location of a minutia corrected for center point.

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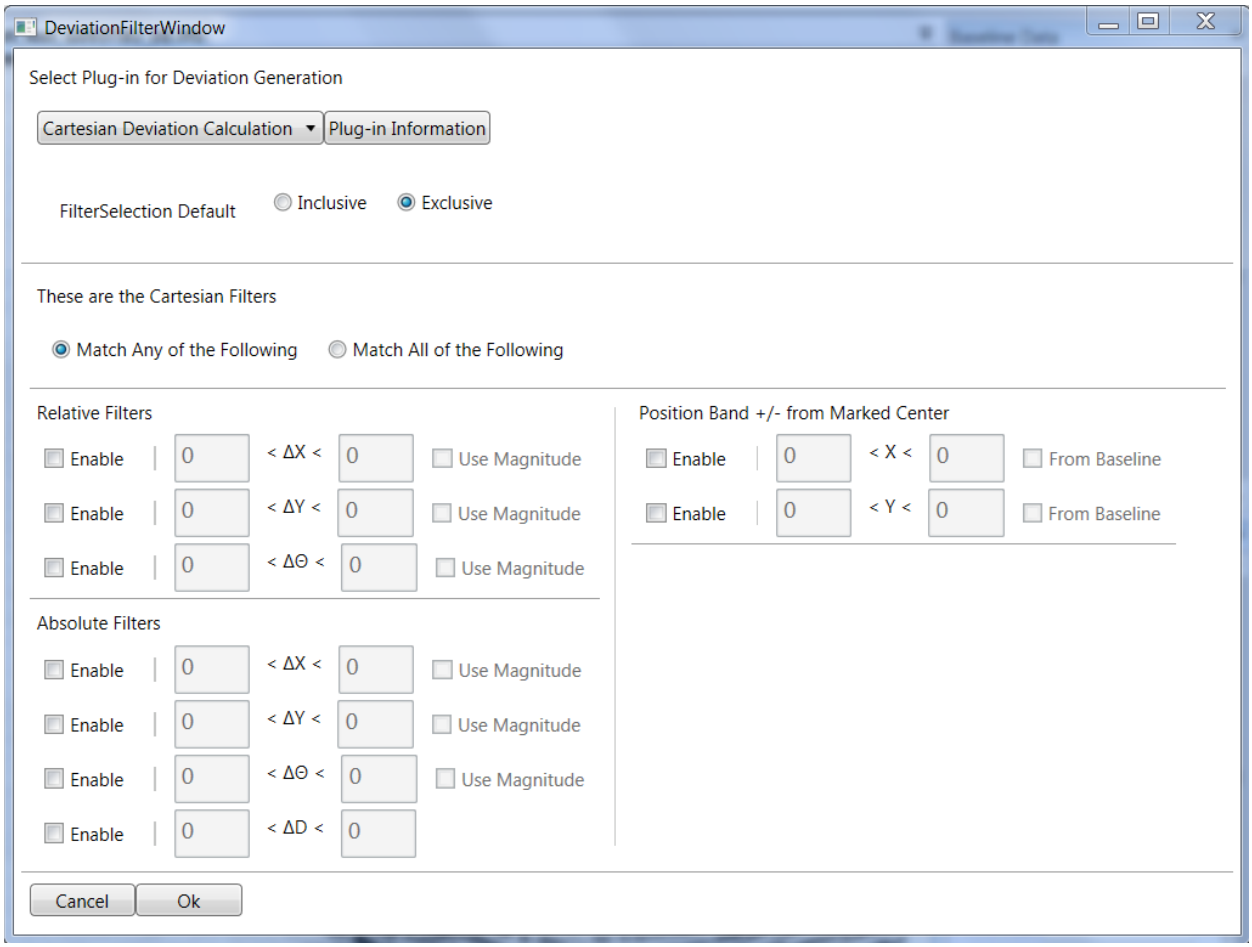

Figure 2: MDT Deviation Filter Window

3.2 Fingerprint Data

The fingerprint data used by this evaluation consisted of finger images collected in the CFPv1 WVU biometric collection and then processed to produce LFFS EBTS files that had been reviewed by a CLPE. A detailed summary of the preparation of the Contactless Minutia Dataset is available in the report, *Contactless Fingerprint Minutia Marking Report*.[4] Data processing and analysis was limited to the right index rolled (or rolled-equivalent) fingerprints collected from ~500 subjects using three devices. This was chosen due to resource and schedule limitations. The device subsets were selected to facilitate baseline and comparative analyses of traditional and contactless systems.

The images from four devices underwent several processing and data integrity steps before use in the matching runs and analysis contained herein. Details of data processing and selection of the original collection can be found in the CFPv1 evaluation report,[1] but are summarized here:

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1. CFPv1 Dataset
    a. Two sets of images were collected for each subject from each device. For consistency with CFPv1, Set 1 data was used throughout these evaluations.
    b. All images are 500 ppi.
    c. All images are 2D grayscale images produced by the CFP device software transformations, 3D images generated by CFP devices were not used.
    d. TBS images in their native form were found to be mirrored along the horizontal axis. These images were flipped to be consistent with biometrics standards.
2. Original Images
    a. Device image subsets were reviewed to correct any file naming errors to ensure that subject identification (IDs) were properly represented.
    b. Duplicate subject IDs were removed.
3. Original LFFS files
    a. Image sets submitted to MM minutia extractor to produce EBTS files with minutiae. Type 9 records encoded using EFS QSP2 specifications. Type 13 record contains original image.
4. Markup LFFS files
    a. Original LFFS files reviewed by CLPE using the ACE-V methodology to delete incorrect or false minutia markings and to verifying correct minutia classification for each marking. Details of this effort are contained in a previous report.[4]
    b. LFFS files output from the Universal Latent Workstation (ULW) 6.4.1 processed to correct missing Field 9.325/9.326 for No Cores and/or No Deltas.
    c. Removed files that contained no minutia markings or only one (1).
    d. All device datasets cross referenced to remove any subject files that did not exist in all three sets to guarantee 100% N:N compatibility.

After following the data processing steps outlined above, the resulting data consisted of three datasets (3) for each of four (4) devices. Each dataset contains 468 images or EBTS files for the same subject finger for 100% N:N compatibility.

- Devices
    - CMR2 rolled prints
    - SEEK rolled prints
    - TBS 2D grayscale rolled-equivalent prints
    - FS3D 2D grayscale rolled-equivalent prints
- Dataset Types
    - Original Images
    - Original LFFS Files
    - Markup LFFS Files

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3.3 Minutia Pairing for Deviation Analysis

To facilitate an investigation of minutia deviations, the Markup LFFS files were input into the MDT to create another dataset. To calculate minutia deviations, LFFS files from the same subject collected across different devices were opened in an MDT session. The minutiae were examined manually; using the surrounding fingerprint image features as context identical minutiae in each LFFS file were mated into pairs. This created a log of all common minutiae across the two devices. Then, to facilitate deviation calculations, an image landmark approximately in the center of the captured print image was chosen to serve as the common center point in each image. The center point was positioned and rotated in each of the baseline and comparison images using the landmark. The emphasis was on identifying a center location that could be reliable aligned in both position and rotation and that was recognizably present across all three device images; maintaining the same x-axis used during actual fingerprint capture was not a priority. However, the tendency was to not veer to far from the image horizontal axis. The CMR2 was used as the baseline in pairings with both the SEEK and TBS. The center point was consciously kept at the same position and rotation for CMR2 in both pairings.

The minutia pairing process was performed on **130 subjects** across three devices – CMR2 vs. SEEK and CMR2 vs. TBS. More data would have been desirable, but resources and schedule limited the effort. The FS3D data had poorer image quality and fewer minutia per image and therefore was not processed so that efforts could be focused on analyzing the difference between SEEK and TBS minutiae relative to CMR2. As a side note, processing a single LFFS pairing took an operator approximately 15 – 20 minutes to pair all of the common minutiae and adjust the center points for the two images. This companion MDT dataset, "ManTech Innovations Fingerprint Study: MDT Minutia Pairs Dataset," can also be requested for use by third-parties by contacting WVU at wvubiometricdata@mail.wvu.edu. However, use of the data will require the MDT software.

3.4 Matching Run Evaluation Methodology

The MM algorithm was utilized to evaluate the match performance of the baseline processed fingerprint data and minutia deviation-filtered datasets. The focus of the evaluation was on the comparative performance of the fingerprint data from different devices containing different minutiae markings and not the performance of the well-established biometric matching algorithm. A custom-made biometric test environment was utilized that incorporated the matcher software development kits (SDKs) with an SQL database for storing matching run results. This test environment had the same framework as the one used in CFPv1, but modified to utilize MM 4.5 (vs. MM 4.2 in previous work) and to be able to accept LFFS EBTS files as gallery and probe submissions.

For a given matching run, the gallery was created by enrolling a set of images. MM had no issues with enrolling the pre-determined images or EBTS files and was a relatively straightforward process. The SQL gallery database was double checked to confirm that there were no duplicate enrollments. The probe datasets were submitted using the same biometric test environments against the previously loaded gallery. A new gallery was created for each probe

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set to ensure a blank slate for matching activities. MM did not accept probe submissions that did not possess a fingerprint, as determined by its own internal quality checks.

The output of a matching run was an SQL database populated with matching results and data parameters. The database was used to generate matching run reports that were used as inputs to a robust excel spreadsheet used to generate matching run statistics and analyses. Data integrity checks were used in all matching runs to ensure that the results were consistent with the known probe and gallery image set inputs and that all subjects present in the probe set also existed in the gallery set. The primary matching run metrics used in subsequent analyses were the True Match Rate at Rank 1 (TMR), False Match Rate at Rank 1 (FMR), Non-Match Rate (NMR), Similarity Score Mean, Similarity Score Standard Deviation, True Match (TM) rate at ranks 1 – 10, and Detection Error Tradeoff (DET) curves.

3.4.1 Match Rates

The number of TMs was calculated as the number of matches at rank 1 returned by the algorithm where the probe ID number was equal to the gallery ID number. Similarly the number of False Matches was the number of matches at rank 1 where the ID numbers were not equal. The TMR and FMR were determined by dividing the number of matches in each case by the total number of probe submissions.

3.4.2 Similarity Score

The similarity score is a metric for the probability that a matched pair of biometrics originated from the same person. Each algorithm utilizes its own (proprietary) method to arrive at a similarity score, thus resulting in different scales and common values. Based on the Gallery vs. Gallery matches (see Section 4.1.1 Gallery Matching Runs), the scores range from 0 – 7,500 for MM, with a higher score indicating a higher confidence of the match being a TM. For each matching run, the mean similarity score and its standard deviation were calculated for comparison purposes. Generally, a matcher threshold (specific similarity score value) is used to truncate all matches below the threshold to a null value to guarantee a non-match result. Because the matcher similarity score threshold was set to zero all matches returned a similarity score value that was needed and used in this analysis.

To aid in visualization, the scores were binned across the range of common values as determined by the maximum scores observed in the various matching runs. In this evaluation the Original Image Gallery vs. Gallery matching results produced the largest similarity scores and thus provided a guideline for the axis settings and bin values for created the graphs. According to MM documentation, the matching threshold of its system is directly linked to the FAR, the probability that biometrics from different subjects are erroneously accepted as a TM. Neurotechnology provides an equation and resulting FAR-Threshold equivalence table in the SDK documentation.[6]

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Table 2: MegaMatcher False Accept Rate vs. Similarity Score

FAR	Matching Threshold Score
100%	0
10%	12
1%	24
0.1%	36
0.01%	48
0.001%	60
0.0001%	72
0.00001%	84
0.000001%	96

3.4.3 DET Curve

In general signal detection, Receiver Operating Characteristic (ROC) curves are an established method of analyzing the performance trade-off between true and false positives for an imperfect pattern matching system when varying a detection threshold. A variation of an ROC curve commonly used in biometrics engineering is the DET curve. This plot measures the FRR as a function of FAR. The data to generate a DET curve for a given matching run is generated by measuring all of the matches that are accepted and rejected above range of similarity score thresholds and then plotting the corresponding (FAR, FRR) data points. The resulting plot can be used by system implementers and engineers to select the proper score threshold for a given intended application.

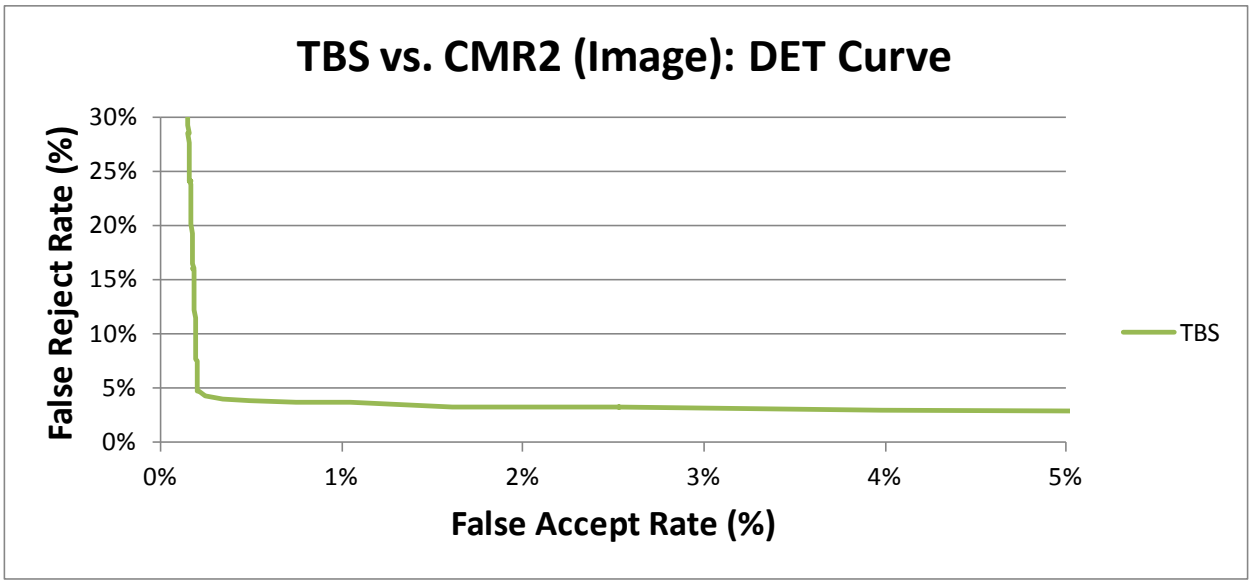

Figure 3: Example DET Curve

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4.0 EXPERIMENT RESULTS

Three sets of experiments were performed to explore and understand the contact and contactless fingerprint data and their paired minutia deviations.

1. The full datasets from the three stages of the CLPE vetting process (see Section 3.2 Fingerprint Data) were used to perform matching runs. These experiments provided insight into the vetting process and established a foundational match performance for deviation filtered matching.
2. The full deviation logs from paired MDT sessions (see Section 3.3 Minutia Pairing for Deviation Analysis) were exported and used to investigate the nature and context of the minutiae in those sets.
3. The MDT sessions were filtered by distance deviation to create two datasets and then used as probe data in matching runs. Companion datasets with an equal number of random minutiae were used as controls. These experiments were to explore the effect of deviation on matching performance.

4.1 Matching Runs – CFP Markup Datasets

Matching runs were performed using the MM test environment with different data from different devices and file types. These tests were performed to establish a baseline performance and to evaluate the effect (if any) of processing the starting fingerprint images to LFFS files and then on to CLPE vetted LFFS files.

4.1.1 Gallery Matching Runs

Probe Set	Probes	Gallery Set	Enrollment	TM Rank 1	Score, Mean	Score, Std Dev
TBS (Image Original)	468	TBS (Image Original)	468	100%	2938	815
FS3D (Image Original)	468	FS3D (Image Original)	468	100%	2883	1014
SEEK (Image Original)	468	SEEK (Image Original)	468	100%	2441	834
CMR2 (Image Original)	468	CMR2 (Image Original)	468	100%	2276	717
TBS (LFFS Original)	468	TBS (LFFS Original)	468	100%	707	10
SEEK (LFFS Original)	468	SEEK (LFFS Original)	468	100%	697	15
CMR2 (LFFS Original)	468	CMR2 (LFFS Original)	468	100%	693	13
SEEK (LFFS Markup)	468	SEEK (LFFS Markup)	468	100%	674	27
CMR2 (LFFS Markup)	468	CMR2 (LFFS Markup)	468	100%	672	22
FS3D (LFFS Original)	468	FS3D (LFFS Original)	468	100%	662	27
TBS (LFFS Markup)	468	TBS (LFFS Markup)	468	100%	661	31
FS3D (LFFS Markup)	468	FS3D (LFFS Markup)	468	100%	588	90

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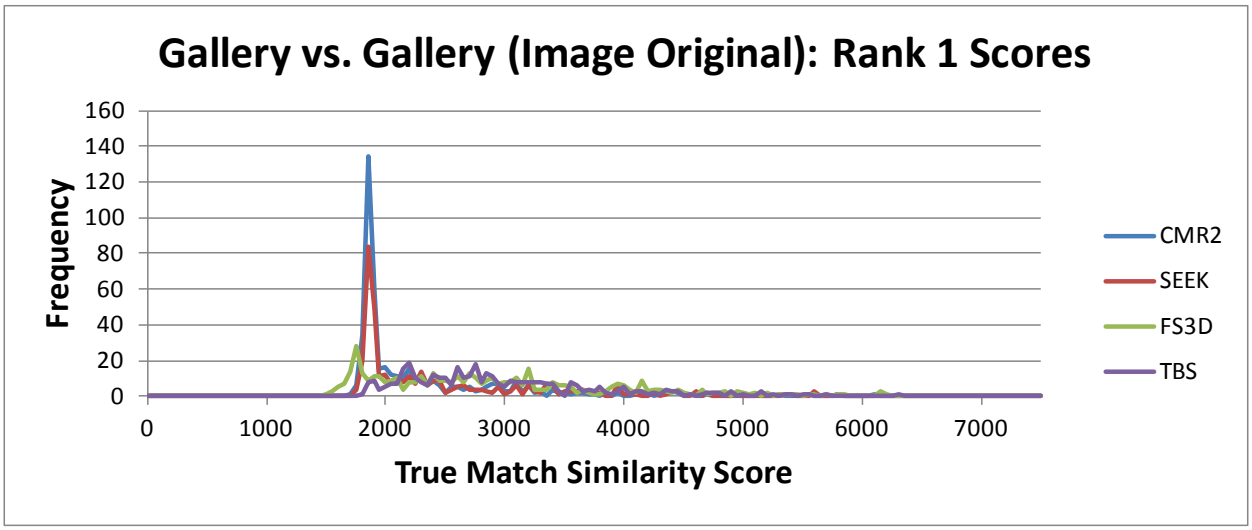

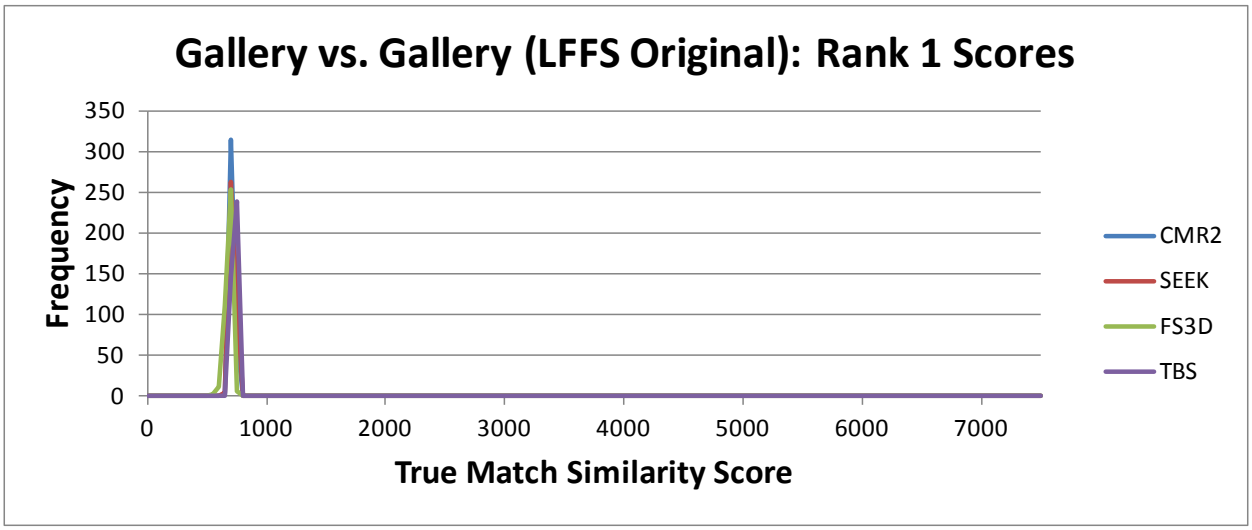

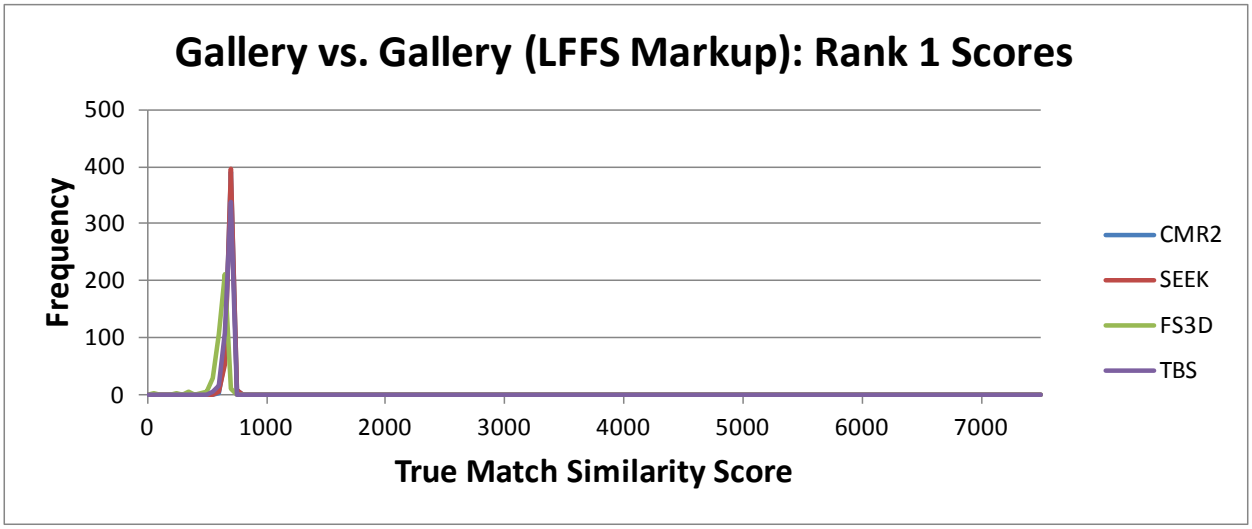

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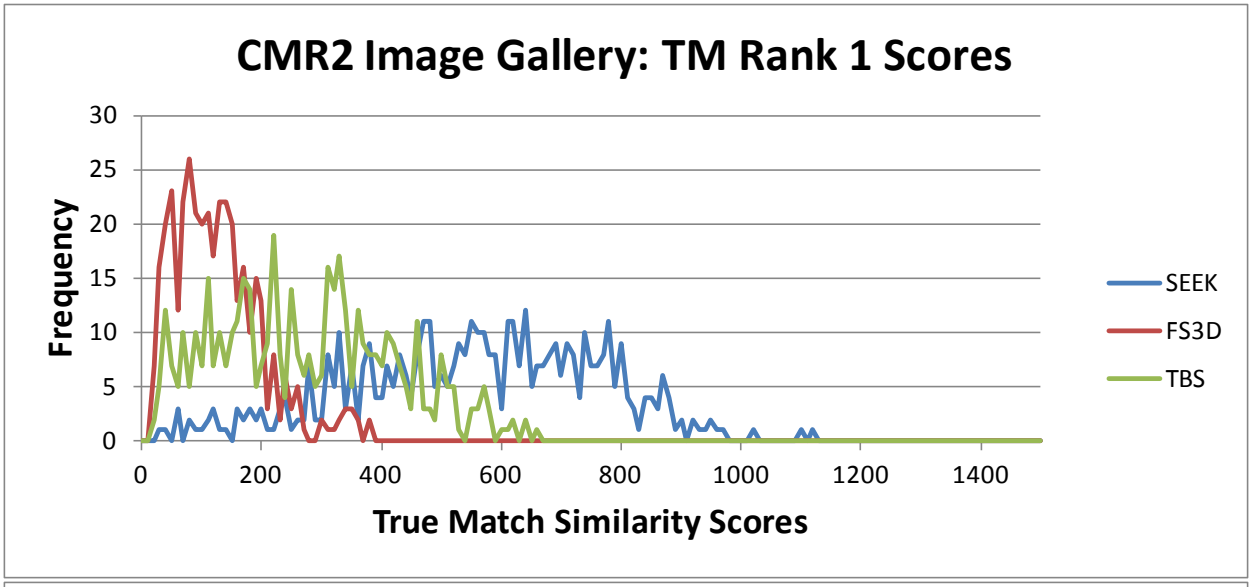
4.1.2 Matching Runs: Image, Original

4.1.2.1 CMR2 Gallery

Full match run details are available in Appendix A.2.1 CMR2 Gallery.

Probe Set	Probes	Gallery Set	Enrollment	TM Rank 1	Score, Mean	Score, Std Dev
SEEK (Image Original)	468	CMR2 (Image Original)	468	99.8%	553	205
FS3D (Image Original)	468	CMR2 (Image Original)	468	81.2%	126	73
TBS (Image Original)	468	CMR2 (Image Original)	468	96.6%	273	147



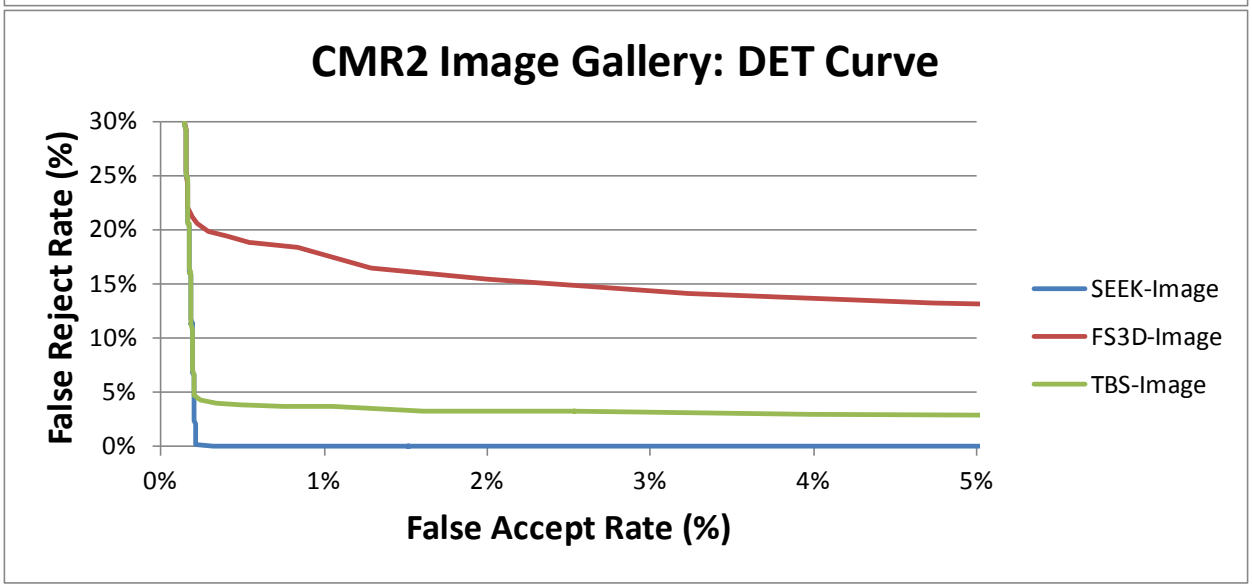


Figure 4: Match Run Summary - CMR2 Image Gallery

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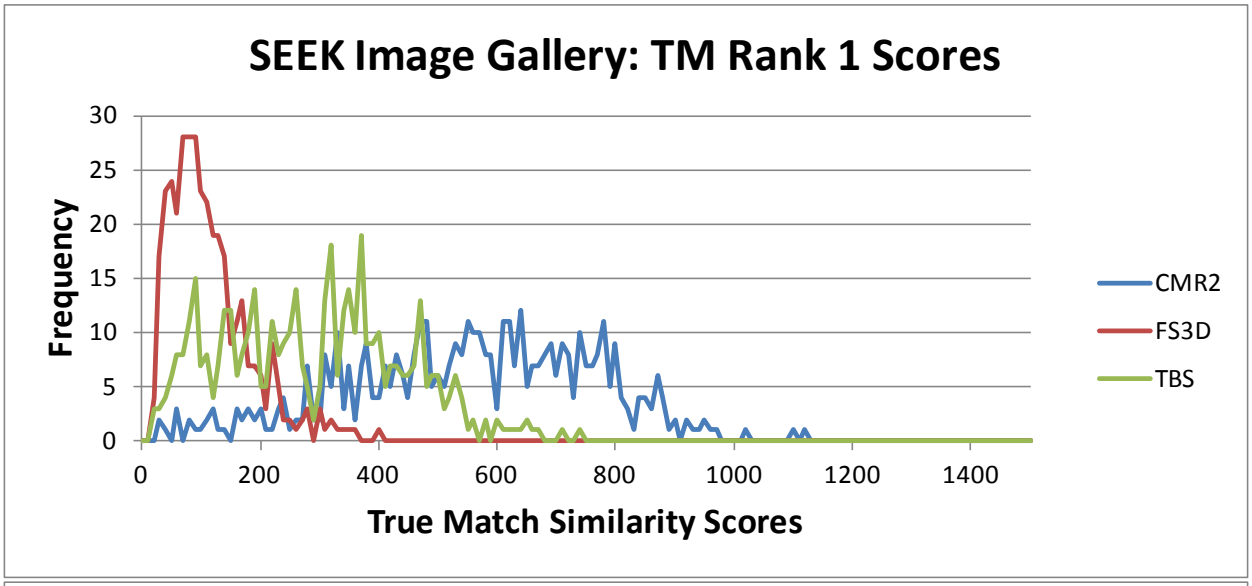
4.1.2.2 SEEK Gallery

Full match run details are available in Appendix A.2.2 SEEK Gallery.

Probe Set	Probes	Gallery Set	Enrollment	TM Rank 1	Score, Mean	Score, Std Dev
CMR2 (Image Original)	468	SEEK (Image Original)	468	100.0%	552	207
FS3D (Image Original)	468	SEEK (Image Original)	468	77.8%	114	68
TBS (Image Original)	468	SEEK (Image Original)	468	95.9%	289	152



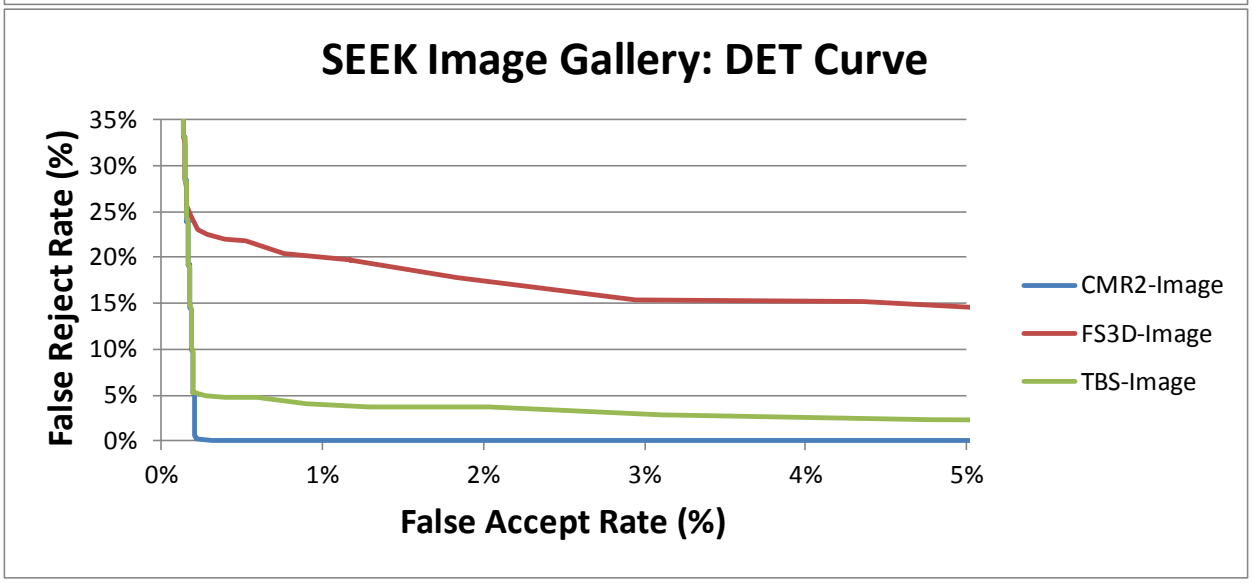


Figure 5: Match Run Summary - CMR2 Image Gallery

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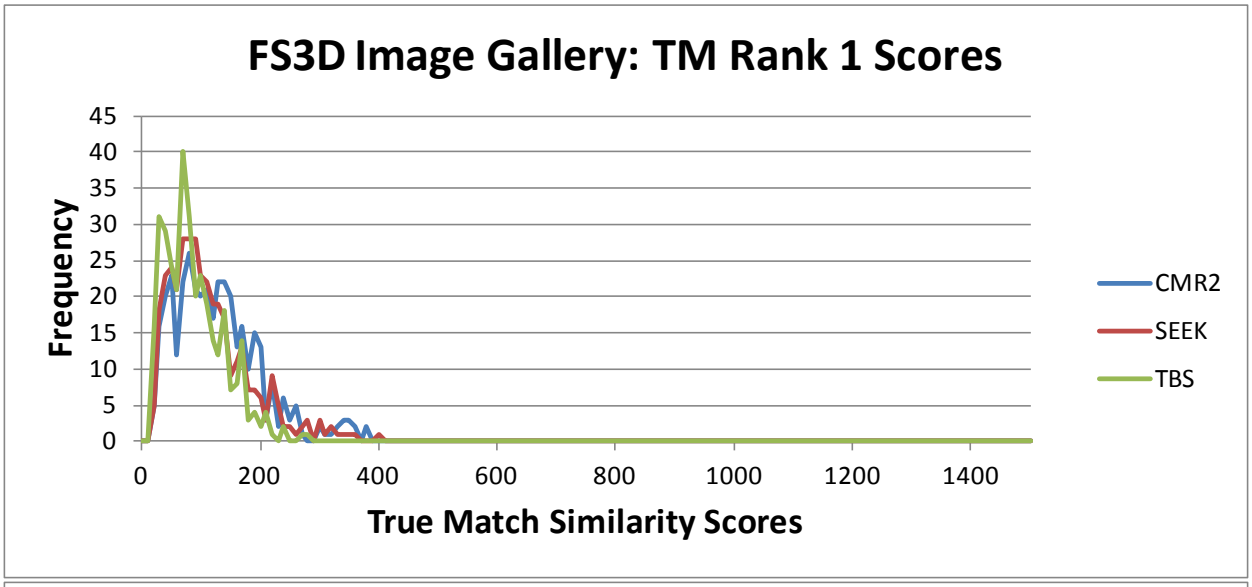
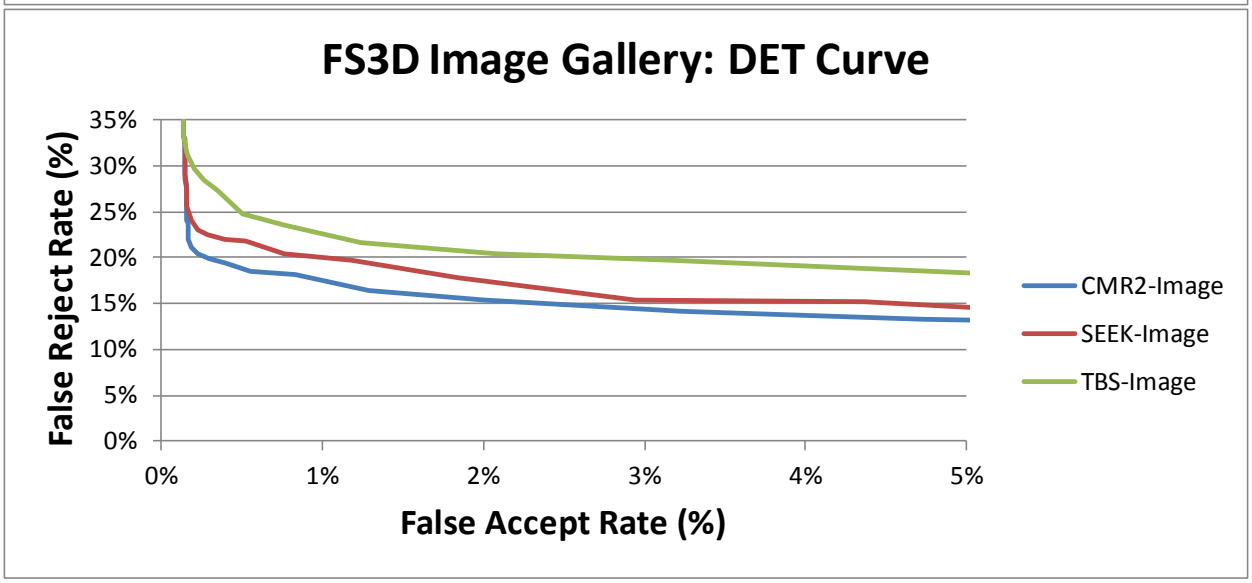
4.1.2.3 FS3D Gallery

Probe Set	Probes	Gallery Set	Enrollment	TM Rank 1	Score, Mean	Score, Std Dev
CMR2 (Image Original)	468	FS3D (Image Original)	468	80.8%	127	73
SEEK (Image Original)	468	FS3D (Image Original)	468	78.2%	114	69
TBS (Image Original)	468	FS3D (Image Original)	468	73.7%	88	50





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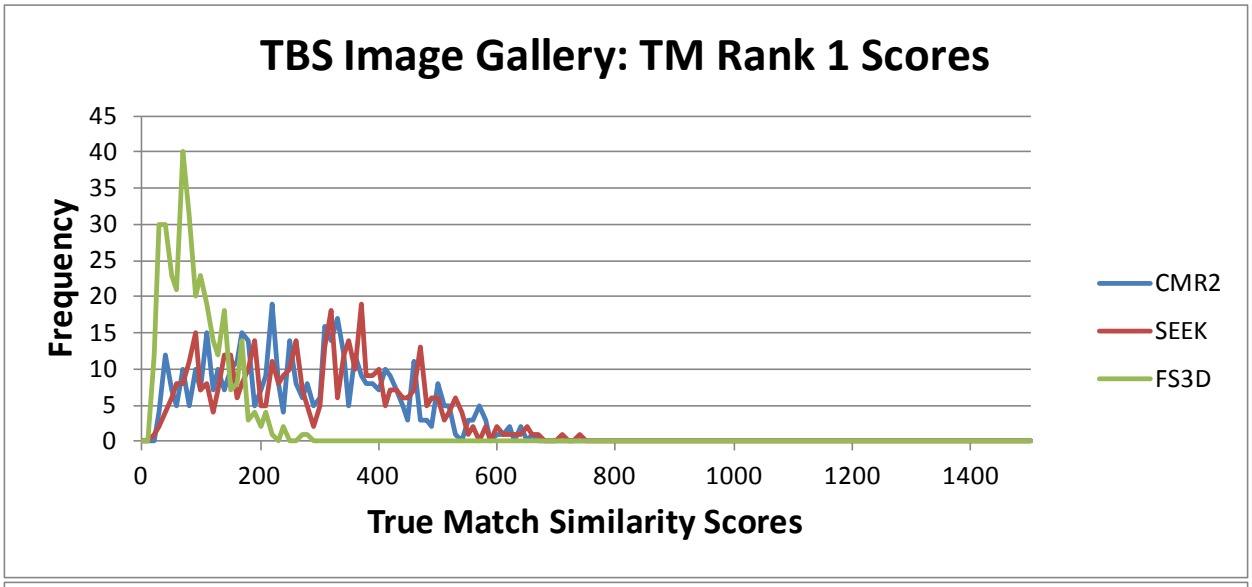
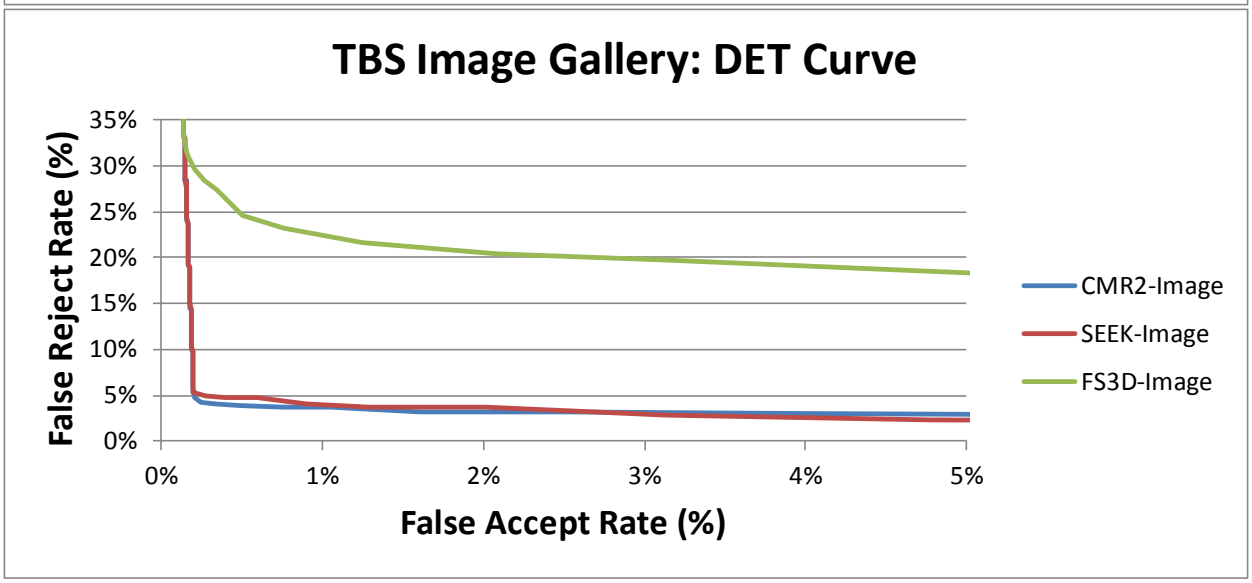
4.1.2.4 TBS Gallery

Probe Set	Probes	Gallery Set	Enrollment	TM Rank 1	Score, Mean	Score, Std Dev
CMR2 (Image Original)	468	TBS (Image Original)	468	95.9%	275	146
SEEK (Image Original)	468	TBS (Image Original)	468	95.3%	291	150
FS3D (Image Original)	468	TBS (Image Original)	468	72.6%	89	49





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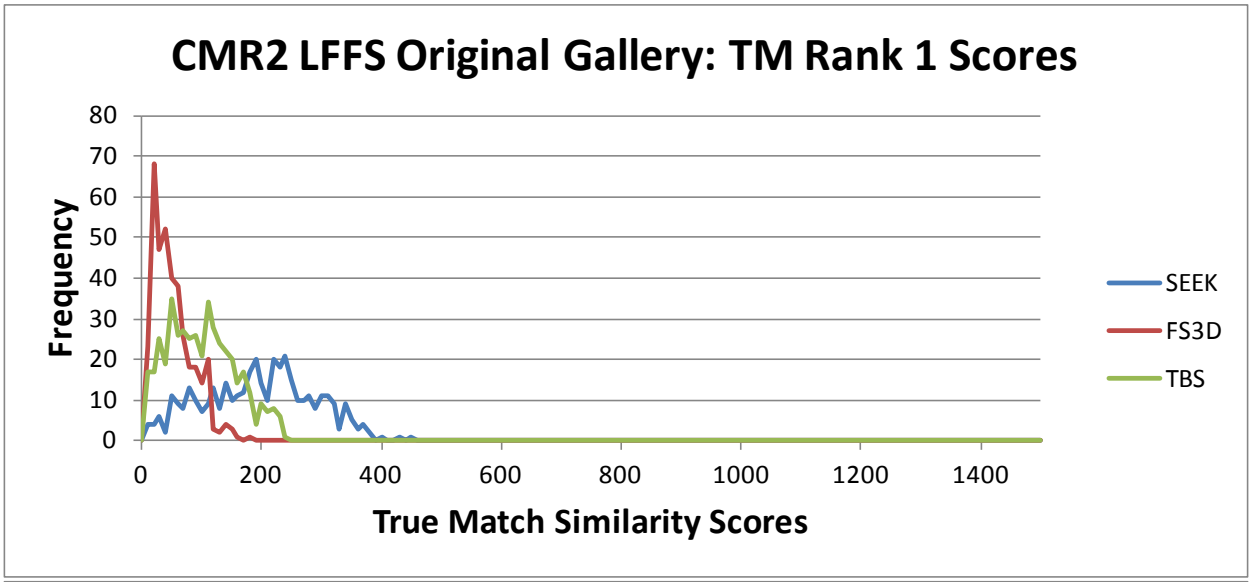
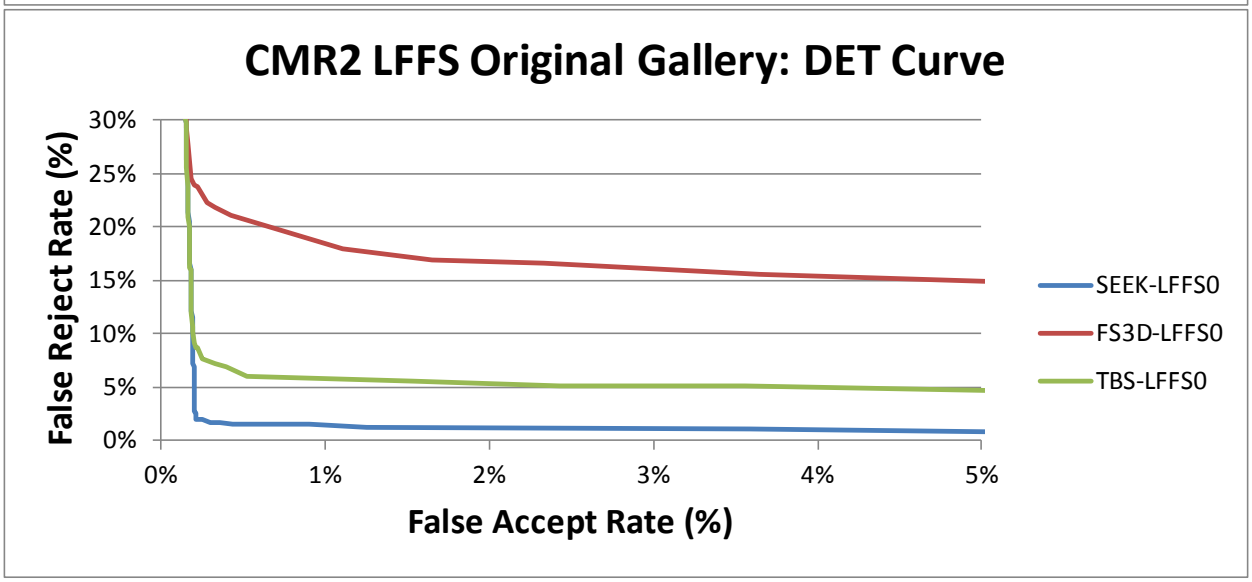
4.1.3 Matching Runs: LFFS, Original

4.1.3.1 CMR2 Gallery

Probe Set	Probes	Gallery Set	Enrollment	TM Rank 1	Score, Mean	Score, Std Dev
SEEK (LFFS Original)	468	CMR2 (LFFS Original)	468	99.4%	197	90
FS3D (LFFS Original)	468	CMR2 (LFFS Original)	468	80.8%	52	33
TBS (LFFS Original)	468	CMR2 (LFFS Original)	468	94.9%	100	56





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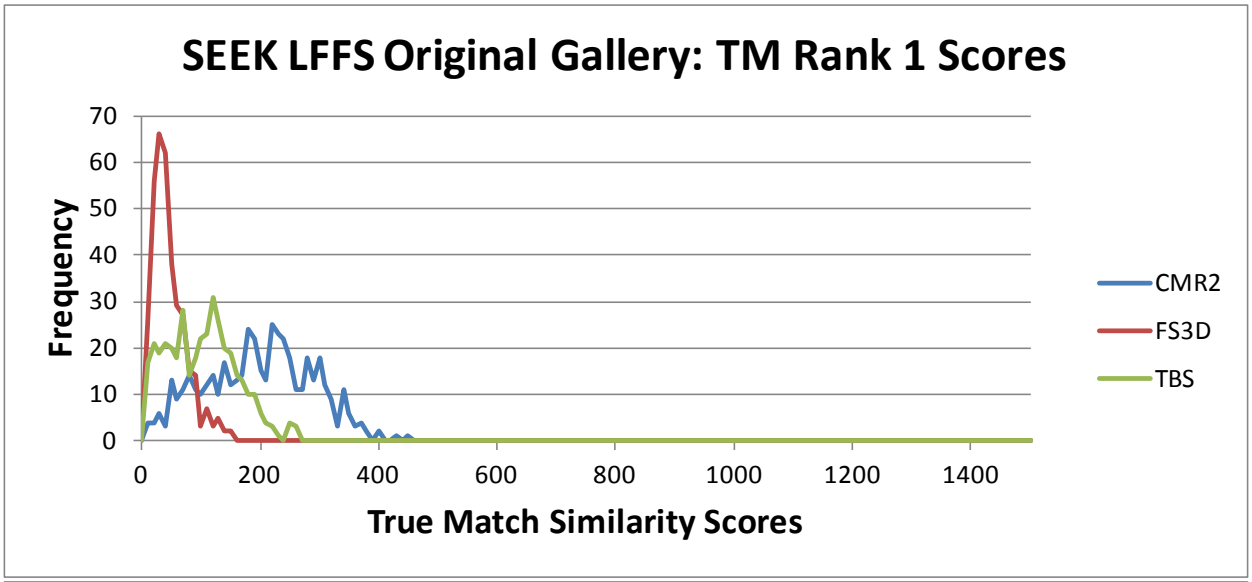
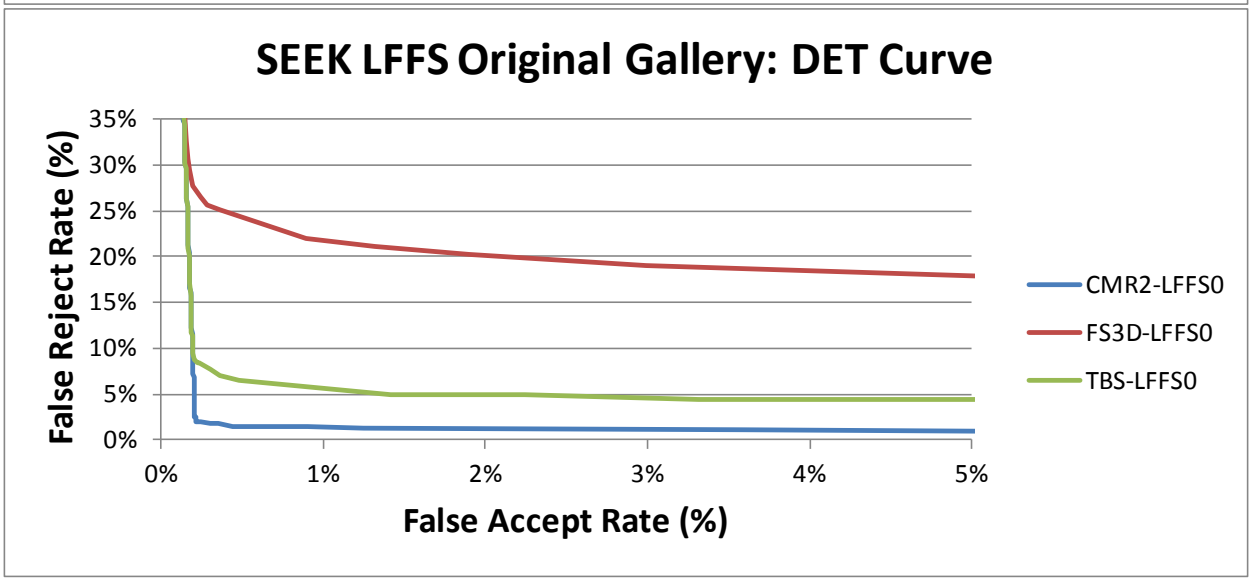
4.1.3.2 SEEK Gallery

Probe Set	Probes	Gallery Set	Enrollment	TM Rank 1	Score, Mean	Score, Std Dev
CMR2 (LFFS Original)	468	SEEK (LFFS Original)	468	99.1%	197	89
FS3D (LFFS Original)	468	SEEK (LFFS Original)	468	75.9%	46	29
TBS (LFFS Original)	468	SEEK (LFFS Original)	468	96.2%	101	58





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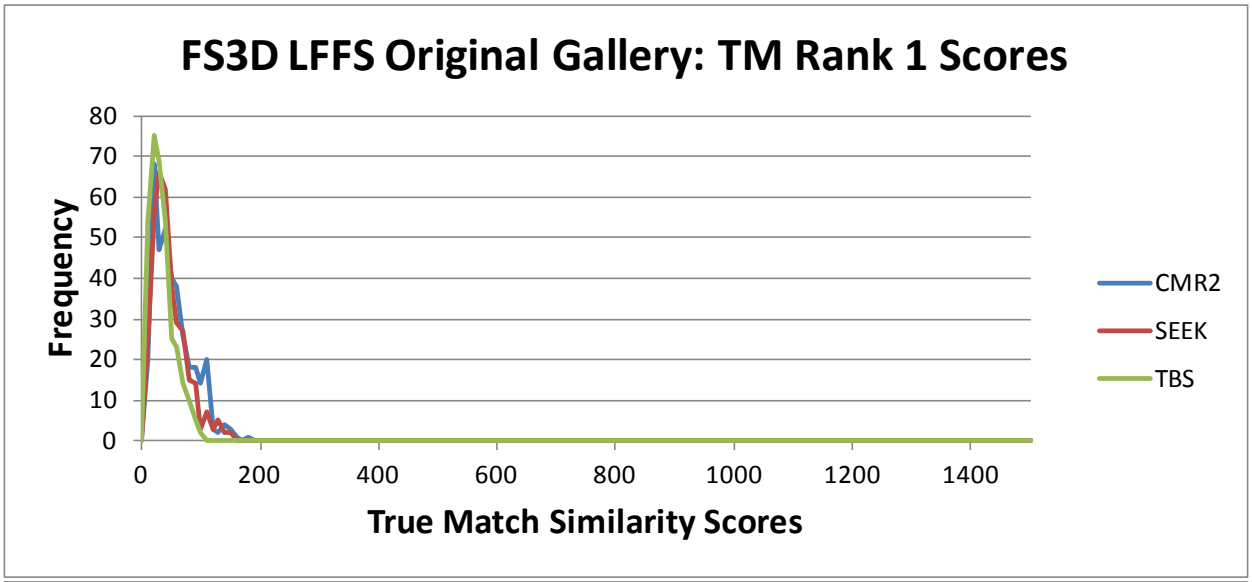
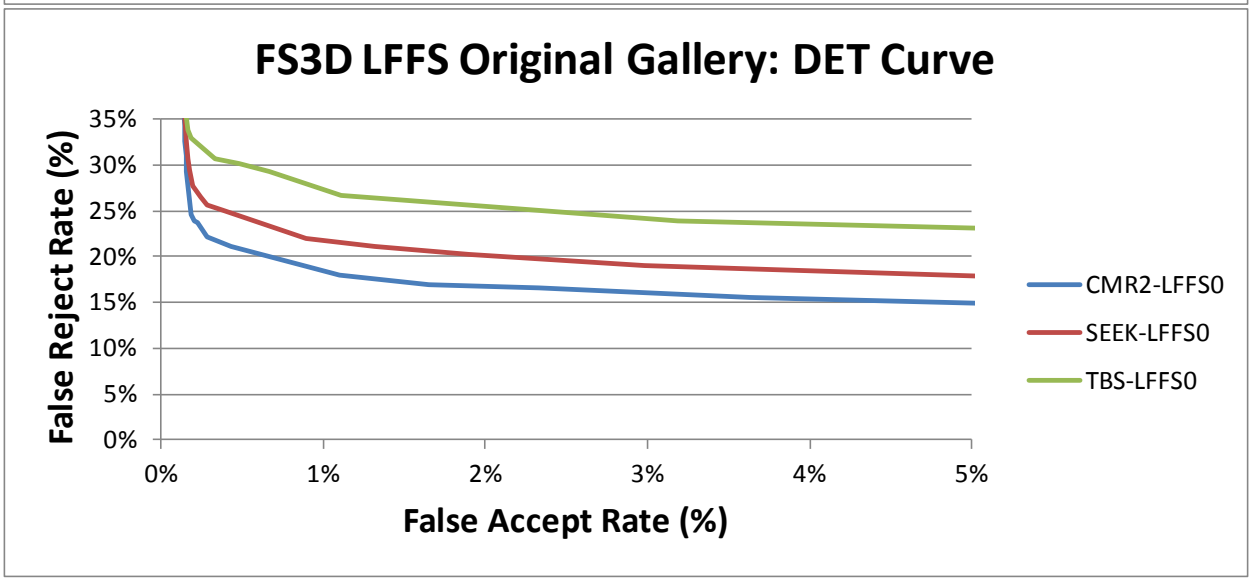
4.1.3.3 FS3D Gallery

Probe Set	Probes	Gallery Set	Enrollment	TM Rank 1	Score, Mean	Score, Std Dev
CMR2 (LFFS Original)	468	FS3D (LFFS Original)	468	80.1%	52	33
SEEK (LFFS Original)	468	FS3D (LFFS Original)	468	75.4%	46	29
TBS (LFFS Original)	468	FS3D (LFFS Original)	468	70.7%	34	20





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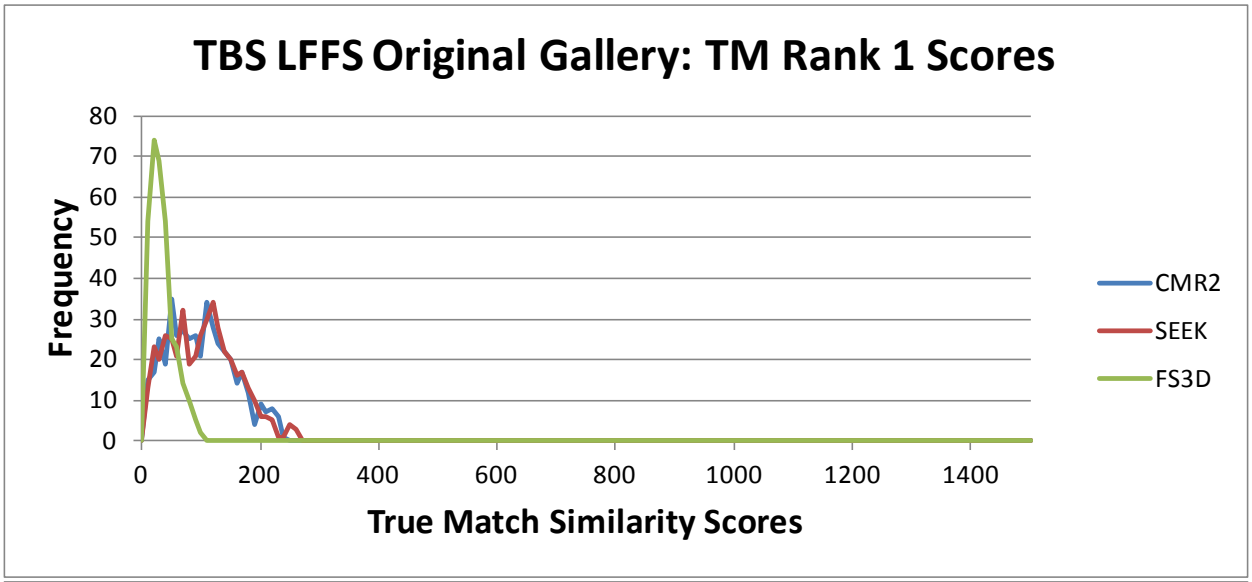
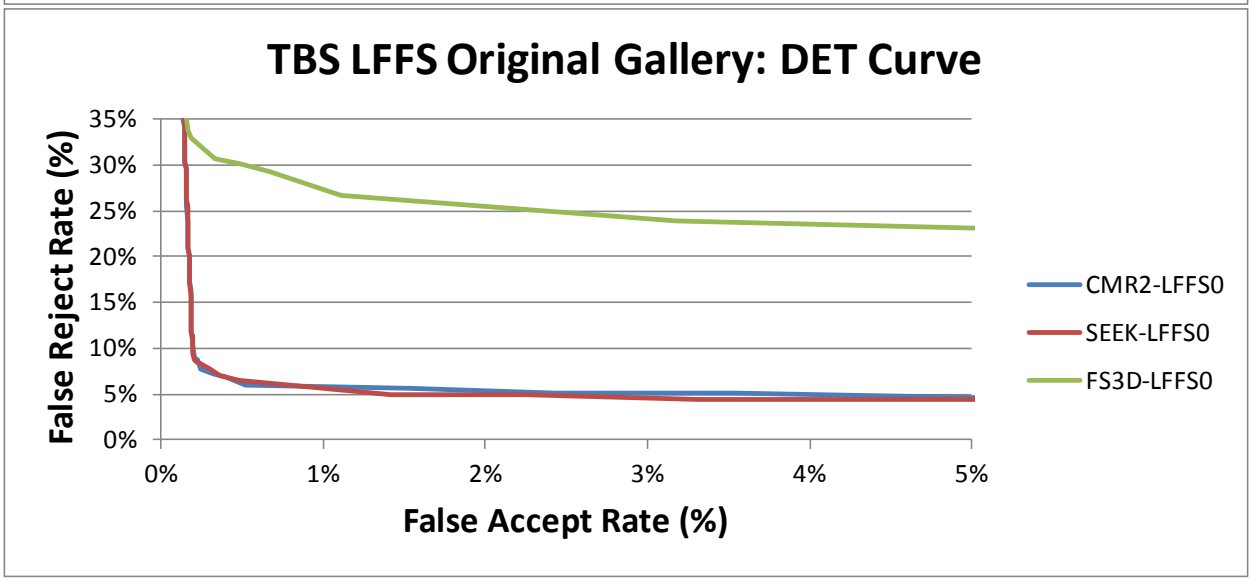
4.1.3.4 TBS Gallery

Probe Set	Probes	Gallery Set	Enrollment	TM Rank 1	Score, Mean	Score, Std Dev
CMR2 (LFFS Original)	468	TBS (LFFS Original)	468	94.4%	101	56
SEEK (LFFS Original)	468	TBS (LFFS Original)	468	94.4%	103	57
FS3D (LFFS Original)	468	TBS (LFFS Original)	468	70.5%	34	20





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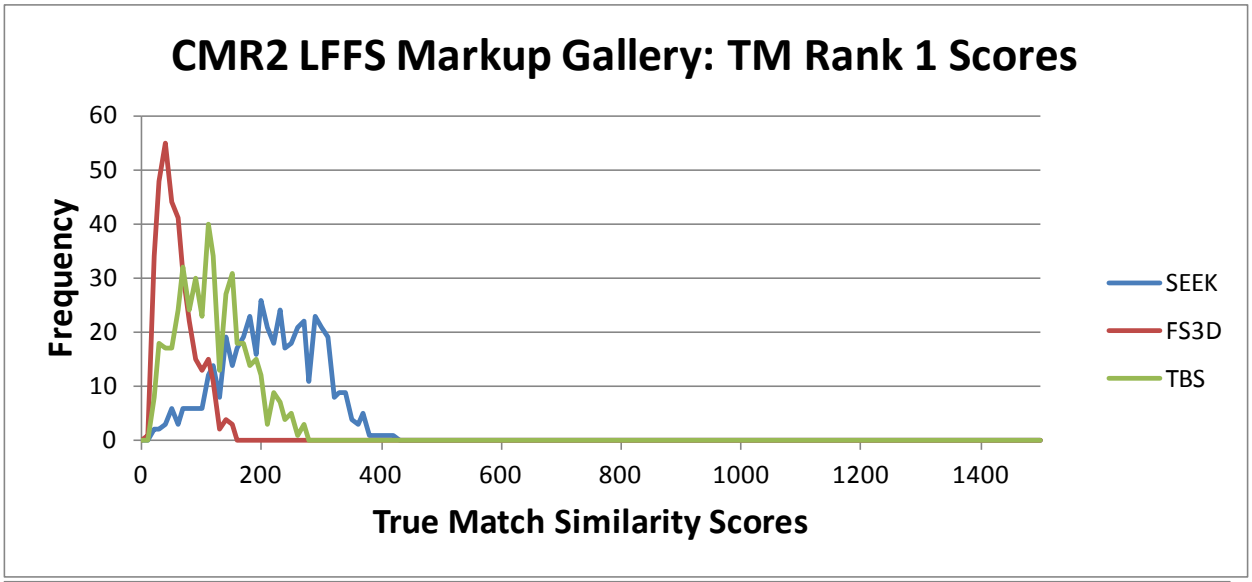
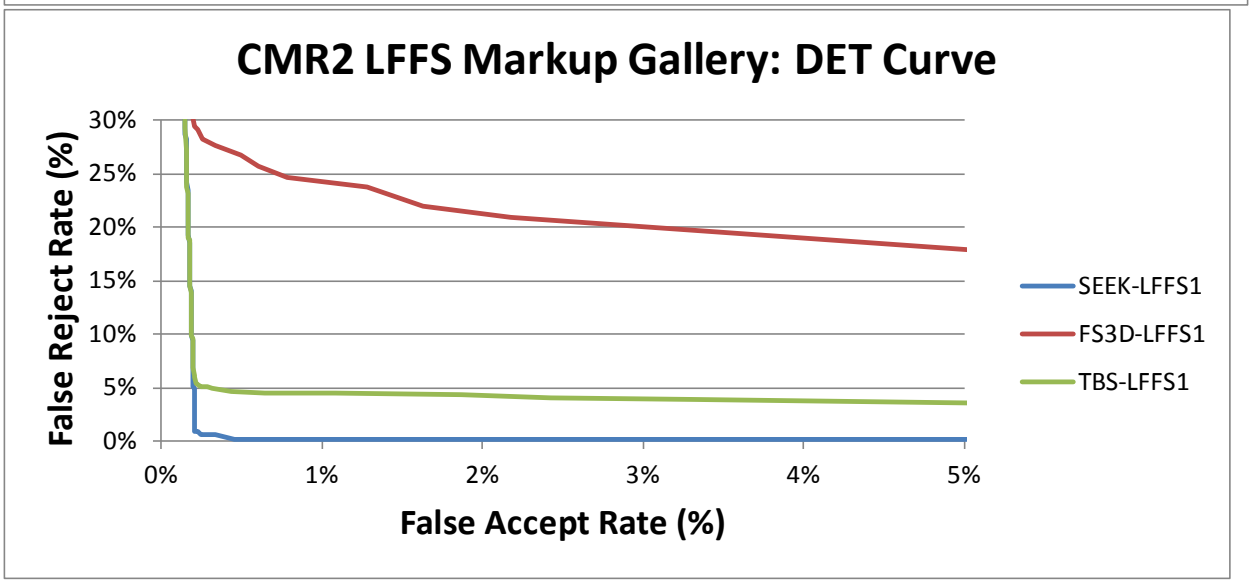
4.1.4 Matching Runs: LFFS, Markup

4.1.4.1 CMR2 Gallery

Probe Set	Probes	Gallery Set	Enrollment	TM Rank 1	Score, Mean	Score, Std Dev
SEEK (LFFS Markup)	468	CMR2 (LFFS Markup)	468	99.6%	215	79
FS3D (LFFS Markup)	468	CMR2 (LFFS Markup)	468	72.4%	58	30
TBS (LFFS Markup)	468	CMR2 (LFFS Markup)	468	95.5%	117	56





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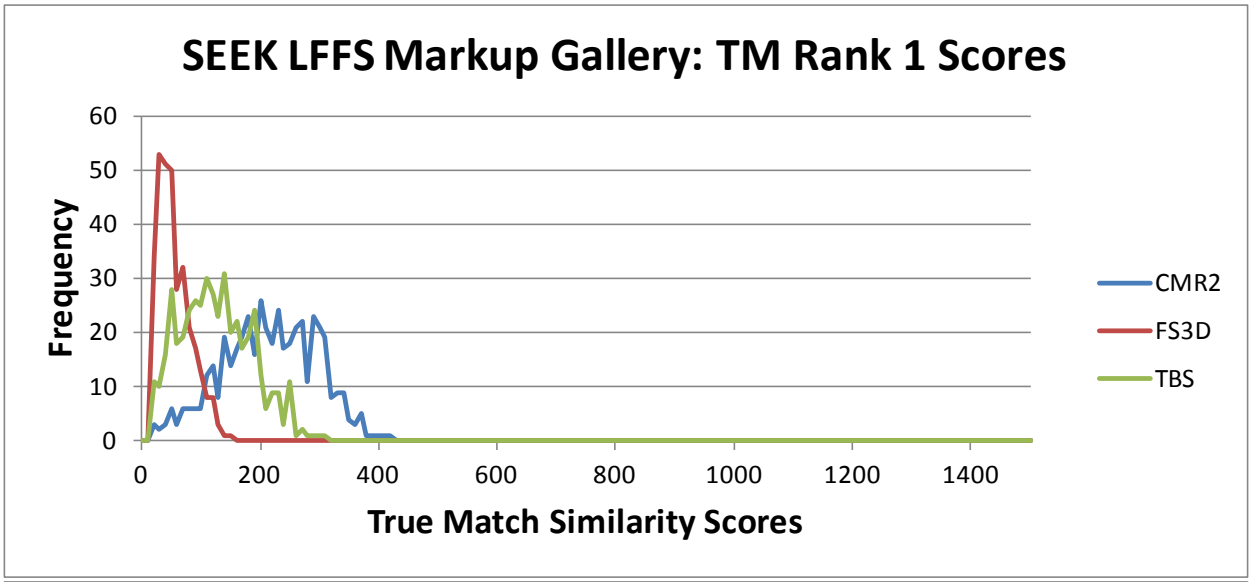
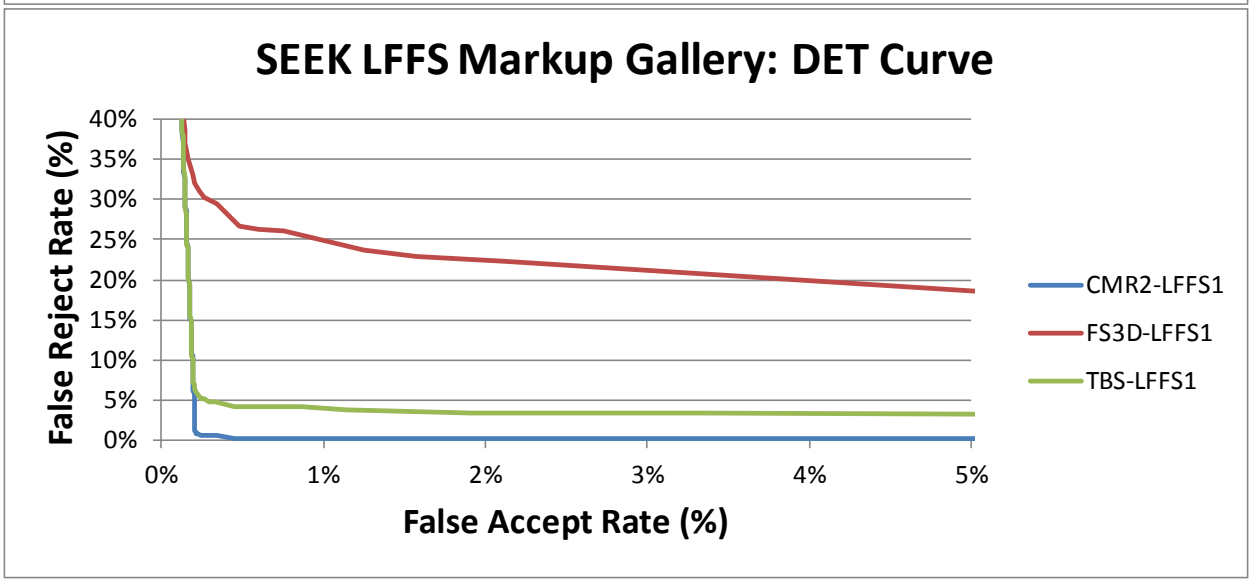
4.1.4.2 SEEK Gallery

Probe Set	Probes	Gallery Set	Enrollment	TM Rank 1	Score, Mean	Score, Std Dev
CMR2 (LFFS Markup)	468	SEEK (LFFS Markup)	468	99.8%	215	80
FS3D (LFFS Markup)	468	SEEK (LFFS Markup)	468	68.4%	55	28
TBS (LFFS Markup)	468	SEEK (LFFS Markup)	468	95.5%	125	61





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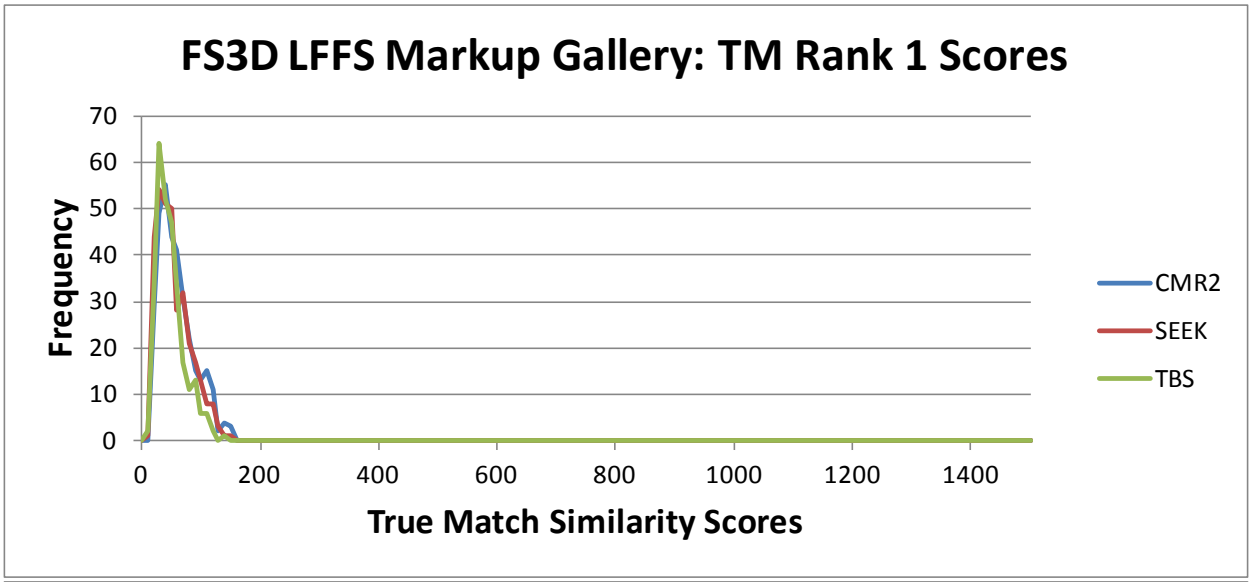
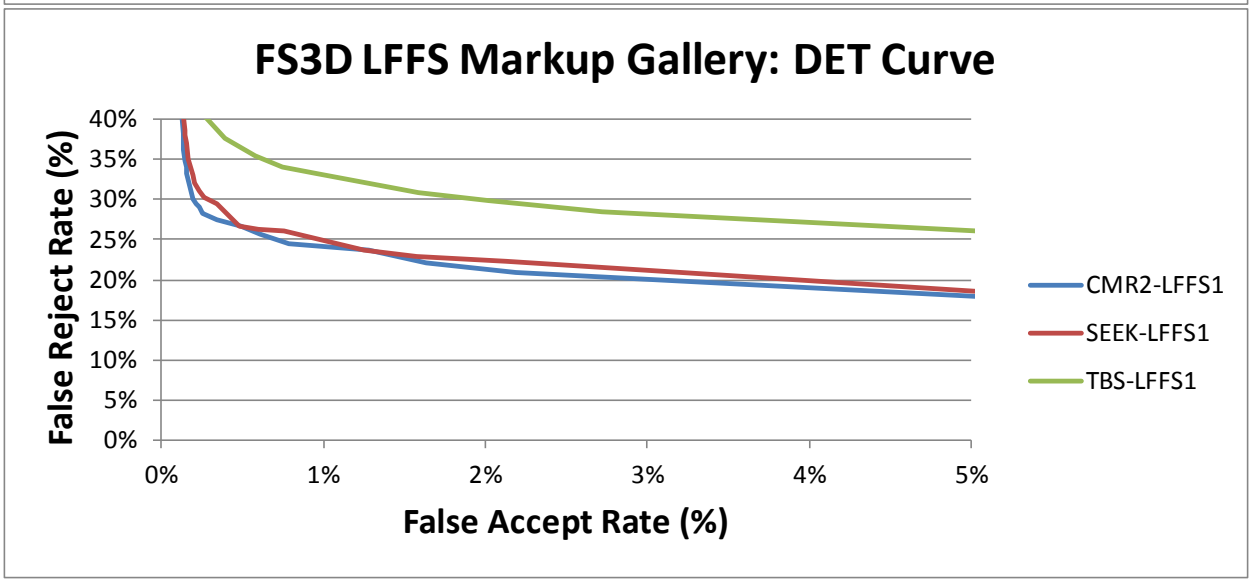
4.1.4.3 FS3D Gallery

Probe Set	Probes	Gallery Set	Enrollment	TM Rank 1	Score, Mean	Score, Std Dev
CMR2 (LFFS Markup)	468	FS3D (LFFS Markup)	468	71.4%	59	30
SEEK (LFFS Markup)	468	FS3D (LFFS Markup)	468	70.9%	54	28
TBS (LFFS Markup)	468	FS3D (LFFS Markup)	468	61.8%	48	24





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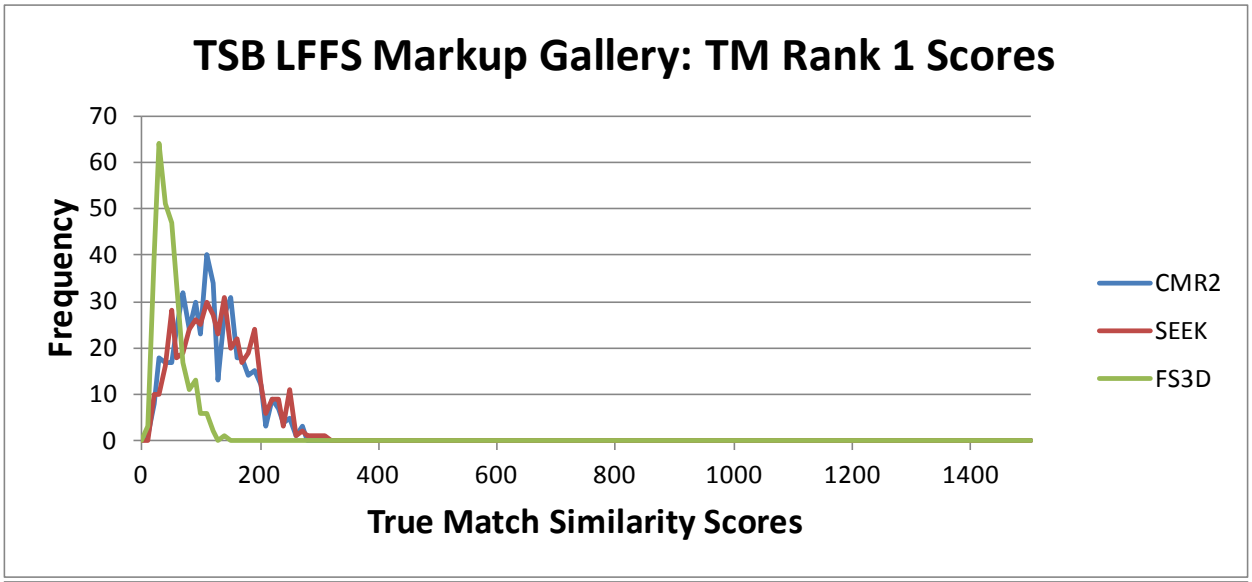
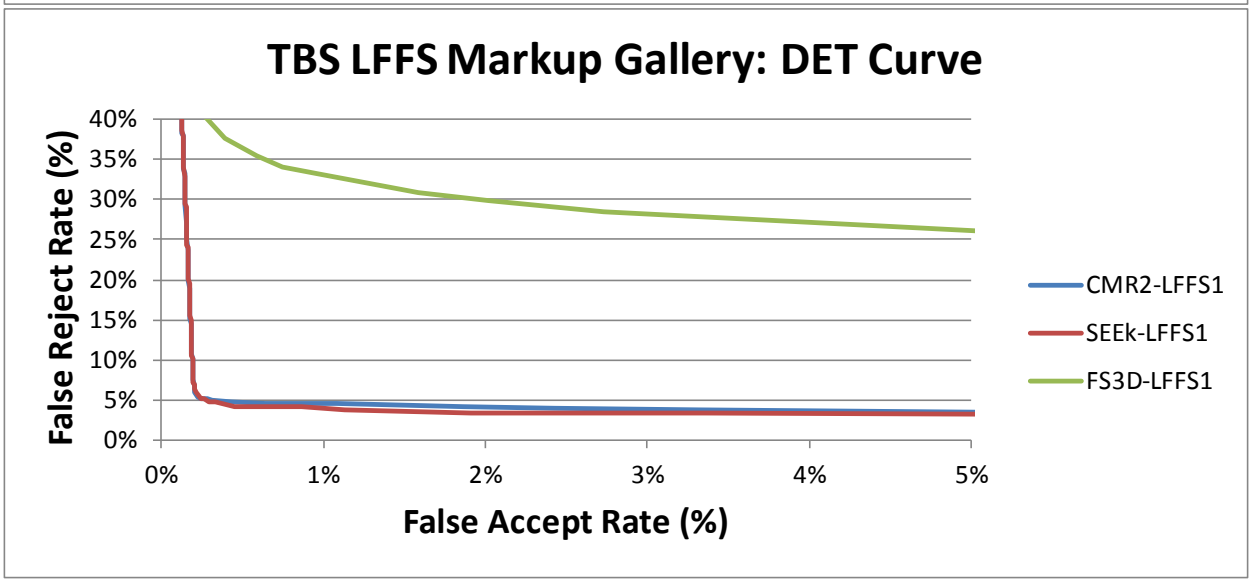
4.1.4.4 TBS Gallery

Probe Set	Probes	Gallery Set	Enrollment	TM Rank 1	Score, Mean	Score, Std Dev
CMR2 (LFFS Markup)	468	TBS (LFFS Markup)	468	95.7%	117	56
SEEK (LFFS Markup)	468	TBS (LFFS Markup)	468	95.3%	125	60
FS3D (LFFS Markup)	468	TBS (LFFS Markup)	468	63.0%	47	24





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4.2 Deviation Logs

The Paired MDT Sessions of images from different devices were used to export complete deviation logs. This was done for the 130 subjects processed for common minutiae (see Section 3.3 Minutia Pairing for Deviation Analysis). Those deviation logs included spatial coordinates, minutia types, and deviations for all common minutia pairs. All the logs for a given device pair (e.g., CMR2-SEEK and CMR2-TBS) were combined to produce a master list of minutiae deviations. An excerpt from a deviation log is included in Table 3 for one paired MDT session as an example of the data (note that the log is from the pairing shown in Figure 1). The paired MDT sessions resulted in **6,004 minutia pairs for CMR2-SEEK** and **4,498 minutia pairs for CMR2-TBS**.

The data was manipulated and analyzed in many different views and approaches to better understand the distribution of deviations and minutia context. The analysis can be found in Section 5.2 Deviation Logs.

Table 3: Paired MDT Session Deviation Log Example

Baseline X	Baseline Y	Baseline Theta	Baseline Minutiae Type	Comparison X	Comparison Y	Comparison Theta
853	2708	46	Bifurcation	3028	1570	125
879	2347	243	RidgeEnding	2784	1641	123
879	2916	15	Bifurcation	3053	2296	199
884	2530	67	RidgeEnding	2885	2057	151
909	2779	16	RidgeEnding	2911	2195	177
Comparison MinutiaeType	**Baseline Center X**	**Baseline Center Y**	**Baseline Center Theta**	**Comparison Center X**	**Comparison Center Y**	**Comparison Center Theta**
RidgeEnding	1935	2352	7	2286	1849	9
Bifurcation	1935	2352	7	2286	1849	9
RidgeEnding	1935	2352	7	2286	1849	9
RidgeEnding	1935	2352	7	2286	1849	9
RidgeEnding	1935	2352	7	2286	1849	9
Relative DeltaX	**Relative DeltaY**	**Relative DeltaTheta**	**Absolute DeltaX**	**Absolute DeltaY**	**Absolute DeltaTheta**	**Absolute Deviation Delta Distance**
346	-523	-1	4	7	-3	8
320	-518	-3	-24	0	-5	24
340	-503	5	-30	23	3	38
330	-488	2	-32	32	0	45
330	-487	6	-37	33	4	50

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4.3 Matching Runs – Deviation Filtered Datasets

To investigate the effect of minutia deviations on match performance, the MDT sessions were filtered by distance deviation to create two datasets and then used as probe data in matching runs. The master deviation log for CMR2-SEEK and CMR2-TBS were examined to determine the median deviation point in each log. The average of these two median deviations was then selected as a filter cut-off. That value was determined to be **ΔD = 63**. The paired MDT sessions were filtered twice to produce deviation logs and LFFS probe files. The first filter included only minutia pairs with a deviation distance $\Delta D < 63$ (called *63low*). The second filter included only minutia pairs with a deviation distance $\Delta D \geq 63$ (called *63up*). Table 4 shows the median deviation distance, total number of minutiae, and the average number of minutiae for a given filtered LFFS file.

Table 4: Deviation Filtered Datasets

	Deviation Distance (Median)	Total Minutiae (*63low*)	Total Minutiae (*63up*)	Avg Minutiae (*63low*)	Avg Minutiae (*63up*)
SEEK	60	3141	2863	24	22
TBS	67	2133	2365	16	18

A companion dataset was created for both *63low* and *63up* consisting of an equal number of random minutiae. Each paired MDT session was random filtered to produce a deviation log and LFFS file with the same number of random minutiae as the corresponding filtered MDT session. Since each filtered MDT session resulted in a different number of minutiae satisfying the given filter (i.e., *63low* or *63up*), the randomizing number seed was custom selected for each paired MDT session. The number of random minutiae was selected in this manner to ensure that for a given probe for a subject and device, it could be directly compared to its counterpart control to determine the effect of deviation. The only variable differing between those two specific probes would be the contained minutia details and not the number of minutiae. The spatial location and minutia type (i.e., ridge ending vs. bifurcation) were not controlled or restricted. This approach produced four control datasets (SEEK vs. TBS, *63low* vs. *63up*).

The four LFFS datasets (per device) were submitted as probes against the full CMR2 LFFS Markup gallery using the MM 4.5 matching algorithm. Ground truth matching runs were performed using the LFFS markup files for the 130 subjects as a probe dataset, as well as a probe dataset with those same LFFS files filtered to only included paired minutiae (no deviation filtering).

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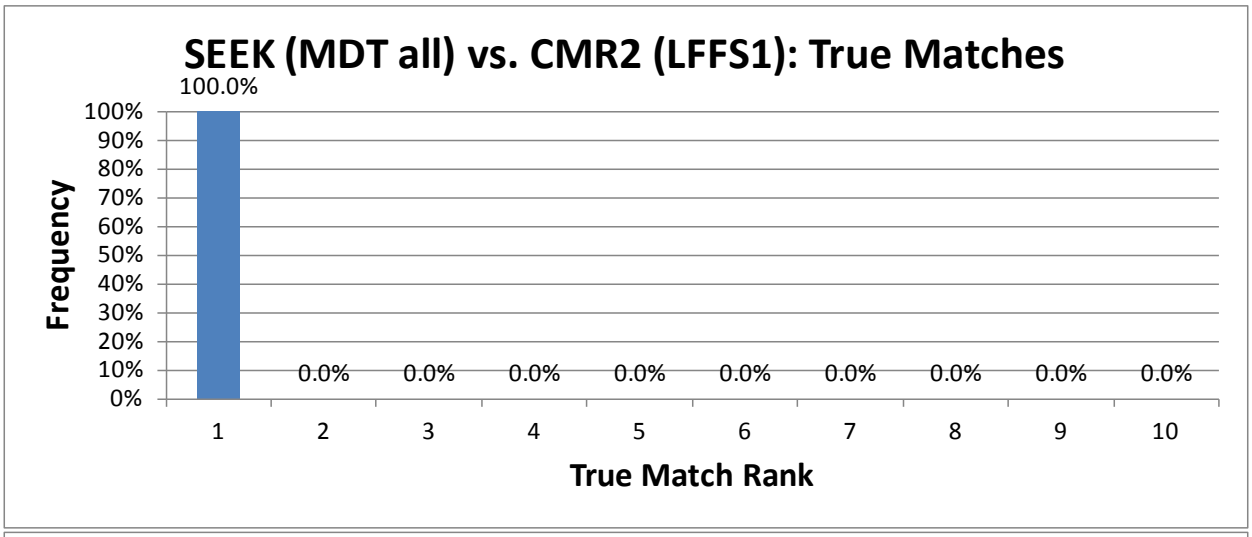
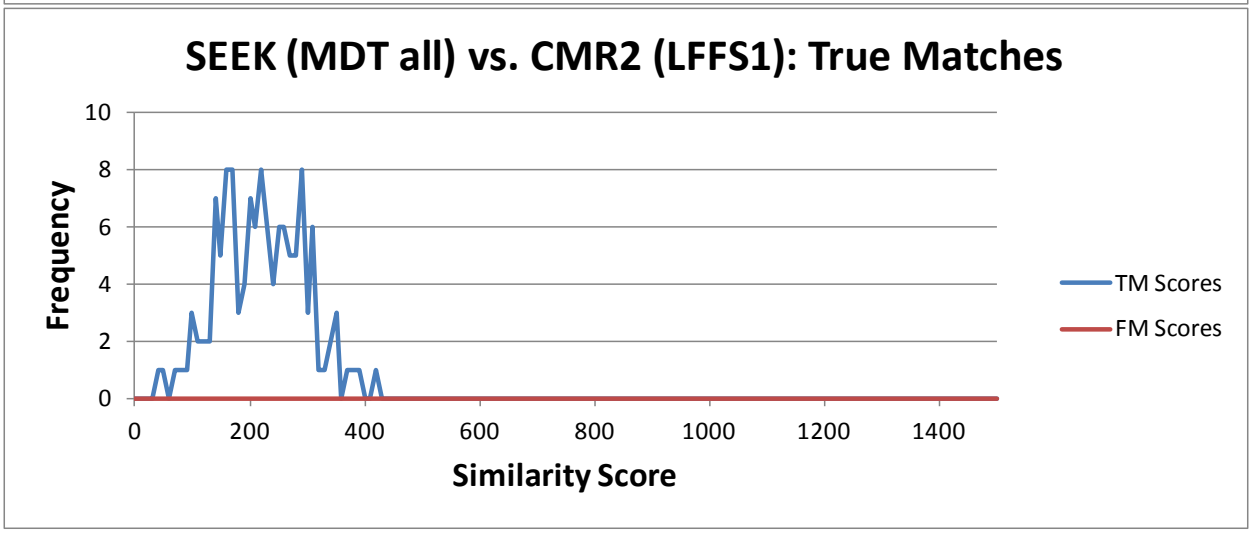
4.3.1 Matching Runs – Filtered CMR2-SEEK

4.3.1.1 SEEK All Minutiae

A matching run using the 130 SEEK LFFS markup files as probes.

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Markup	**Unique Galleries**	468			
Probe	**Total Qualified**	130	100.0%		
SEEK MDT	**UniqueProbes**	130			
All Minutiae					
Matches	**True Matches**	130	100.0%	219	75
	False Matches	0	0.0%	#DIV/0!	#DIV/0!
	Total Matches	60840			





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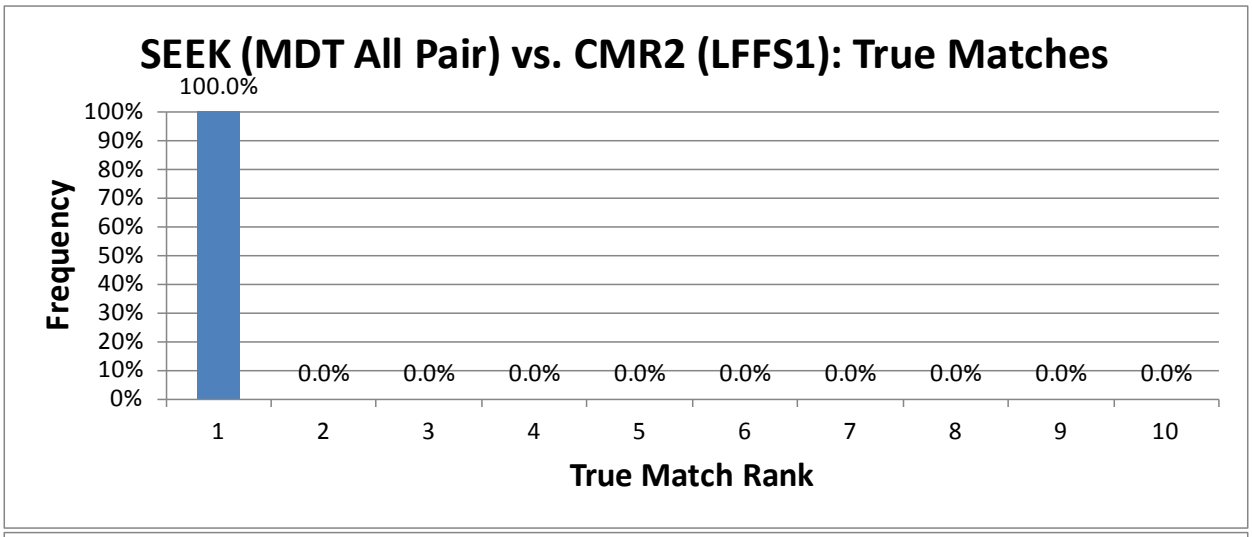
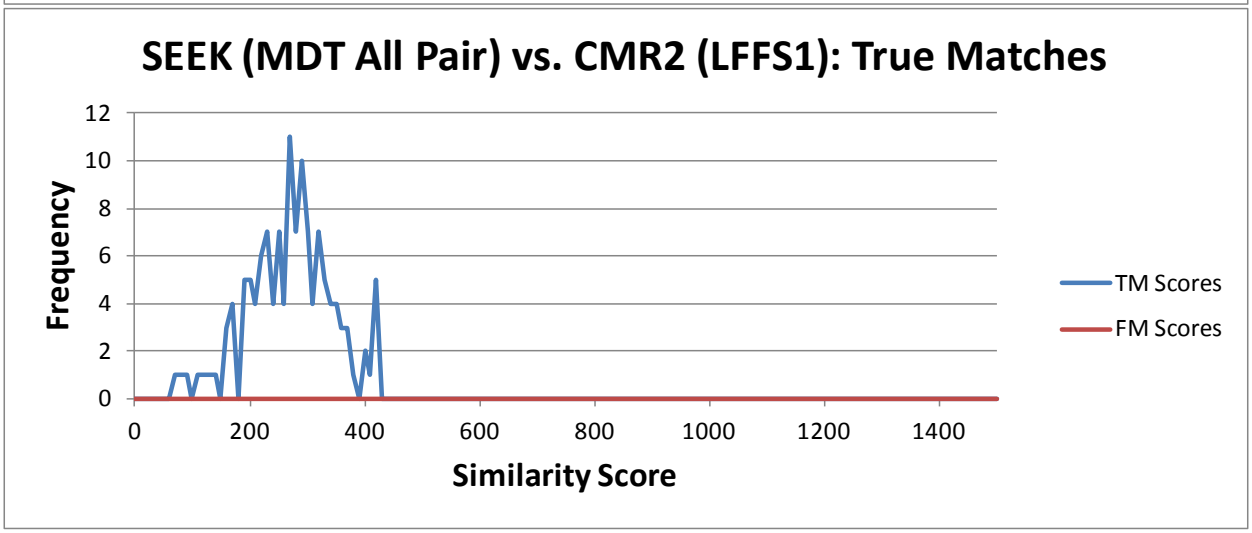
4.3.1.2 SEEK All Pairs

A matching run using the 130 SEEK LFFS files with only paired minutiae as probes.

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Markup	**Unique Galleries**	468			
Probe	**Total Qualified**	130	100.0%		
SEEK MDT	**UniqueProbes**	130			
All Paired					
Matches	**True Matches**	130	100.0%	269	74
	False Matches	0	0.0%	#DIV/0!	#DIV/0!
	Total Matches	60840			





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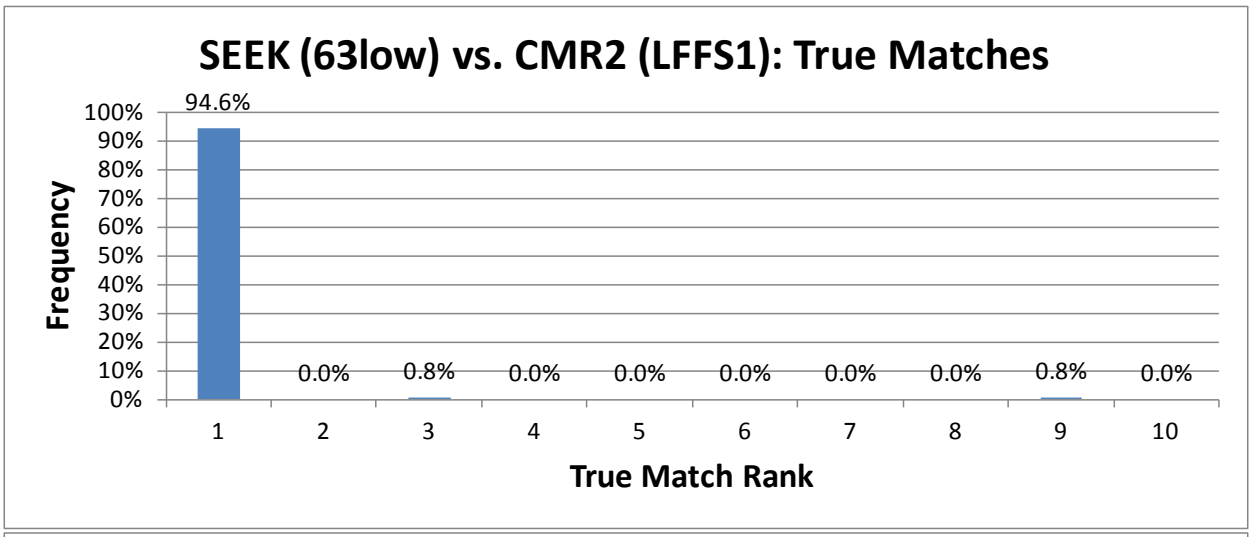
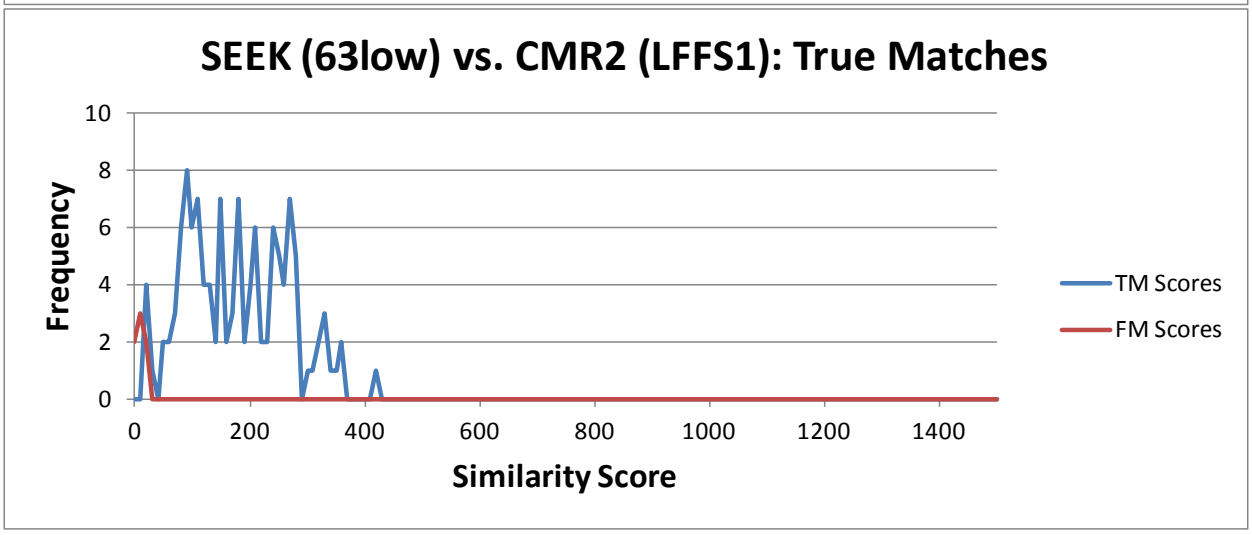
4.3.1.3 SEEK 63low

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Markup	**Unique Galleries**	468			
Probe	**Total Qualified**	130	100.0%		
SEEK MDT	**UniqueProbes**	130			
63low					
Matches	**True Matches**	123	94.6%	178	89
	False Matches	7	5.4%	10	7
	Total Matches	60840			





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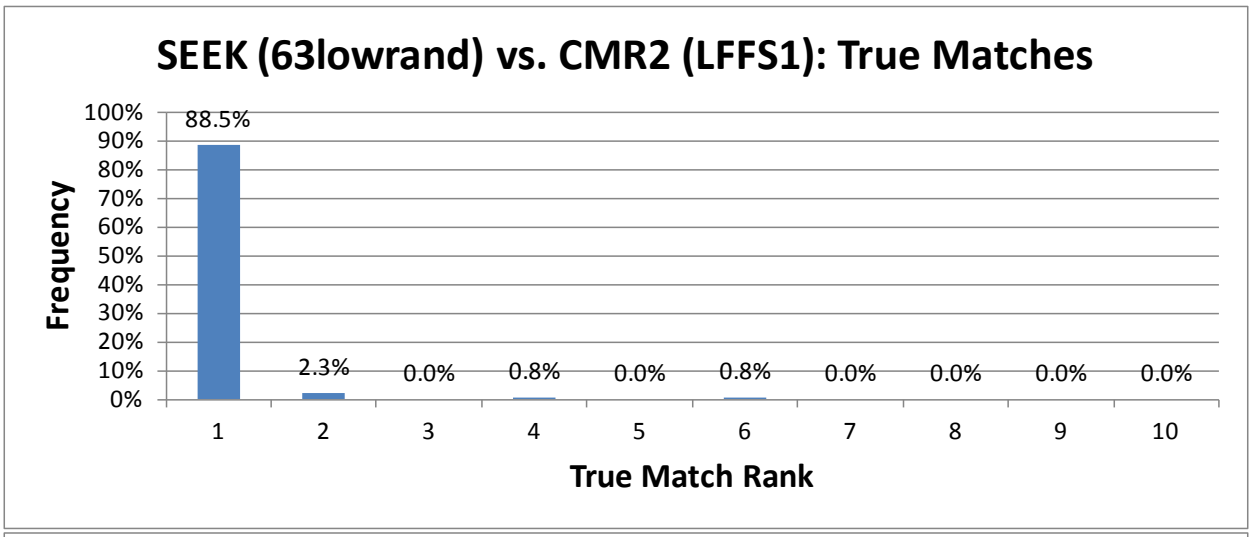
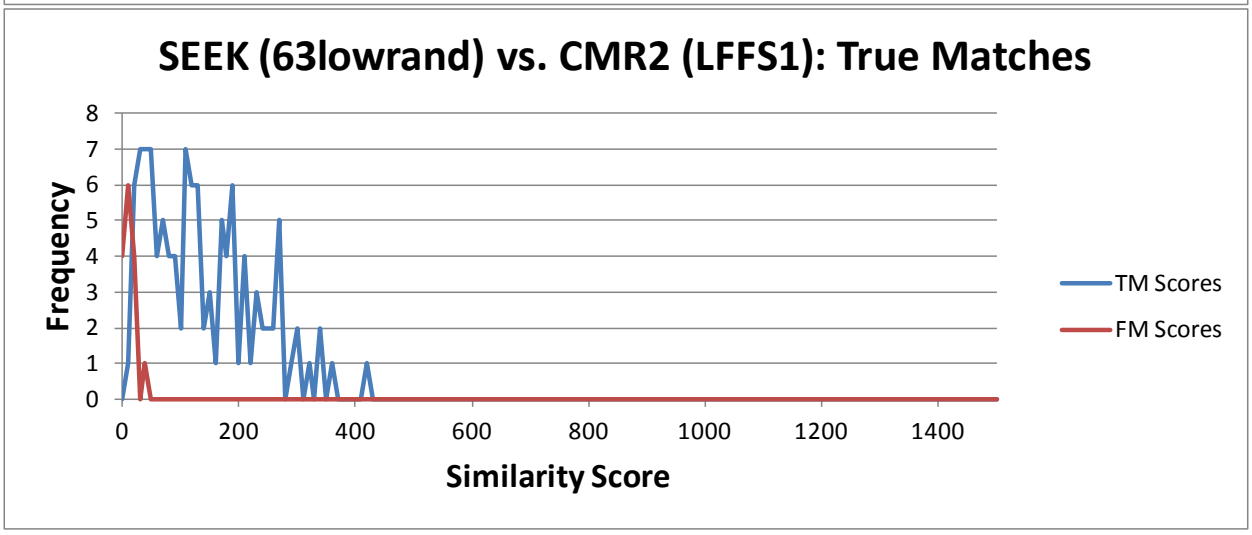
4.3.1.4 SEEK 63low random

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Markup	**Unique Galleries**	468			
Probe	**Total Qualified**	130	100.0%		
SEEK MDT	**UniqueProbes**	130			
63low random					
Matches	**True Matches**	115	88.5%	137	91
	False Matches	15	11.5%	12	9
	Total Matches	60840			





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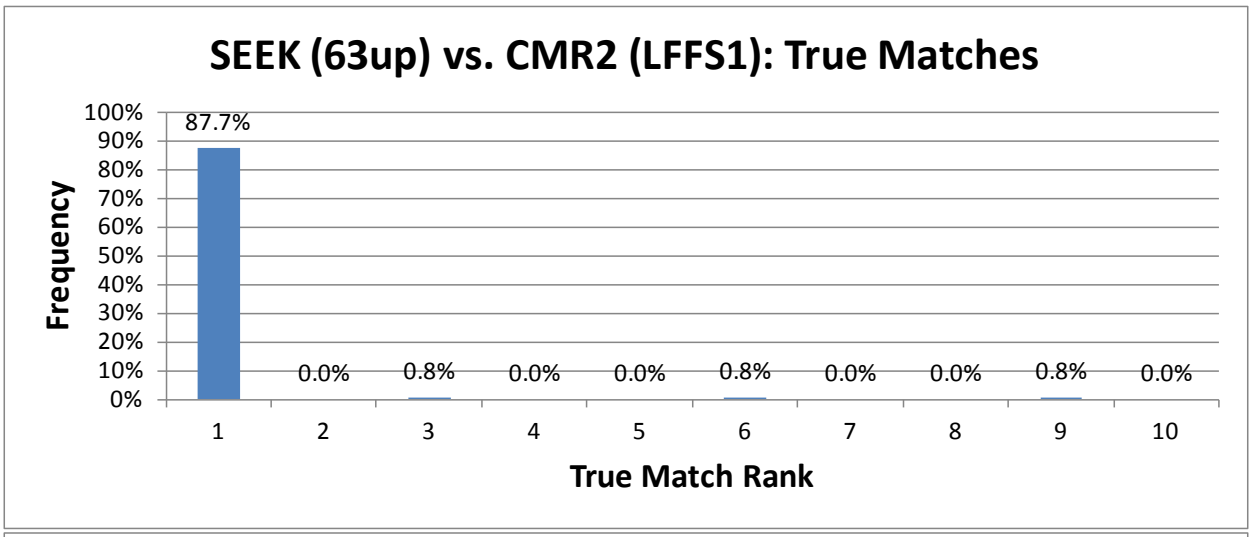
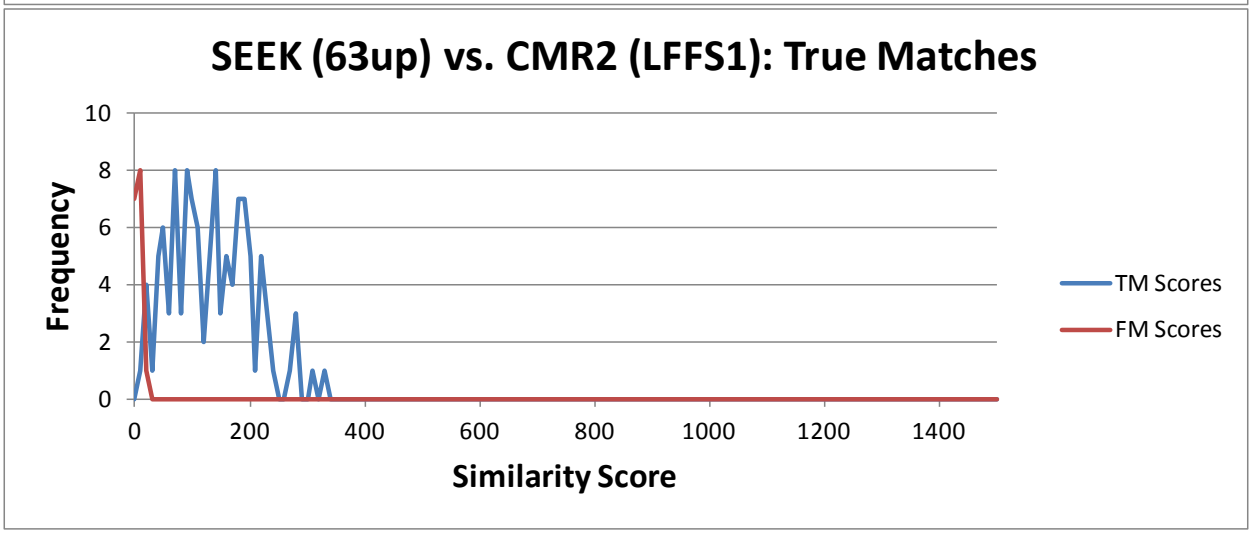
4.3.1.5 SEEK 63up

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Markup	**Unique Galleries**	468			
Probe	**Total Qualified**	130	100.0%		
SEEK MDT	**UniqueProbes**	130			
63up					
Matches	**True Matches**	114	87.7%	132	70
	False Matches	16	12.3%	5	6
	Total Matches	60840			





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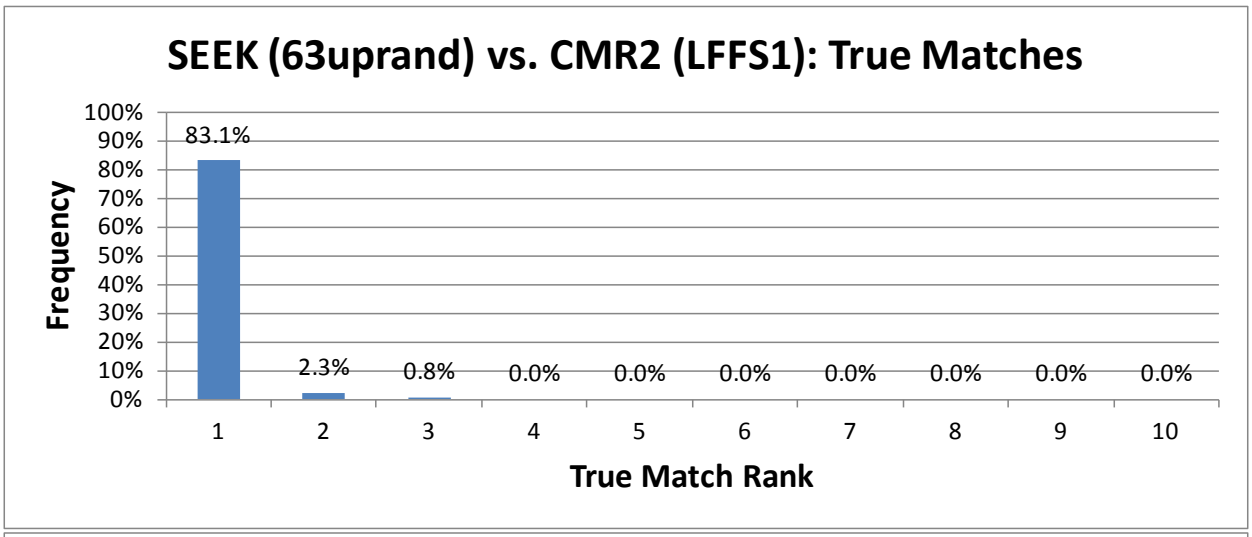
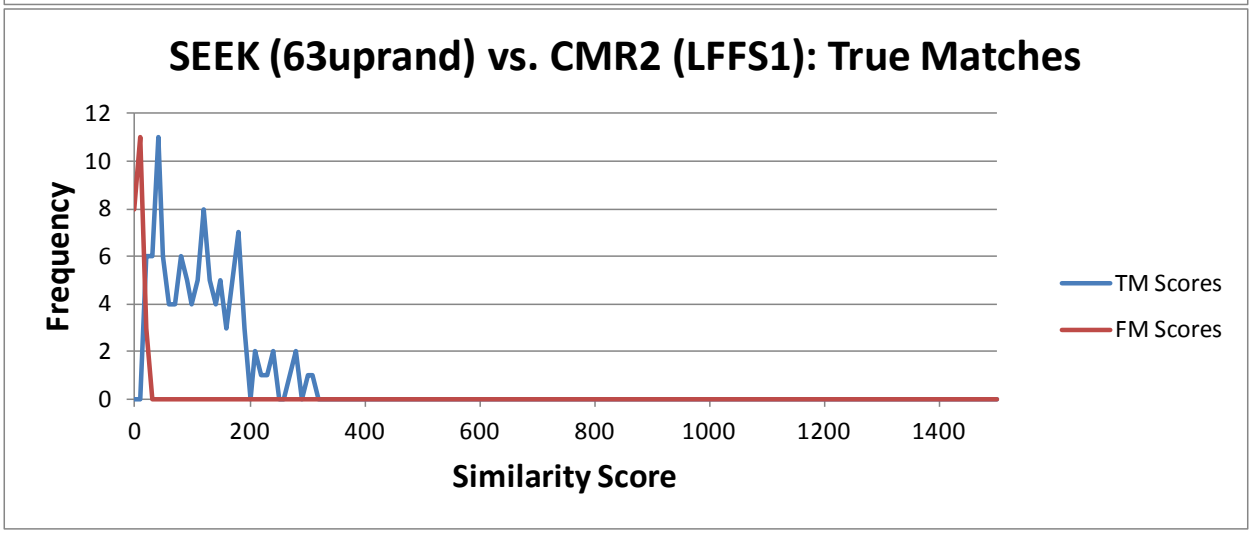
4.3.1.6 SEEK 63up random

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Markup	**Unique Galleries**	468			
Probe	**Total Qualified**	130	100.0%		
SEEK MDT	**UniqueProbes**	130			
63up random					
Matches	**True Matches**	108	83.1%	113	70
	False Matches	22	16.9%	7	7
	Total Matches	60840			





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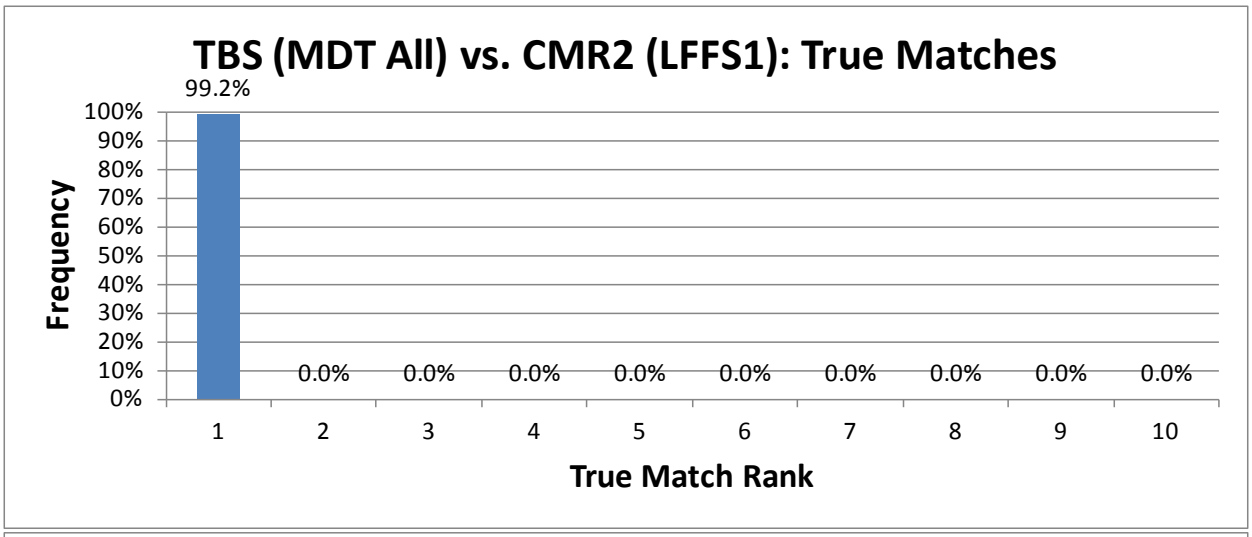
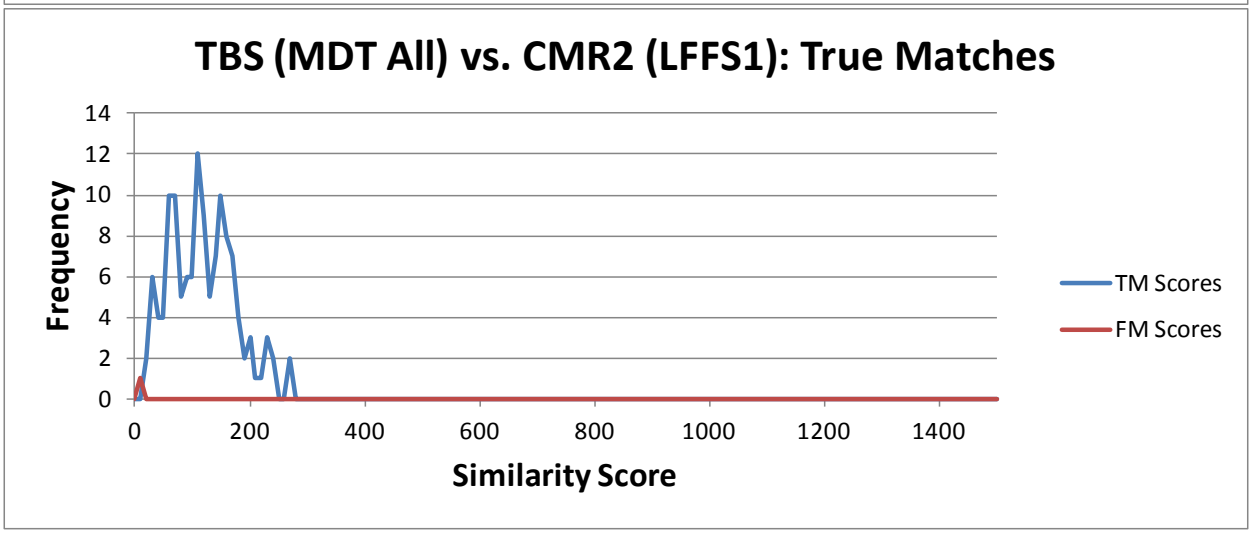
4.3.2 Matching Runs – Filtered CMR2-TBS

4.3.2.1 TBS All Minutiae

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Markup	**Unique Galleries**	468			
Probe	**Total Qualified**	130	100.0%		
TBS MDT	**UniqueProbes**	130			
All Minutiae					
Matches	**True Matches**	129	99.2%	118	56
	False Matches	1	0.8%	11	#DIV/0!
	Total Matches	60840			





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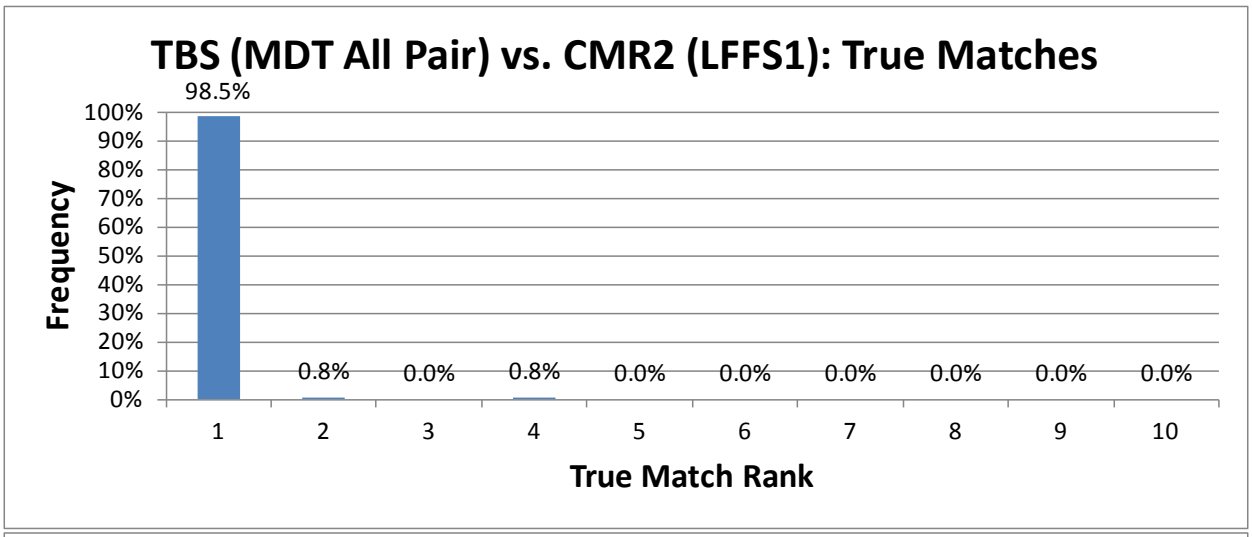
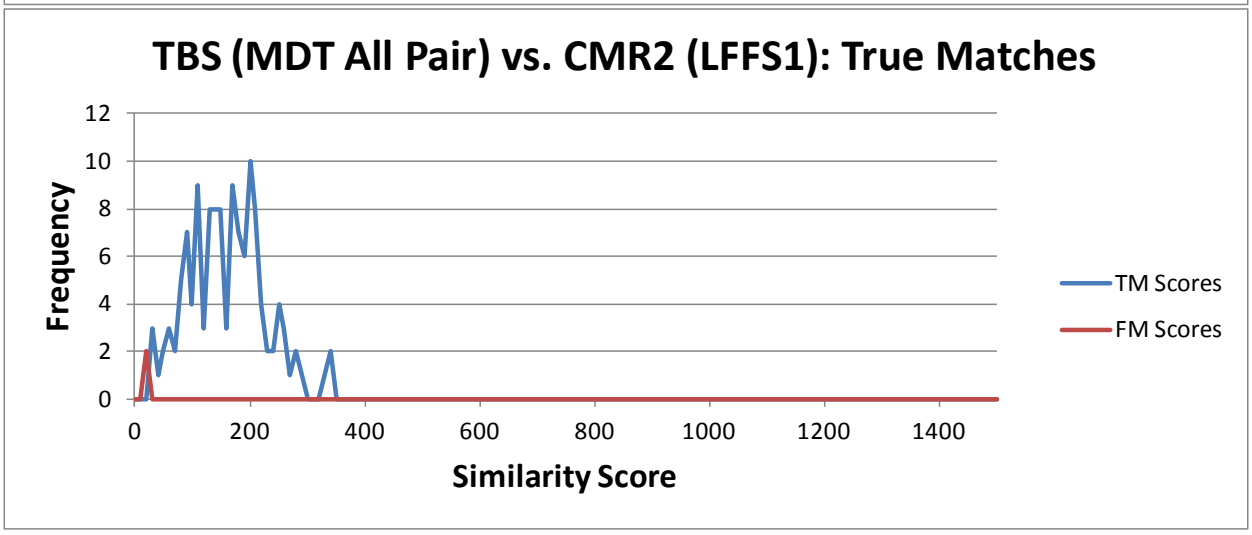
4.3.2.2 TBS All Pairs

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Markup	**Unique Galleries**	468			
Probe	**Total Qualified**	130	100.0%		
TBS MDT	**UniqueProbes**	130			
All Pairs					
Matches	**True Matches**	128	98.5%	159	66
	False Matches	2	1.5%	20	2
	Total Matches	60840			





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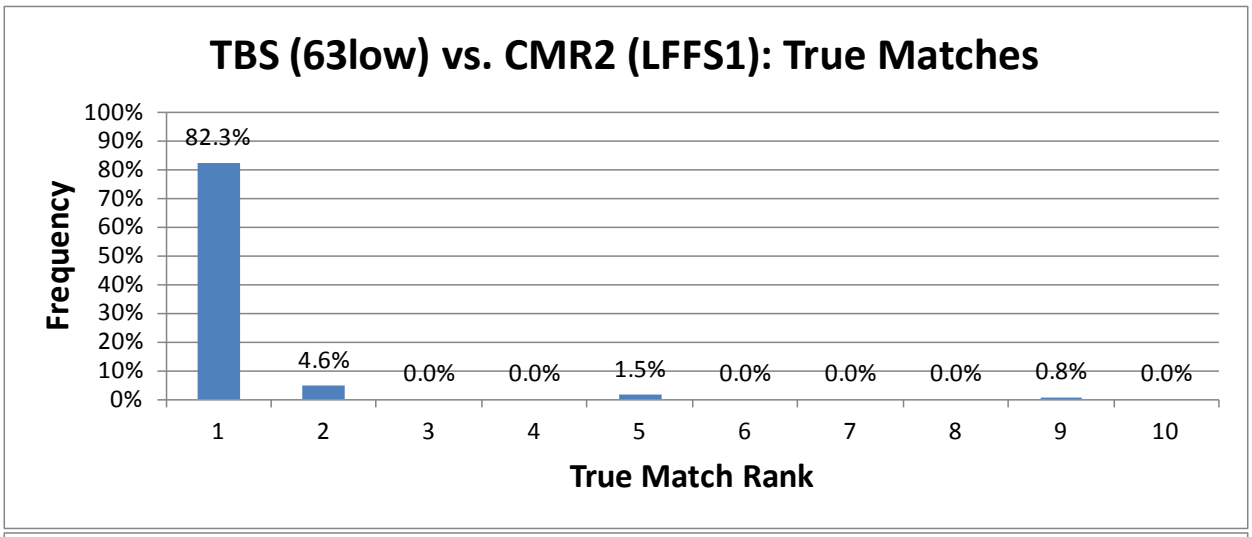
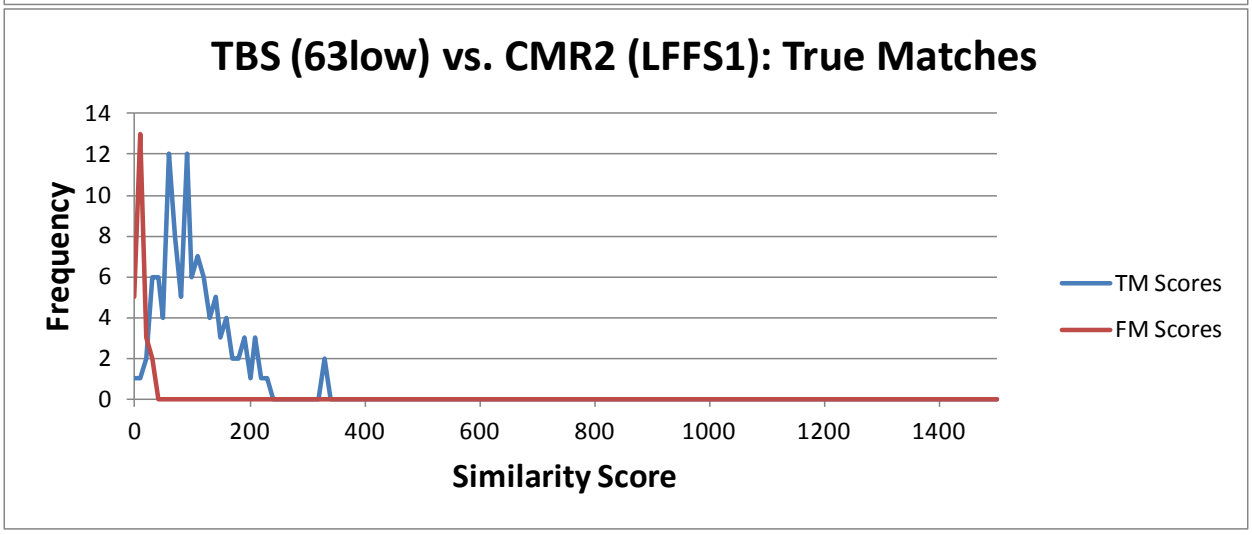
4.3.2.3 TBS 63low

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Markup	**Unique Galleries**	468			
Probe	**Total Qualified**	130	100.0%		
TBS MDT	**UniqueProbes**	130			
63low					
Matches	**True Matches**	107	82.3%	102	60
	False Matches	23	17.7%	10	9
	Total Matches	60840			





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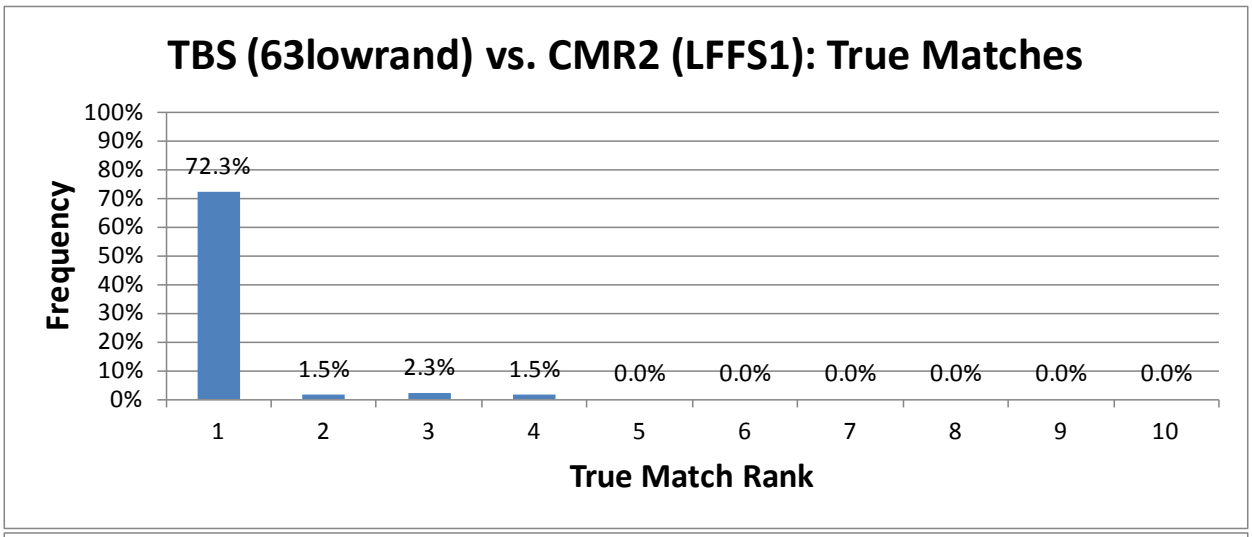
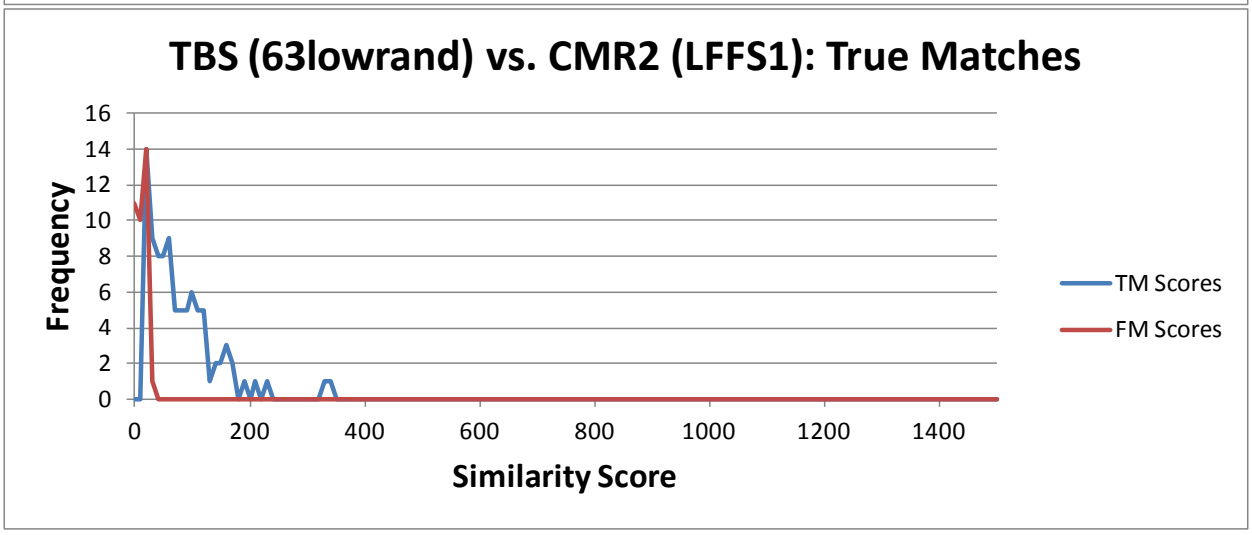
4.3.2.4 TBS 63low random

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Markup	**Unique Galleries**	468			
Probe	**Total Qualified**	130	100.0%		
TBS MDT	**UniqueProbes**	130			
63low random					
Matches	**True Matches**	94	72.3%	80	61
	False Matches	36	27.7%	10	9
	Total Matches	60840			





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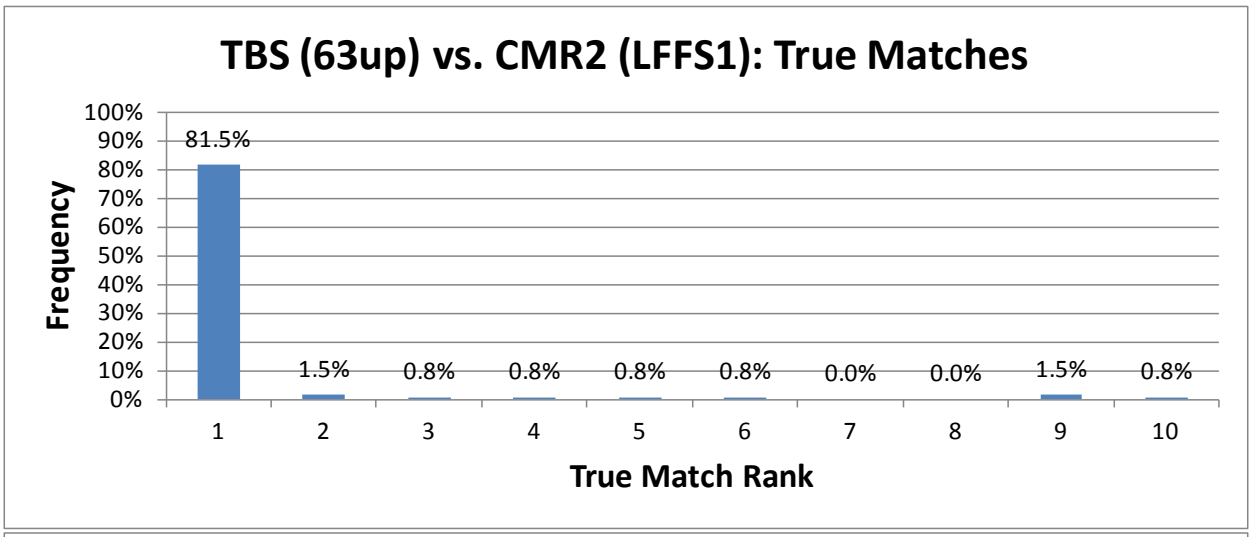
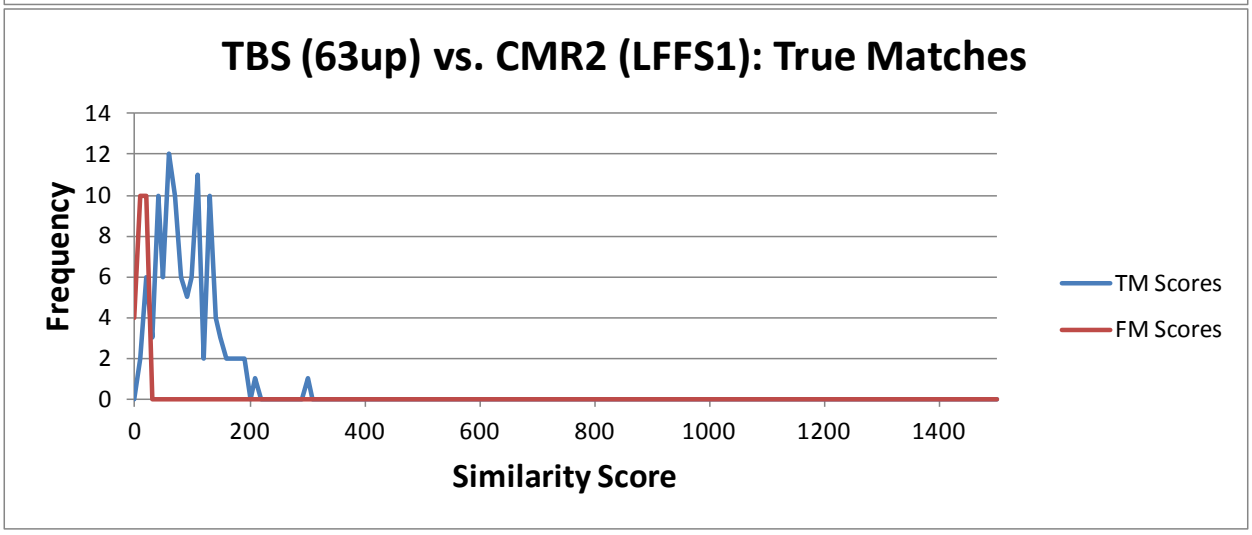
4.3.2.5 TBS 63up

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Markup	**Unique Galleries**	468			
Probe	**Total Qualified**	130	100.0%		
TBS MDT	**UniqueProbes**	130			
63up					
Matches	**True Matches**	106	81.5%	89	50
	False Matches	24	18.5%	12	6
	Total Matches	60840			





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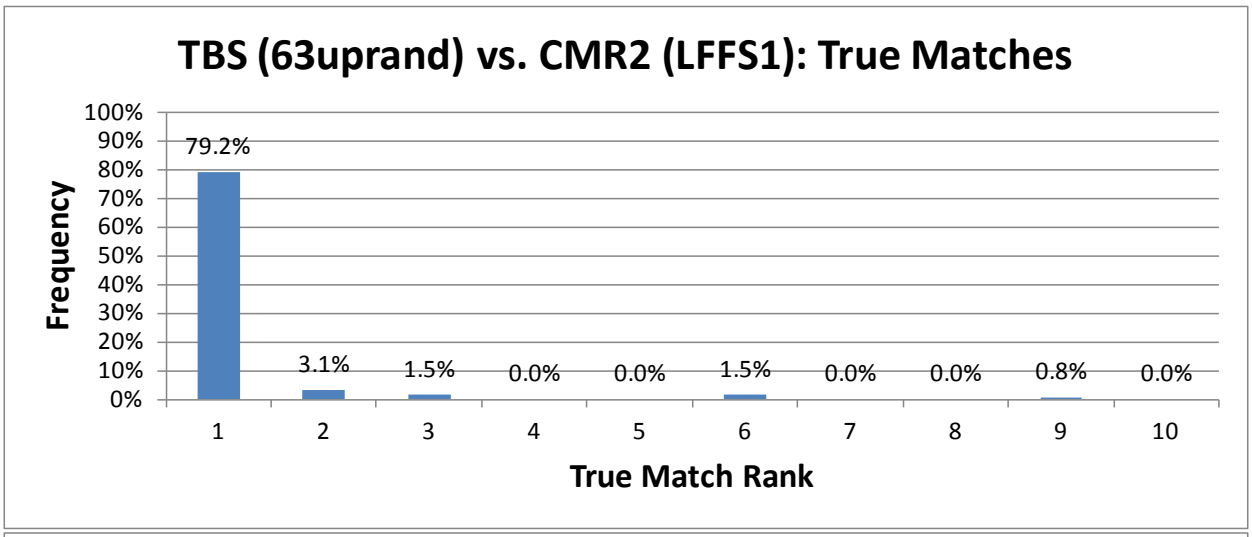
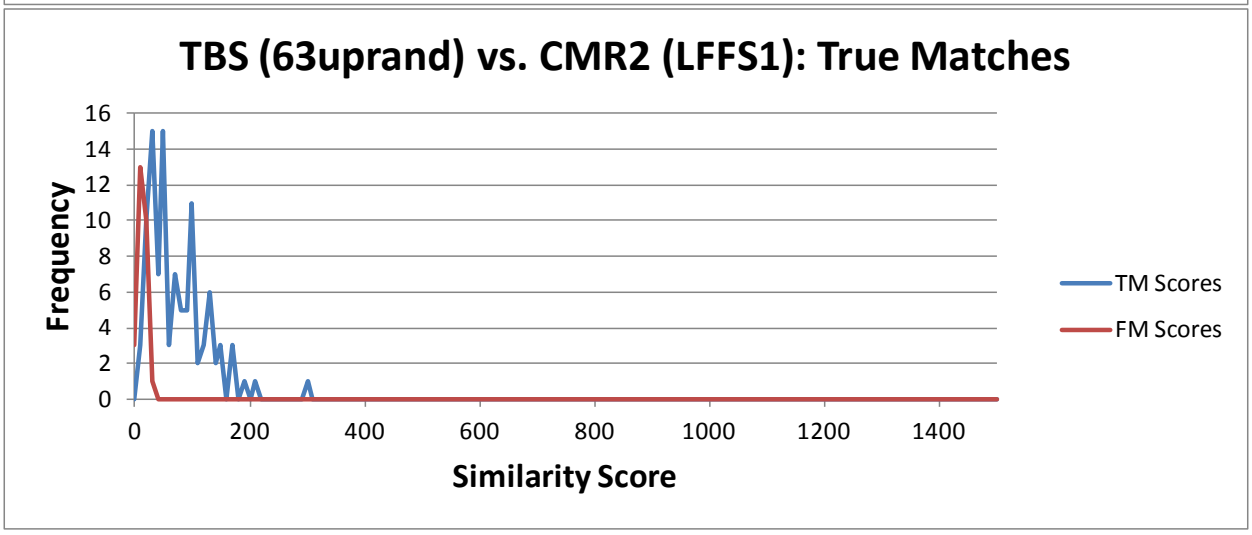
4.3.2.6 TBS 63up random

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Markup	**Unique Galleries**	468			
Probe	**Total Qualified**	130	100.0%		
TBS MDT	**UniqueProbes**	130			
63up random					
Matches	**True Matches**	103	79.2%	73	50
	False Matches	27	20.8%	13	7
	Total Matches	60840			





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5.0 ANALYSIS & DISCUSSIONS

This work is focused on minutiae and their deviations between sensor collections of the same subject to better understand contact vs. contactless fingerprint collections and data match performance. The experiments performed in the previous section and the subsequent analysis contained here attempt to answer the following questions:

1. What is the performance of the vetted LFFS files as compared to image probes or EBTS files with automated minutia extraction? These results establish a baseline, not only for this work, but for other researchers who will use the fingerprint dataset and its companion markup dataset.

2. What can be learned about the distribution of minutiae and their spatial deviations in the contact and contactless fingerprint probe dataset when compared to a traditional contact legacy gallery? Specifically:
    a. What is the magnitude distribution of spatial deviations?
    b. Is there correlation between spatial position and minutia deviations?
    c. How is the similarity score affected by minutia deviation?
    d. How is the similarity score affected by the number of minutia pairs? Fraction of minutiae paired with the gallery?
    e. How does the NFIQ score affect similarity score? Average minutia deviation?

3. How is the match performance affected by probe data with lower/higher minutia deviations? This speaks directly to the common belief often held by biometrics practitioners that minutia deviations are a primary factor in determining the similarity score of a fingerprint match and that 2D rolled-equivalent images from contactless sensors are at a disadvantage due to this fact when submitted as probes against a legacy database.

NOTE: Raw 3D and contactless images are not compatible with existing fingerprint matching algorithms. As a result, all analysis discussed in this report does not utilize this contactless fingerprint data directly, rather the analysis is performed on images obtained from the contactless system's transformation of the scanned data into 2D grayscale images that are intended to be matchable against existing fingerprint databases.

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5.1 Matching Runs – CFP Markup Datasets

The three types of data produced from the CLPE vetting process (see Section 3.2 Fingerprint Data) were submitted as probe and gallery datasets to the MM matcher to determine the performance of the vetted LFFS files as compared to image probes or EBTS files with automated minutia extraction. The primary motivation for these experiments was to confirm that the datasets are valid candidates for more in-depth analysis with respect to contact vs. contactless fingerprint performance and to establish a baseline for other researchers who might use the datasets.

5.1.1 Comparison of TMR at Rank 1

Table 5 below shows an aggregation of matching runs for the various dataset types and sensors. The TMR at Rank 1 is shown for different probe/gallery combinations. The values have been color coded for ease of read using arbitrary values of 0-79%, 80-89%, and 90-100% as conditions for red, yellow, and green respectively.

Table 5: Summary of CFP Markup Dataset TMR at Rank 1

	Image Original (%)				LFFS Original (%)				LFFS Markup (%)			
Probe→ Gallery↓	CMR2	SEEK	FS3D	TBS	CMR2	SEEK	FS3D	TBS	CMR2	SEEK	FS3D	TBS
CMR2	100.0	99.8	81.2	96.6	100.0	99.4	80.8	94.9	100.0	99.6	72.4	95.5
SEEK II	100.0	100.0	77.8	95.9	99.1	100.0	75.9	96.2	99.8	100.0	68.4	95.5
FS3D	80.8	78.2	100.0	73.7	80.1	75.4	100.0	70.7	71.4	70.9	100.0	61.8
TBS	95.9	95.3	72.6	100.0	94.4	94.4	70.5	100.0	95.7	95.3	63.0	100.0

The gallery-gallery ground truth matching runs for all sensor and data types produced a TMR of 100%. This confirmed their validity as gallery dataset candidates.

The CMR2, SEEK, and TBS produced TMR above 90%, and in most cases above 94%, when matched against each other for all three data types – images, automated LFFS (i.e., LFFS0), and vetted LFFS (i.e., LFFS1). The TMR was highest for the image probe/gallery matching runs. The interesting outcome was that the LFFS1 matching runs improved slightly, but consistently, over the LFFS0 matching runs. This was observed in all three sensors. An example of this trend is shown in Figure 6. An explanation for the LFFS datasets performing slightly poorer than the image datasets is that the process used to create the LFFS files required a conversion of the minutia details from the Neurotechnology feature profile used in MM, which did not follow standard conventions, to the ANSI-NIST EFS QSP2 Profile. In performing the conversion of angles and spatial coordinates, rounding errors were unavoidably introduced. This results in the minutia locations, although contextually and visually identical in the image and LFFS0 datasets, to have some discrepancies and therefore non-optimized matching. The improvement from LFFS0 to LFFS1 is attributed to the removal of minutiae that were the result of false image features, and therefore were not real features that were captured from the finger in both sensors. Removing these false minutiae improved the registry of remaining marks even though information was removed from the LFFS files.

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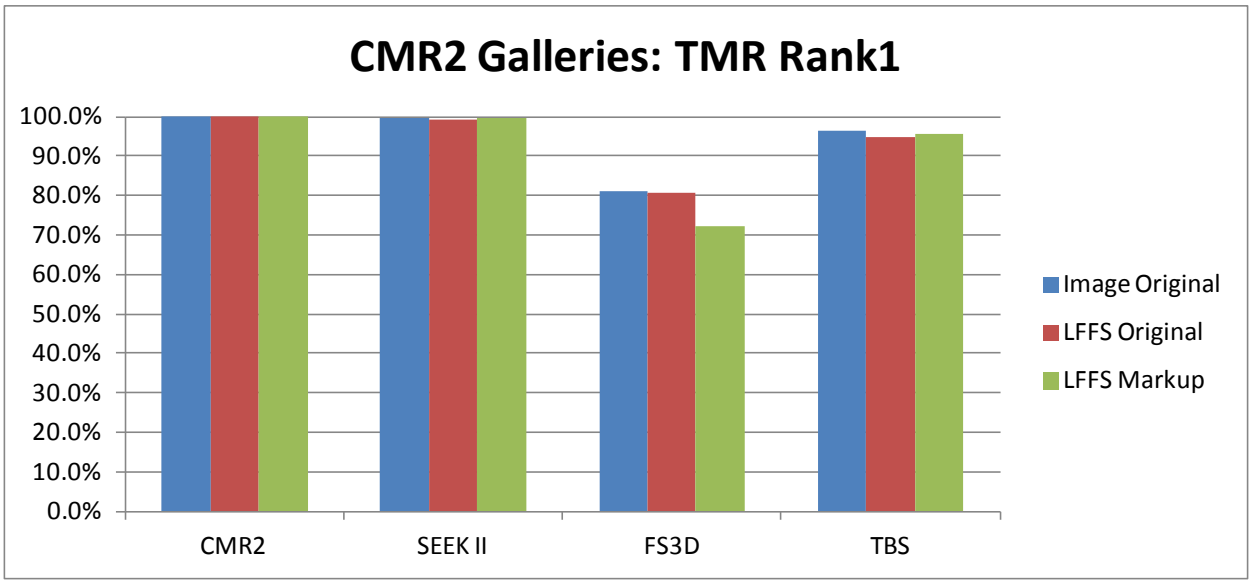

Figure 6: Comparison of TMR Across Data Types

FS3D data did not perform well, as either probes or galleries. This is not surprising given the performance detailed in a previous research report.[1] This sensor is a prototype that was still under development and refinement at the time of collection. It also utilizes optical structured light to capture the fingerprint features and 3D topography, as opposed to the other contactless device in this study (TBS) that utilizes three fixed cameras with diffuse illumination to detect and capture an image of an inserted finger. The FS3D is more ambitious and, if fully realized as a commercial product, should allow for richer 3D information of fingerprints. However, this capture approach likely contributed to image quality issues in the 2D gray scale transformation and reduced visual fidelity of minutia marks. Figure 7 depicts example LFFS1 fingerprint images with minutia marks from each sensor from the same subject. The FS3D file produced the highest similarity score in the FS3D-CMR2 LFFS1 matching run (score = 152). For comparison, the same subject file in the same matching run type produce similarity scores of 295 for SEEK and 167 for TBS. However, in the SEEK set it was the 384th and for TBS it was 362nd highest similarity score among the TMs.

NOTE: The FS3D devices used in the CFPv1 collection is an early prototype from ~2009. The company has been continually improving and refining the system since then and it is likely that future FS3D devices will have improved image capture and match performance.

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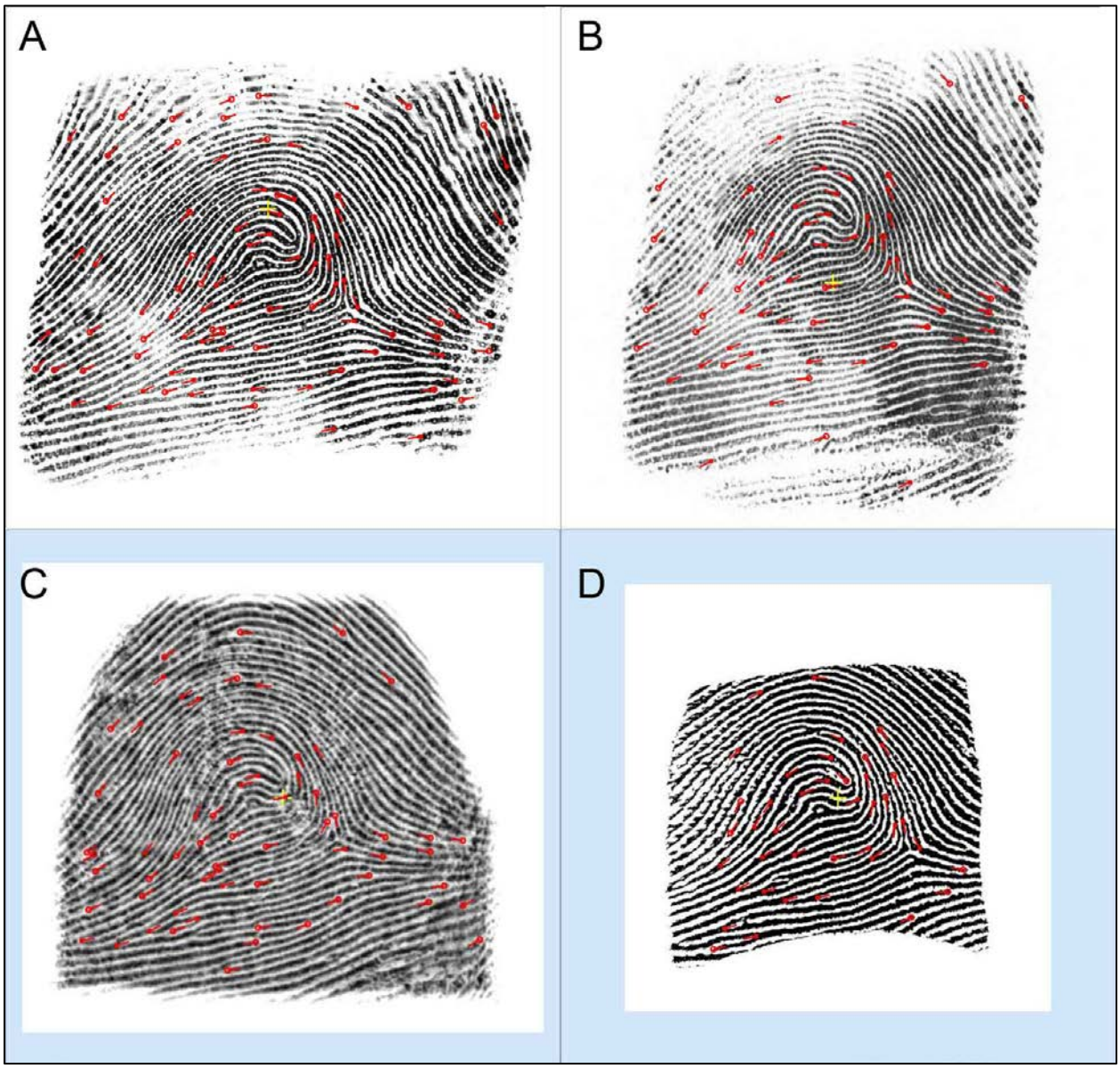

Figure 7: Example Fingerprint Images from All Sensors
Fingerprint images from the same subject captured using (A) CMR2, (B) SEEK, (C) TBS, and (D) FS3D.

5.1.2 DET Curves

DET curves were produced for the matching runs to provide a different view of matching performance as compared to TMR. Figure 8 shows the DET curves for all sensor and data types submitted against the CMR2 data. The plots are consistent with the results and analysis of the TMR in the preceding section. The SEEK data performs the best, with TBS data performing nearly as well. The DET curves provide a clearer picture of how poor the FS3D prototype's data performed in matching runs. Similar to the TMR results, the LFFS1 was seen to perform better than LFFS0 for both the SEEK and TBS. However, the FS3D LFFS1 data was notably poorer in matching than the LFFS0. This is attributed to the removal of false or incorrect minutiae that

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drops the total number of minutiae in the image files below a threshold needed for reliable matching. The match performance as a function of available minutia marks is not expected to increase perpetually, but will approach a limit and plateau (as demonstrated in later analysis in Figure 25). The FS3D images have fewer minutiae marks and a greater fraction of those are false or incorrect and therefore removed in the LFFS1 files.

DET curves are often used to characterize a system for a specific application such that a user can select the best system for a fixed FAR or FRR requirement or adjust the FAR or FRR for a fixed system. However, in this case no specific application or threshold is set and therefore the determination of whether the TBS and/or SEEK performance is acceptable is unknown.

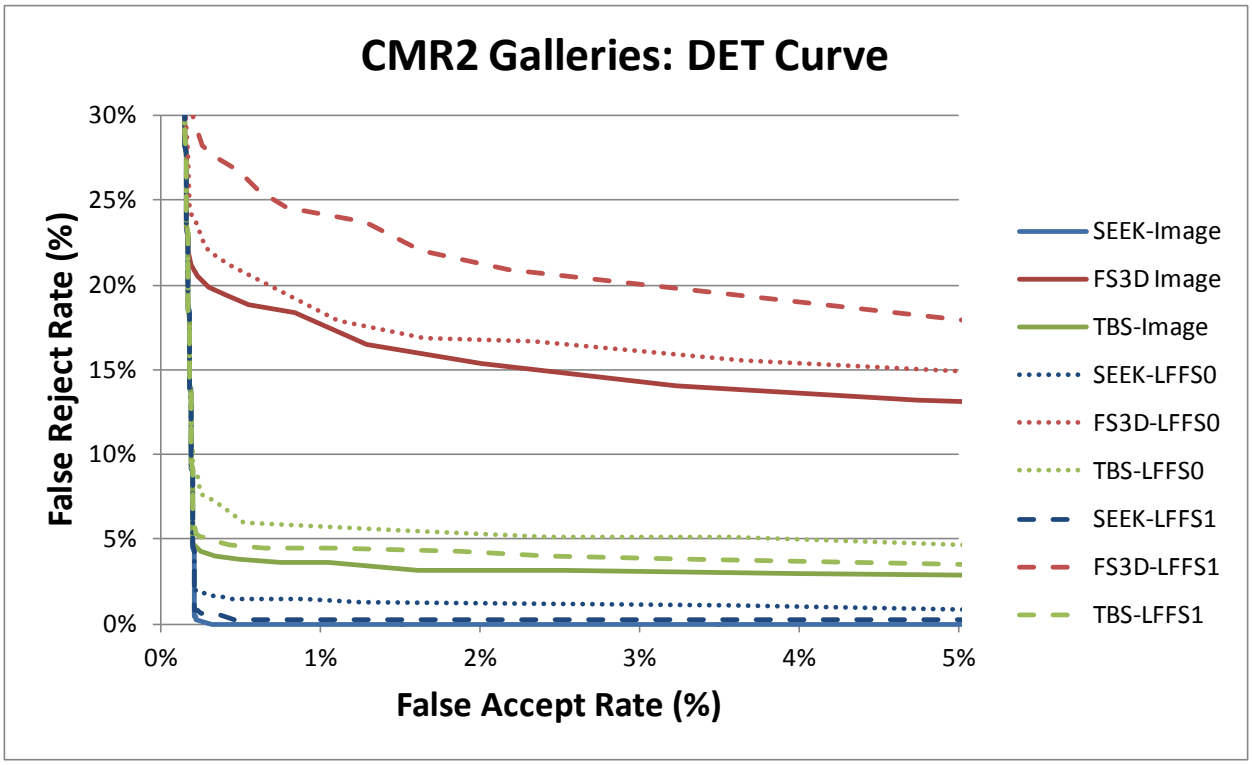

Figure 8: CMR2 Galleries DET Curves

5.1.3 Comparison of Similarity Scores

The similarity score distribution and averages from each matching run were examined and compared between devices and data types. The similarity score mean and standard deviation for each specific matching run, including the False Matches, can be found in APPENDIX A: MATCHING RUN DETAILS. A comparison of the TM similarity score averages are shown in Figure 9. The averages are consistent with the analyses of the TMR and DET curves – image matching scores were the highest, with the LFFS1 scores slightly (but consistently) higher than the LFFS0 matching scores.

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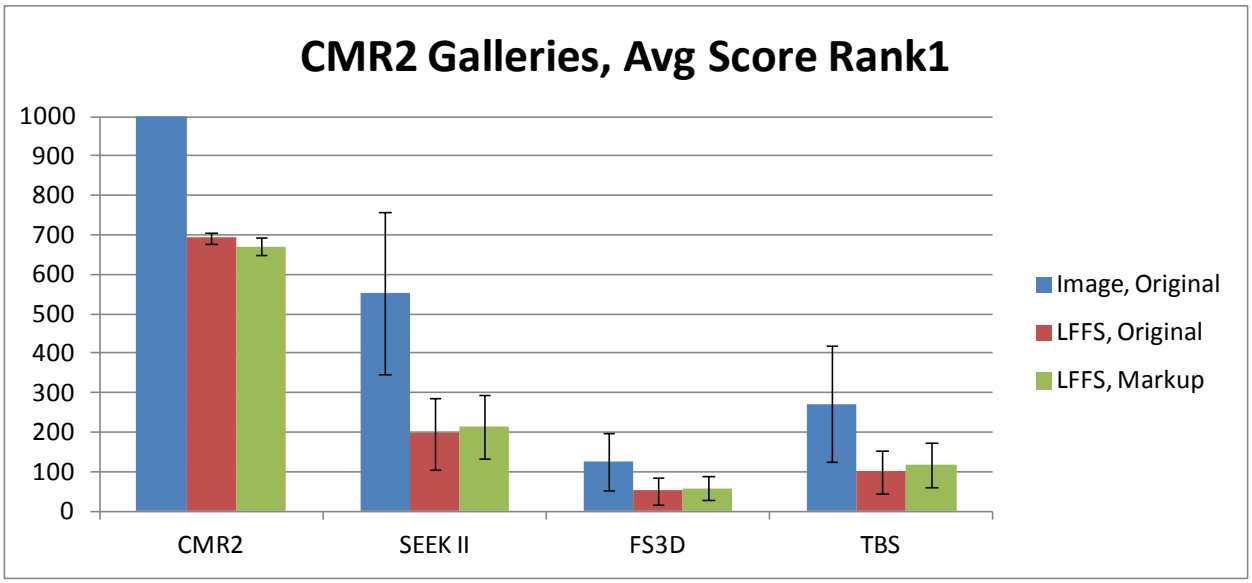

Figure 9: Comparison of CMR2 Galleries Similarity Scores

An examination of the similarity score distributions of the TMs yielded an interesting but expected trend. When moving from the image probe sets to the LFFS0, the scores collapsed to a narrower distribution and shifted to a lower mean value. The overall shape and position of the LFFS1 vs. LFFS0 did not noticeably change (within the inherent fluctuations of the score frequencies). Figure 10 is an example of this behavior, showing the SEEK matching runs. The other device datasets had similar shifts in distribution.

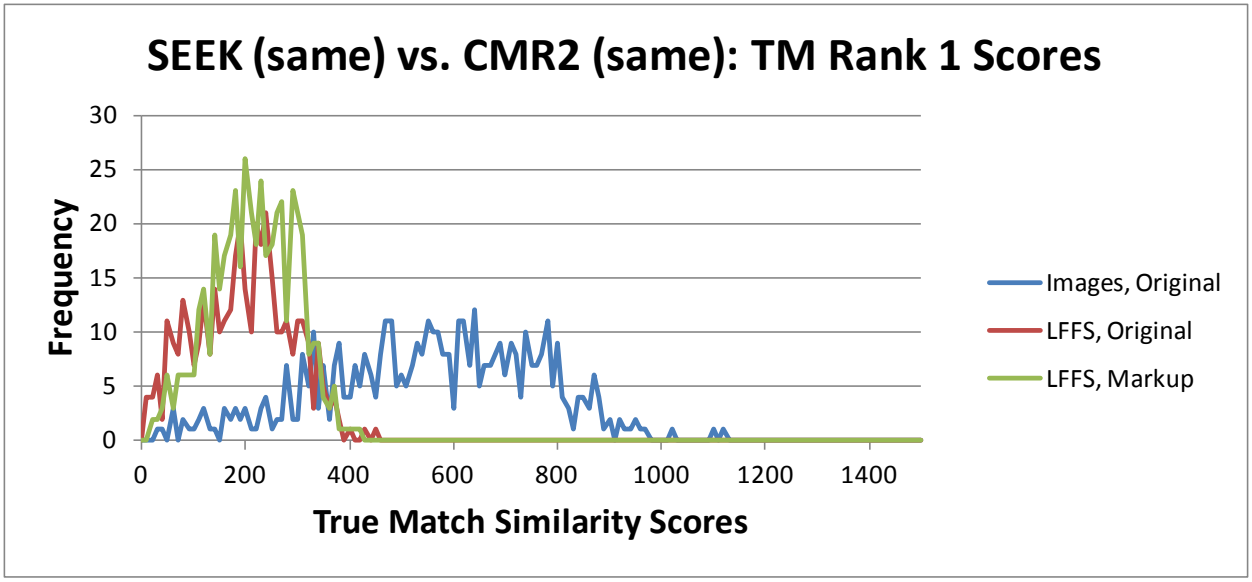

Figure 10: Comparison of Similarity Score Distributions

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5.1.4 Matching Runs – Differing Data Types

Matching runs were also performed using differing probe and gallery dataset types to confirm that there were not any anomalous results. Table 6 shows the TMR and Rank 1 and TM similarity scores for the matching runs for cross data type runs. The results establish a baseline expected performance, no significant outcomes were observed. All matching runs performed well. For the runs with a fixed image gallery and different probe data types, the TMR lowered slightly as the probes moved from image to LFFS0 to LFFS1. This is contrary to the results in Section 5.1.1 Comparison of TMR at Rank 1 where LFFS1 performed better than LFFS0. The conclusion is that more information in the gallery set is beneficial even if automated marking is erroneous since it provides more flexibility in optimizing the mapping of the probe marks. However, when the gallery is processed to possess pre-determined marks during ingestion, minutia accuracy improves matching results.

Table 6: Differing Data Type Matching Runs Results

	TMR @ Rank 1	TM Score		TMR @ Rank 1	TM Score
SEEK Image vs. CMR2 Image	99.8%	553 ± 205	**TBS Image vs. CMR2 Image**	96.6%	273 ± 147
SEEK LFFS0 vs. CMR2 Image	99.4%	207 ± 85	**TBS LFFS0 vs. CMR2 Image**	95.9%	104 ± 55
SEEK LFFS1 vs. CMR2 Image	98.9%	202 ± 76	**TBS LFFS1 vs. CMR2 Image**	95.3%	114 ± 56
SEEK LFFS0 vs. CMR2 LFFS0	99.4%	197 ± 90	**TBS LFFS0 vs. CMR2 LFFS0**	94.9%	100 ± 56
SEEK LFFS1 vs. CMR2 LFFS1	99.6%	215 ± 79	**TBS LFFS1 vs. CMR2 LFFS1**	95.5%	117 ± 56

5.2 Deviation Logs

The master deviation log for CMR2-SEEK and CMR2-TBS paired MDT sessions provides robust data to explore the nature of minutiae and their deviations across the 130 subject sample set. The data content is described in Section 4.2 Deviation Logs. The goal was to understand the distribution and content of minutiae within a contact device dataset (i.e., SEEK) and compare and contrast with a contactless sensor (i.e., TBS).

5.2.1 Magnitude Distribution of Deviations

The minutia deviations were binned across a range of deviation distances and plotted to create frequency distributions. This exercise is intended to answer the question: Do image probes from the contactless TBS possess a different distribution of minutia deviations from the CMR2 baseline than the more traditional SEEK images? Note that this work is examining the 2D gray scale rolled-equivalent transformations of the contactless TBS images and processed by the TBS device and vendor capture software.

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Figure 11 depicts the frequency distribution of distance deviations (i.e., ΔD) for the entire minutia set from CMR2-SEEK and CMR2-TBS. The distributions are nearly identical, which is surprising. One of the primary assumptions in working with contactless biometric scanners is that the contactless fingerprint images are not deformed by pressing onto a platen. Therefore, their minutia features are inherently deviated from those from contacted-based finger captures. The more likely explanation is that the unwrapping method utilized by TBS in translating a round finger surface to a 2D flat image has been implemented well. Information on the type of unwrapping used was unfortunately not available.

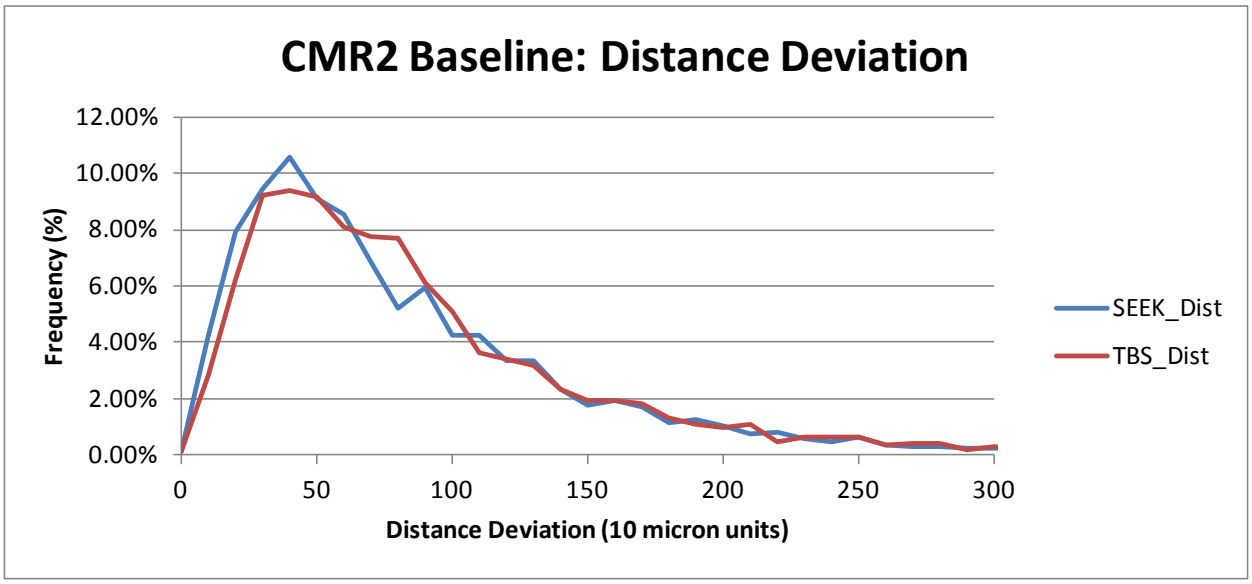

Figure 11: Frequency Distribution of Distance Deviations

The axial deviations along the X and Y axis were also available from the master deviation logs. These X and Y deviations have been derived from coordinates corrected for the center points designated in the MDT session. As a result, they are not collinear with the image's horizontal and vertical axis. Figure 12 depicts the axial deviation distributions. Similar to the distance deviations, these distributions are surprisingly all the same. Even with an unwrapping algorithm that accounts for the curvature perpendicular to the finger's radial component (i.e., around the finger), one would expect to see the X and Y components to have different distributions. The SEEK fingerprint images were from rolled prints whereas the subject's finger was rolled at a pseudo constant pressure along the horizontal axis. Maintaining a constant pressure in the horizontal direction while rotating the finger would seem difficult to accomplish. Plus, having that pressure be the same along the vertical axis of the finger at a given contact point moment in time also seems extremely difficult and or coincidental. The logical conclusion is that the spatial position of a minutia is not sensitive to applied pressure in any linear manner or that other factors may overshadow the contribution from pressure.

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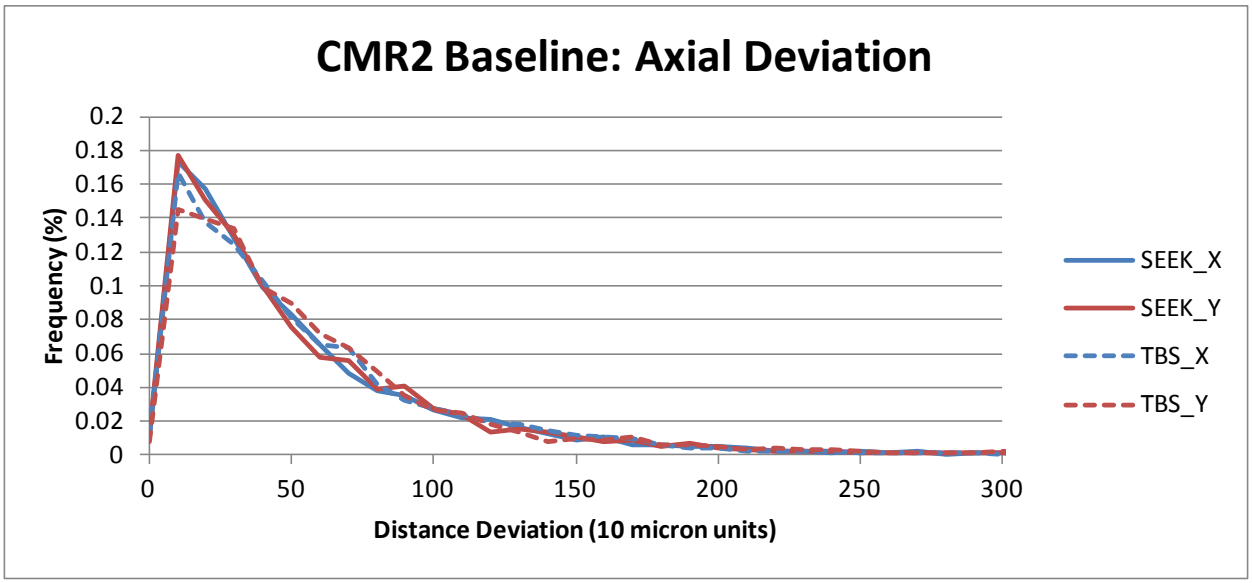

Figure 12: Frequency Distribution of Axial Deviations

5.2.2 Spatial Distribution of Minutiae

The minutia deviations were binned across a range of spatial distances and plotted to create frequency distributions. This exercise was intended to answer the question: How are the automated minutia marks distributed across fingerprint images and is there a difference between the contactless TBS images and the traditional SEEK images? Note that this work is examining the 2D gray scale rolled-equivalent transformations of the contactless TBS images and processed by the TBS device and vendor capture software.

Figure 13 shows the distribution of X positions across each entire dataset. There are two CMR2 minutia sets based on which probe set the image marks were compared and paired. The distributions are similar for all minutia sets, with a shallow bell curve centered slightly above zero. This is reasonable given that the images are rolled prints that should not have a variation in the pressure or finger cross section as the finger is rolled from one side to the other.

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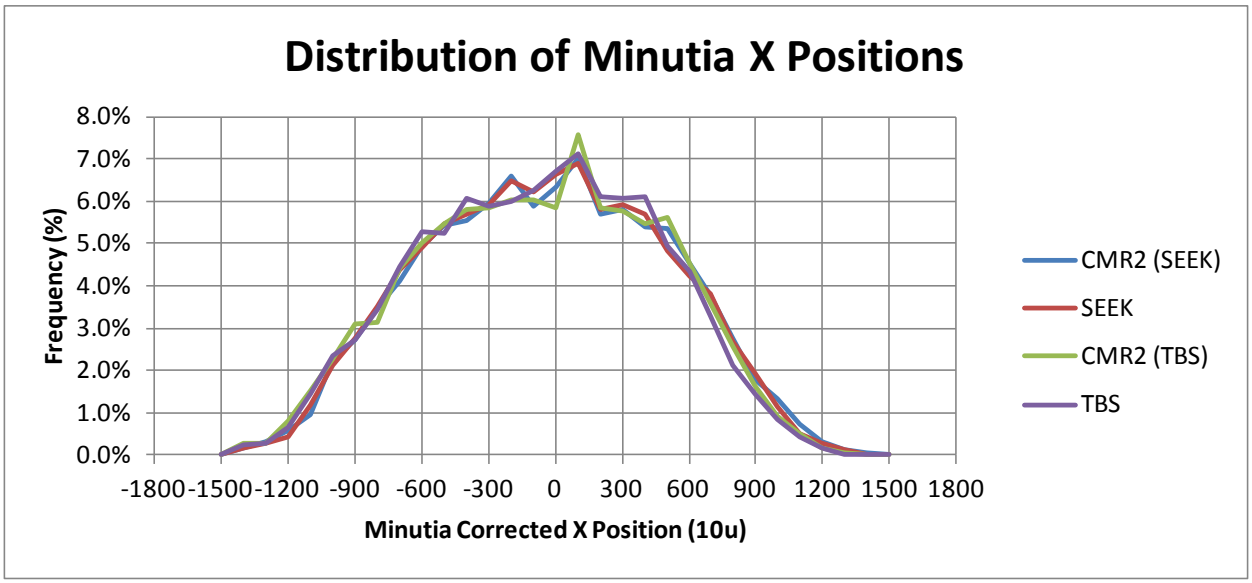

Figure 13: Distribution of Minutia X Positions

Figure 14 shows the distribution of Y positions across each entire dataset. The minutia distributions are again similar in shape. However, the center point of the distributions is not at zero but around 500. The y-axis used in MDT is the same as ULW, such that positive y goes from top to bottom. This means that there is a greater frequency of minutia marks in the lower half of the fingerprint image. This is not unreasonable since that corresponds to a region of the finger with more uniform shape and curvature. The tip of the finger is in the negative Y direction. That region appears to have fewer features or features that are less resolvable, perhaps due to the curvature of the end of the finger.

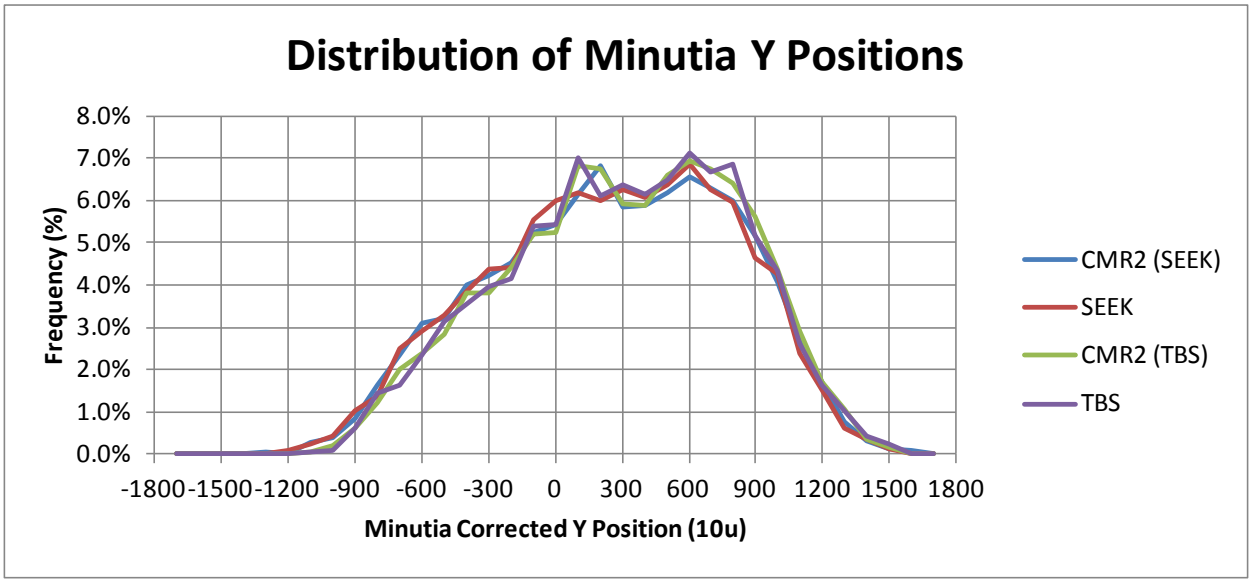

Figure 14: Distribution of Minutia Y Positions

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Figure 15 shows the distribution of calculated radial positions across each entire dataset. The minutia distributions are again similar in shape. The center point of the distributions is at approximately 830. This is mainly due to the off-zero center of the Y position, which is then factored into the radial position value. To illustrate the mean radial position, the fingerprint images from one subject for each device is shown in Figure 16 with a circle added for reference. The circle has a radius of 830 and a minutia mark has been selected on each print that is approximately at that distance from the center point (colored blue). It is unclear if anything further can be concluded from the radial mean position beyond the same explanation of the Y position center frequency.

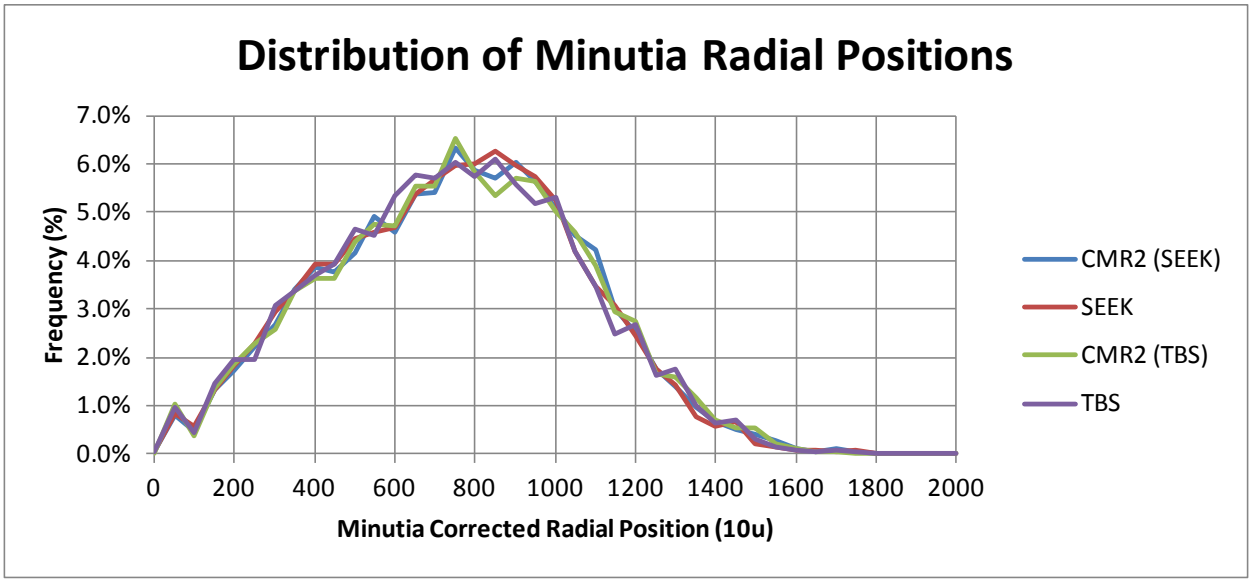

Figure 15: Distribution of Minutia Radial Positions

Figure 16: Comparison of 830 Radius Positions
Fingerprint images with paired minutiae for CMR2, SEEK, and TBS (left to right). A circle guide with radius = 830 units is placed over the center point of each for reference.

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5.2.3 Minutia Spatial Position vs. Deviation

The minutia deviations were plotted against their spatial positions to determine if there is any correlation. The X, Y, and radial positions were plotted against the distance deviation. The radial distance was calculated using the minutia position in the CMR2 baseline fingerprint image.

Figure 17 and Figure 18 show scatter plots of the radial distance vs. deviation with the values in the standard 10 micron units. There does appear to be an upward trend in both cases, but the variability from the individual points makes it difficult to discern.

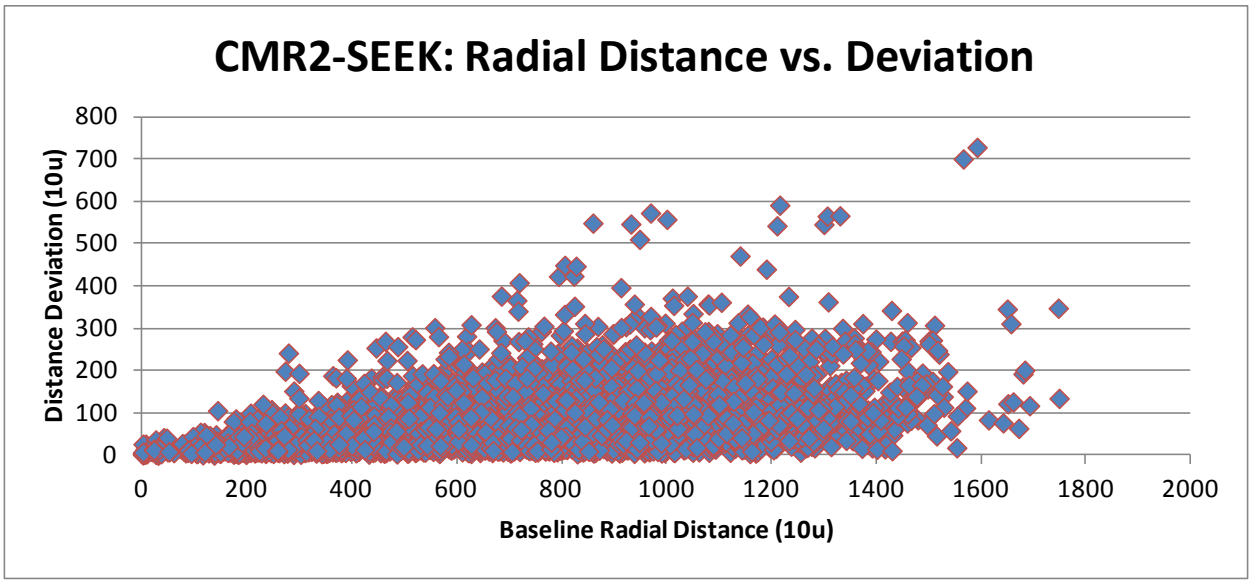

Figure 17: CMR2-SEEK Radial Distance vs. Deviation

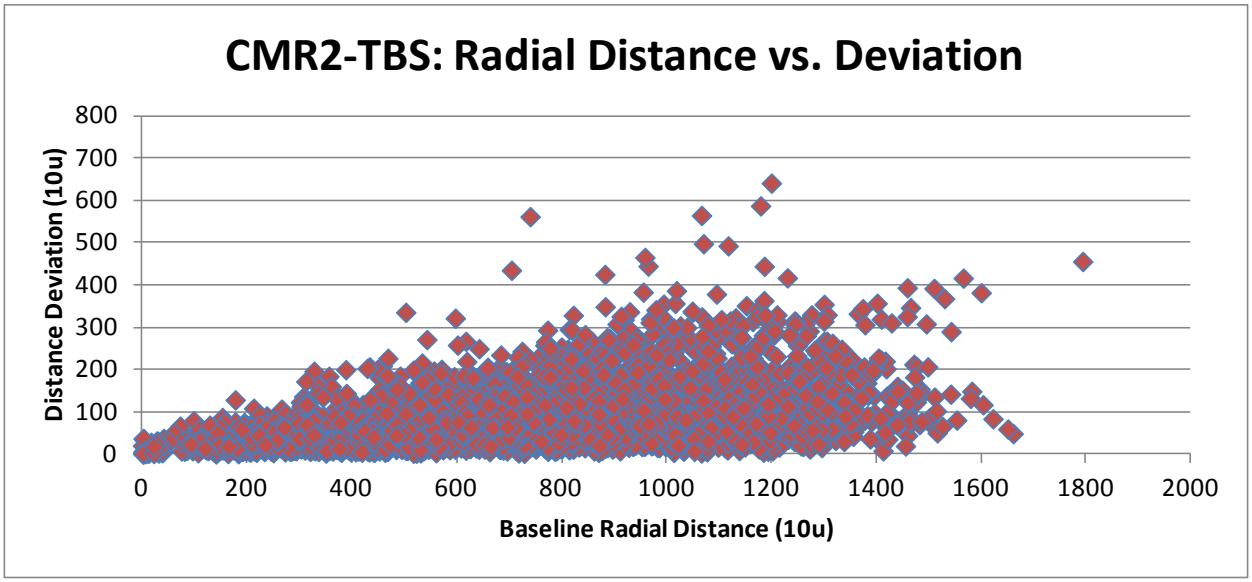

Figure 18: CMR2-TBS Radial Distance vs. Deviation

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To simplify the data presentation, the minutiae were binned into radial distances and then the distance deviations for the minutiae within a bin were averaged. The result is shown in Figure 19. The wide fluctuation at high radial distances is the result of there being significantly few minutiae points available to calculate the average deviation in those bins. For example, there were 16 minutiae points from 1500 – 1550 and only 6 from 1550 – 1600.

Using this approach there is a clear correlation between the distance that a given minutiae is away from the center point and its average deviation. The linear behavior suggests a uniform scaling factor between the CMR2 and the comparison images. The deviation is well beyond the allowed position linearity error allowed under the FBI Appendix F certification (i.e., ±1%). Since the SEEK II is Appendix F certified, this behavior cannot be attributed to an image processing error. Another puzzling outcome is that the plots for the SEEK and TBS are the same. The SEEK images are real 2D contact captured images, while the TBS images are 2D grayscale equivalent images transformed from a contactless capture. The chances that the scaling factors are the same for both would be a notable coincidence. One might explain the trend and the similarity of SEEK and TBS as the result of the change in finger surface curvature at the end of the finger. However, the same finger was captured on the CMR2, which is the baseline image used for comparison. That curvature from rolled-prints should be zeroed out across CMR2 vs. SEEK and probably modeled in the TBS transformation. Although the CMR2 has a larger platen for capture, this also should not be a factor in the deviations since if minutiae are not captured due to a smaller sensor (i.e., CMR2 vs. SEEK), they would not be included in this minutia dataset. This is a result that deserves further research and investigation. Processing rolled-ink ten print cards for the same subjects (which are available in the parent dataset from WVU) might provide further insight as to whether the deviation behaviors are physical or an aspect of the analysis approach that is not readily apparent.

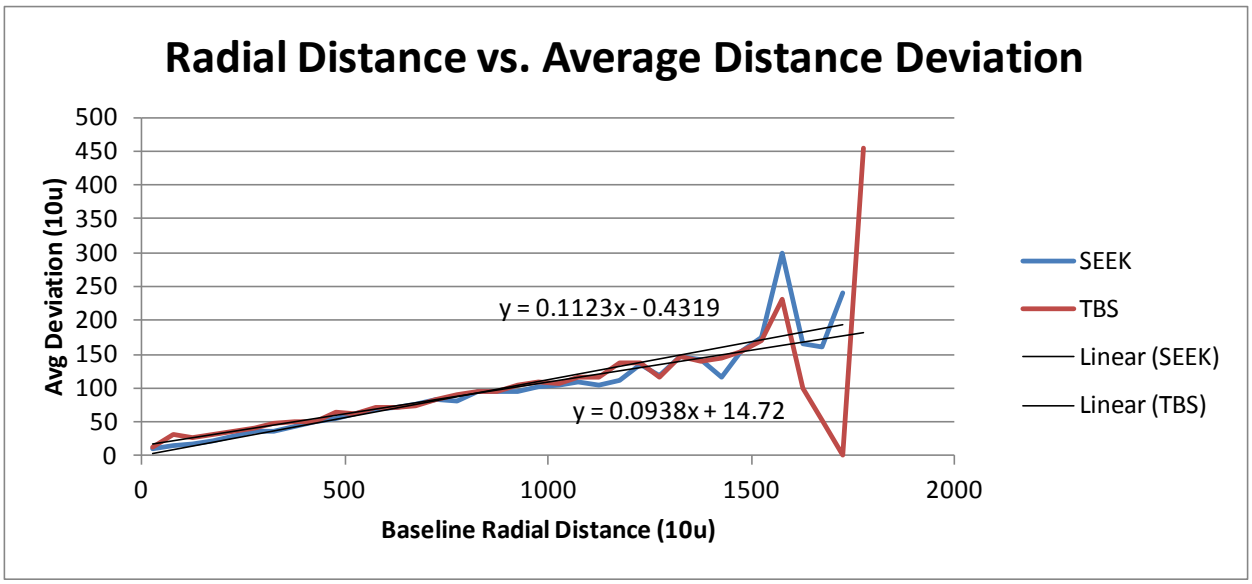

Figure 19: Radial Distance vs. Average Deviation

In an effort to deconvolute and better understand the distance vs. deviation correlation, the X and Y Positions were plotted against the binned and averaged X/Y deviations. The X distance vs.

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deviation plot is shown in Figure 20. The SEEK and TBS plots are the same and show little spatial variation across the images. This is consistent with the rolled print capture method in which the finger is rolled in a pseudo constant motion and pressure in the x direction. The finger curvature and shape is also constant in that direction. Although the corrected X axis is not directly aligned with the image x-axis (as explained in Section 3.3 Minutia Pairing for Deviation Analysis). This might be why there is a slight slope in the linear trend lines of these plots.

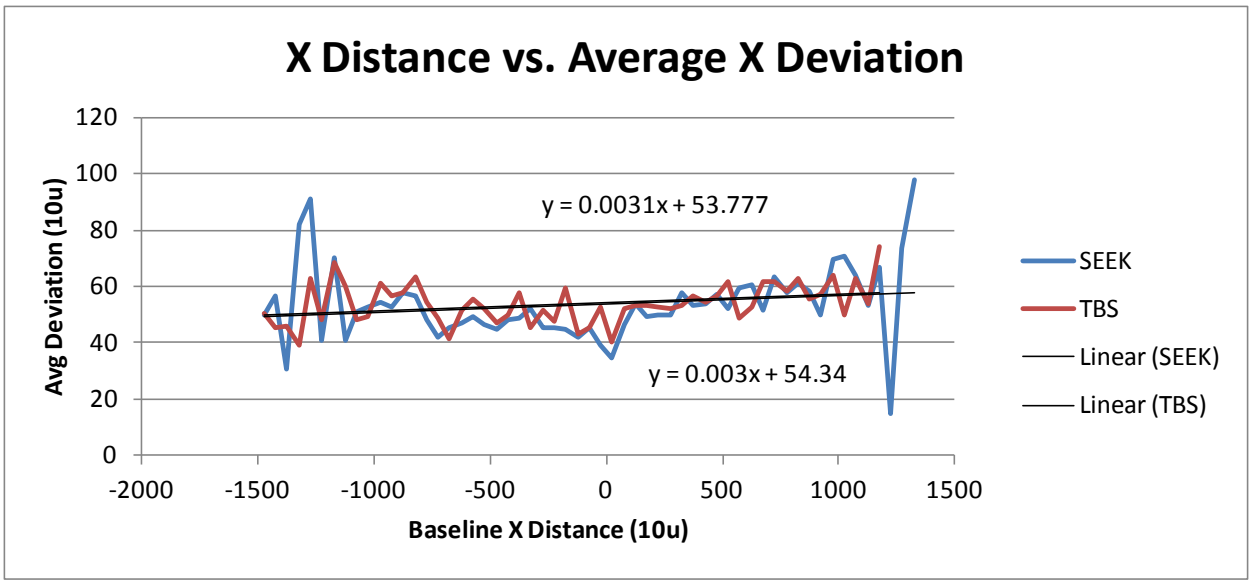

Figure 20: X Position vs. Average Deviation

The Y position vs. deviation plotted using the same binning and averaging approach is shown in Figure 21. This is the only position vs. deviation plot where SEEK and TBS do not have the same trend lines. When examining the Y positions and Y deviations, the SEEK minutiae increase in deviation when moving from the top of the image to the bottom, while the TBS minutiae are the opposite. These differences could be related to the unwrapping model used by TBS to map the contactless image to a 2D rolled-equivalent (e.g., cylinder vs. cone vs. other). The method used was unavailable to the researchers. A more carefully construction research effort that applied different unwrapping methods would be needed to determine if this is the cause. However, the fluctuations are significant and it is possible that these trends are not real artifacts. More minutia data is needed to determine if these are real effects.

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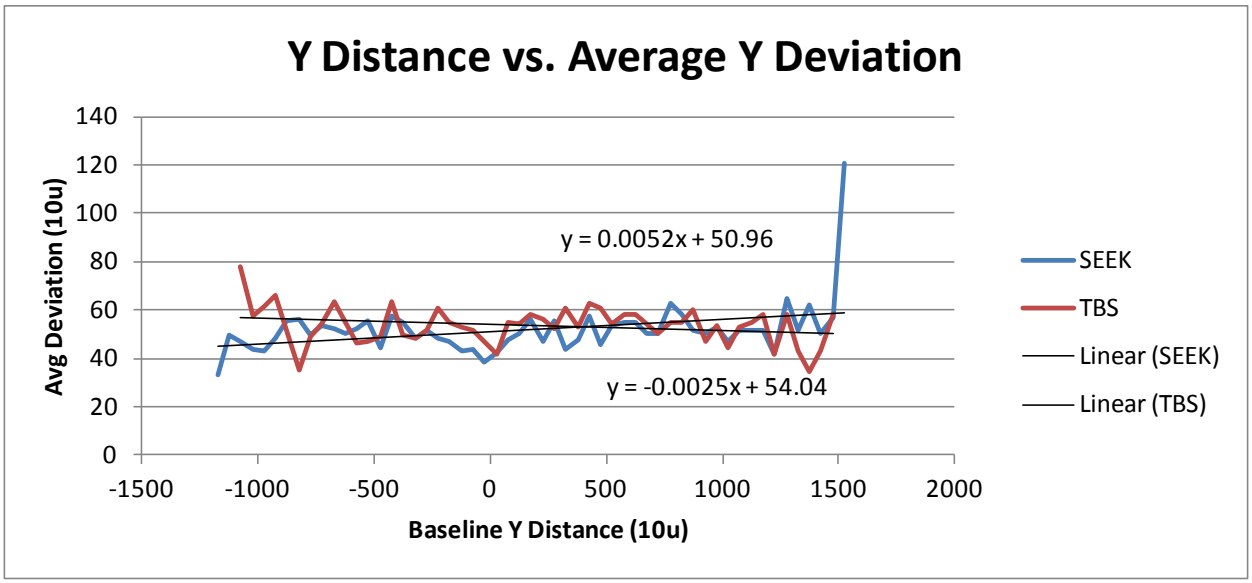

Figure 21: Y Position vs. Average Deviation

5.2.4 Similarity Score

The minutia deviations were plotted against the similarity score from matching to determine whether there is a correlation. The distance deviation for a given MDT session's paired minutiae was averaged and combined with the match score for the comparison image submitted as a probe against the full CMR2 LFFS1 gallery. The scatter plots for SEEK and TBS are shown in Figure 22. As a reminder, the similarity score distributions for the MDT session image probe sets can be found in Sections 4.3.1.2 SEEK All Pairs and 4.3.2.2 TBS All Pairs.

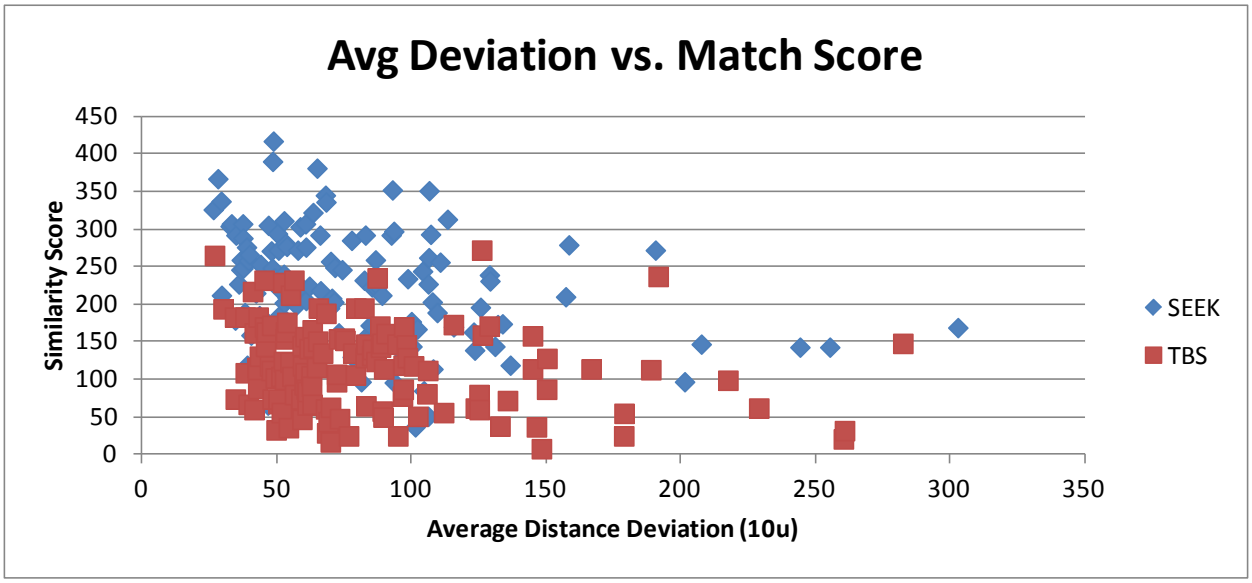

Figure 22: Average Deviation vs. Match Score

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The deviation vs. match score plots are difficult to interpret because of the variation in the data. To mitigate that behavior, a second plot was created wherein the average distance deviations were sorted and then each group of ten values averaged. The corresponding similarity scores were also averaged. The result, Figure 23, reduces the displayed scatter and shows that there is trend. The average similarity score decreases with increasing deviation. This is a reasonable and expected result. The less in register a set of minutiae are between probe and gallery image, the less similar the images are to the matcher. However, the fact that there were significant variations (i.e., noise) in the raw presentation suggest that there may be other factors that contribute more significantly to the calculated similarity score. Without intimate knowledge of how Neurotechnology's MM determines the similarity score on a technical image processing level, it is difficult to postulate what those factors are. Although later analysis does suggest that the position of minutiae relative to nearest neighbors likely plays an important role (see Section

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5.3 Matching Runs – Deviation Filtered Datasets).

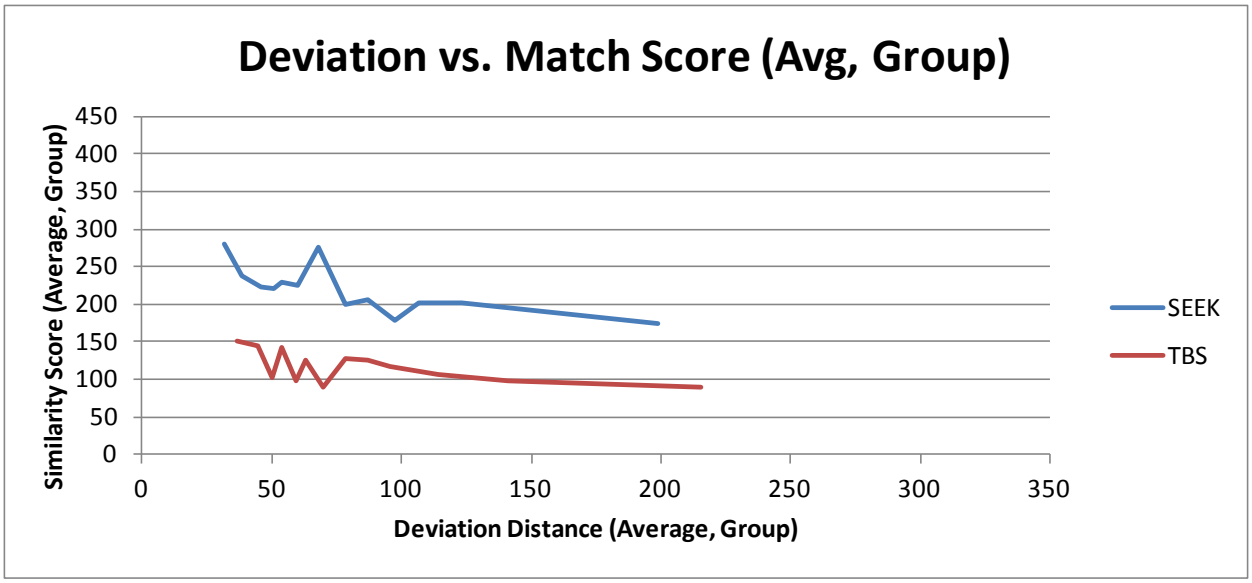

Figure 23: Deviation vs. Match Score (Average, Group)

The deviation logs and MDT dataset matching runs were used to examine the effect that the number of minutia pairs had on similarity score. The similarity scores from the All Pairs matching runs (see Sections 4.3.1.2 SEEK All Pairs and 4.3.2.2 TBS All Pairs) were combined with minutia data. Figure 24 shows the scatter plots for each MDT session. To improve readability, the number of minutia pairs was sorted and then each group of ten averaged, the corresponding similarity scores were also averaged to produce Figure 25. As expected, the number of minutiae present within both probe and gallery is directly related to the similarity score. The average plots also indicate that there is plateau or a reduction in impact upon reaching a certain number of minutiae. For both CMR2-SEEK and CMR2-TBS matches, it appears to be around 50 common minutiae.

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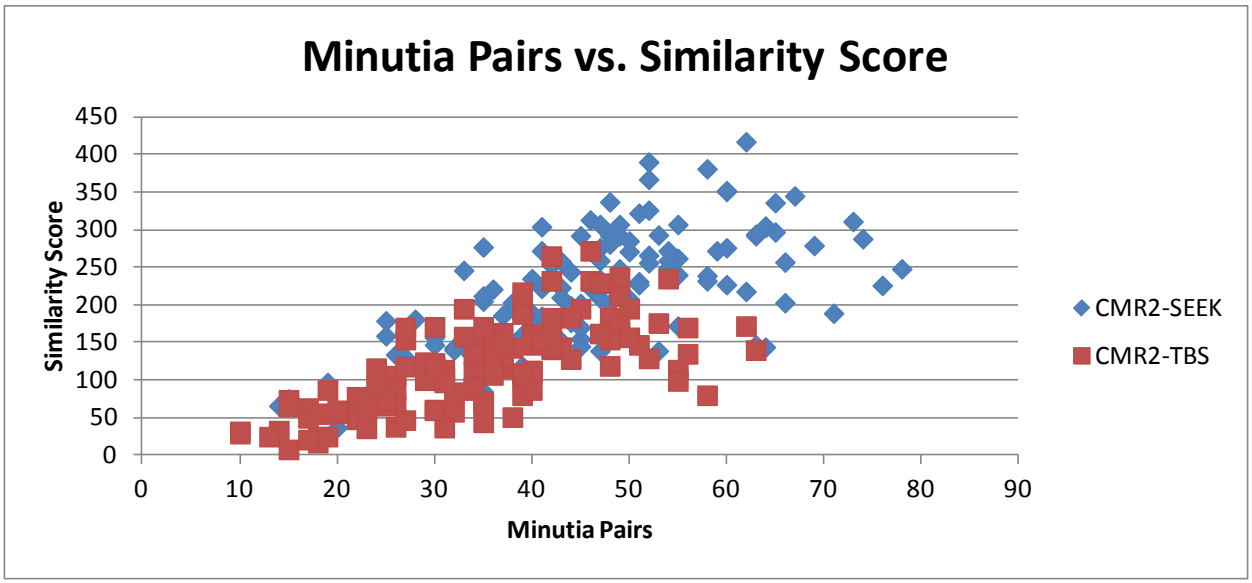

Figure 24: Minutia Pairs vs. Similarity Score

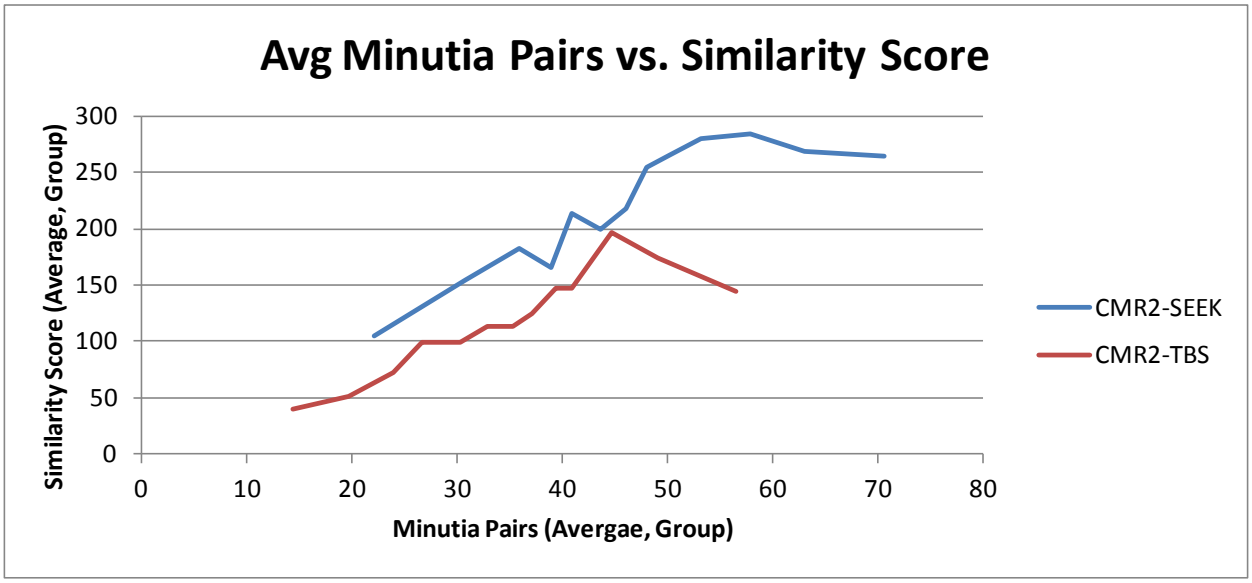

Figure 25: Average Minutia Pairs vs. Similarity Score

In addition to the number of minutia pairs, the fraction of minutia present in the MDT pairing was examined with respect to similarity score. The number of paired minutiae for an MDT session was divided by the total number of minutiae in one of the LFFS1 files to produce a Fraction of Minutiae value for each subject/sensor. This was plotted against the similarity score from the All Pairs matching runs (see Sections 4.3.1.2 SEEK All Pairs and 4.3.2.2 TBS All Pairs). The results are shown in Figure 26 and Figure 27. These graphs investigate the notion that the higher the fraction of minutiae common to both gallery and probe images, the less chance of a false minutia match during the matching run. If there are fewer false alternatives when pairing a minutiae mark in the probe with one in the gallery, then the probability of a

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correct match is improved and therefore the similarity score will increase. Although there is significant variability in both CMR2-SEEK and CMR2-TBS, there is a positive correlation between the fraction of minutiae in pairs and the similarity score. The SEEK matching appears more sensitive to the fraction of minutiae in pairs as compared to TBS minutiae. This is likely due to the fact the CMR2-SEEK sessions have (on average) a greater number of minutiae than CMR2-TBS (46 vs. 35) so a fractional increase in minutiae pairs is a larger absolute number of common minutiae.

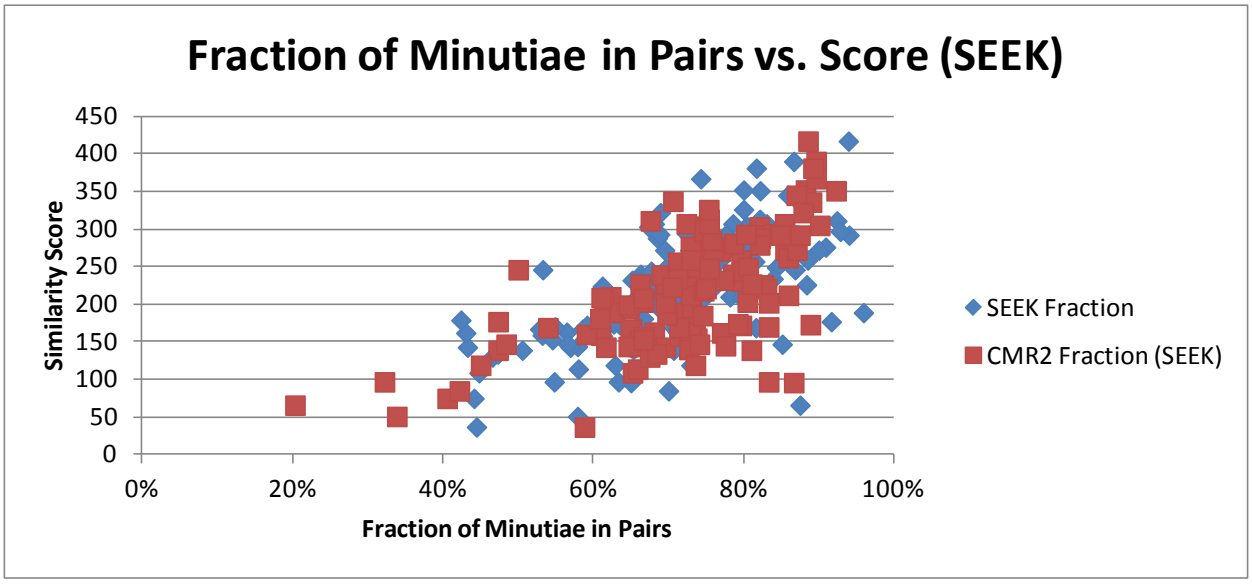

Figure 26: Fraction of Minutiae in Pairs vs. Score (SEEK)

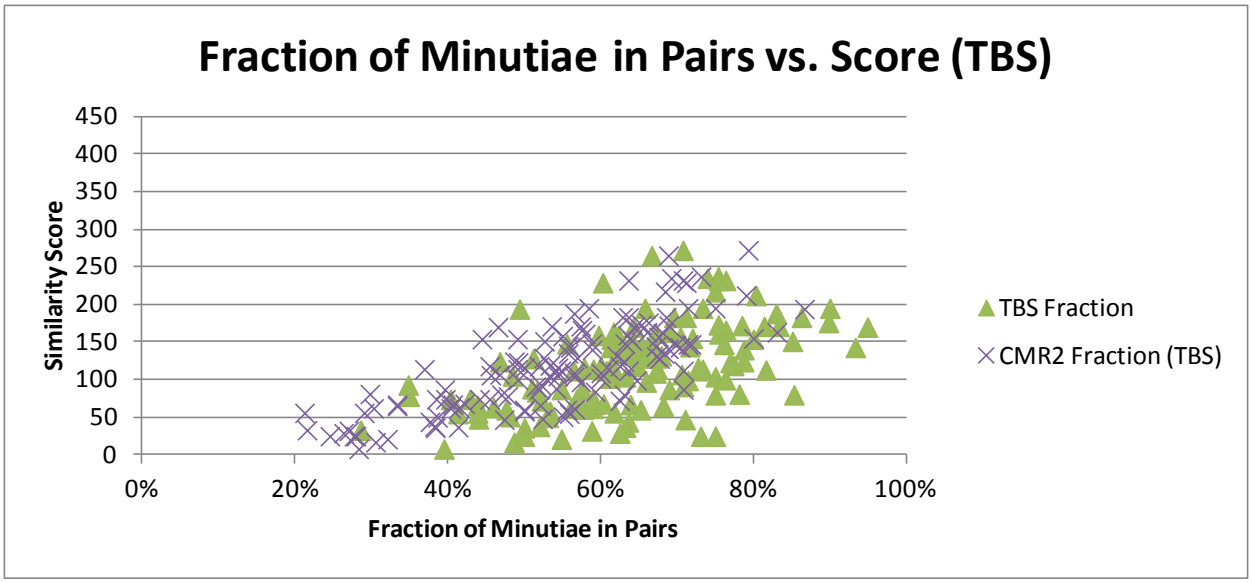

Figure 27: Fraction of Minutiae in Pairs vs. Score (TBS)

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5.2.5 NFIQ Score

The final aspect of the master deviation logs that was analyzed was the correlation between NFIQ score and similarity score or minutia deviations. NFIQ is an algorithm developed by NIST that "produce[s] a quality value from a fingerprint image that is directly predictive of expected matching performance."[7] It is intended to provide a metric for determining the suitability of a given fingerprint image for biometric matching processes. The NFIQ score distributions for the three datasets (i.e., 130 subjects, right index finger image) are provided in Figure 28. CMR2 has the best distribution, with the majority of images categorized as Excellent. SEEK is next in quality with the majority either Excellent or Very Good. The TBS dataset is third with Very Good – Good images.

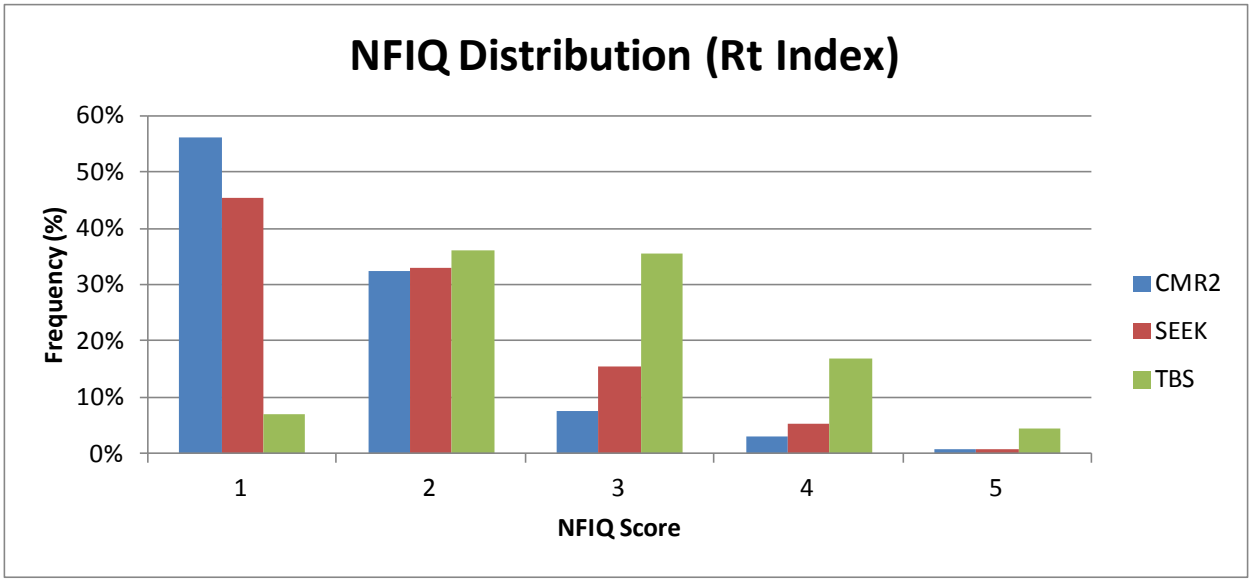

Figure 28: NFIQ Distributions

The similarity scores for images within each NFIQ score were averaged and then plotted as a function of NFIQ score. Two plots for CMR2 are shown in Figure 29 depending on their paired probe image. There is a correlation between image quality and similarity score, with scores decreasing with decreasing quality. However, the effect is not as dramatic as one might expect.

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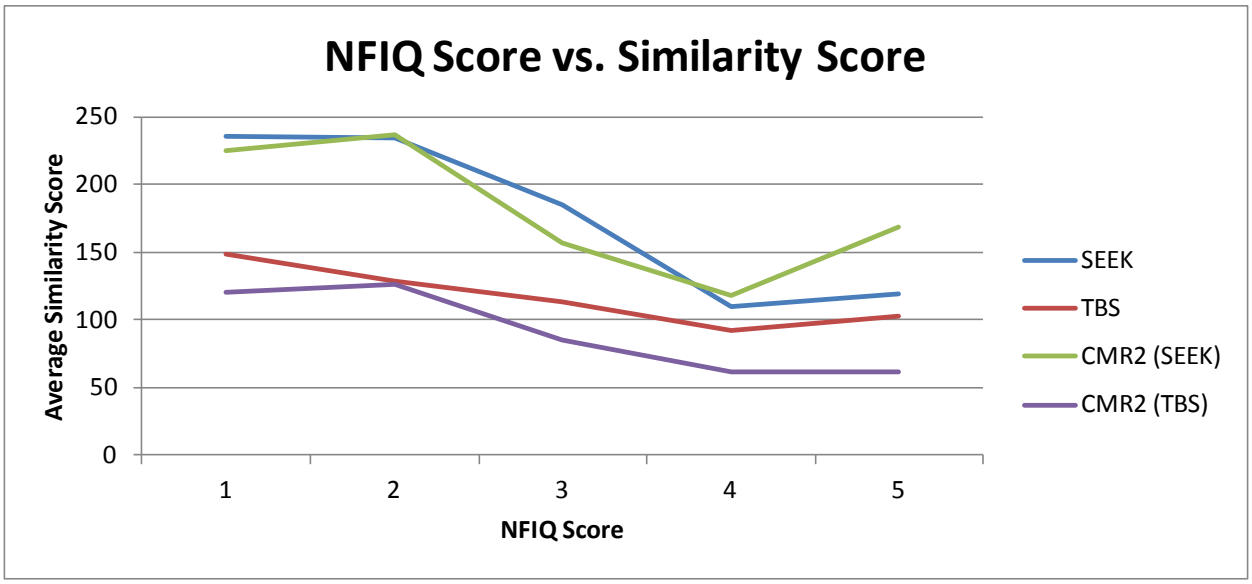

Figure 29: NFIQ Score vs. Similarity Score

The average distance deviation for images within each NFIQ were averaged a second time and then plotted as a function of NFIQ category. These results are shown in Figure 30. From the previous section, there may be a slight correlation between deviation and similarity score (see Figure 23). Combined with the NFIQ score vs. similarity score plots, the expected result from this analysis is that as the NFIQ score increases (i.e., image quality decreases), the average distance deviation would also increase since the location and direction of minutia marks would be adversely affected by any difficult in reading fingerprint image characteristics. That is the case for CMR2-TBS, but is does not appear to be the case for CMR2-SEEK. One explanation is that the subjective nature of the CLPE vetting process allowed a greater degree of error in the position and direction of minutiae when examining TBS images due to their atypical and more obtuse overall appearance. Another possibility is that since the NFIQ score is determined using a multi-dimensional image feature vector (11 different image features),[8] that TBS images have a greater frequency of quality discrepancies that contribute to minutia position errors (and therefore calculated deviations), while SEEK images have other quality issues (when present).

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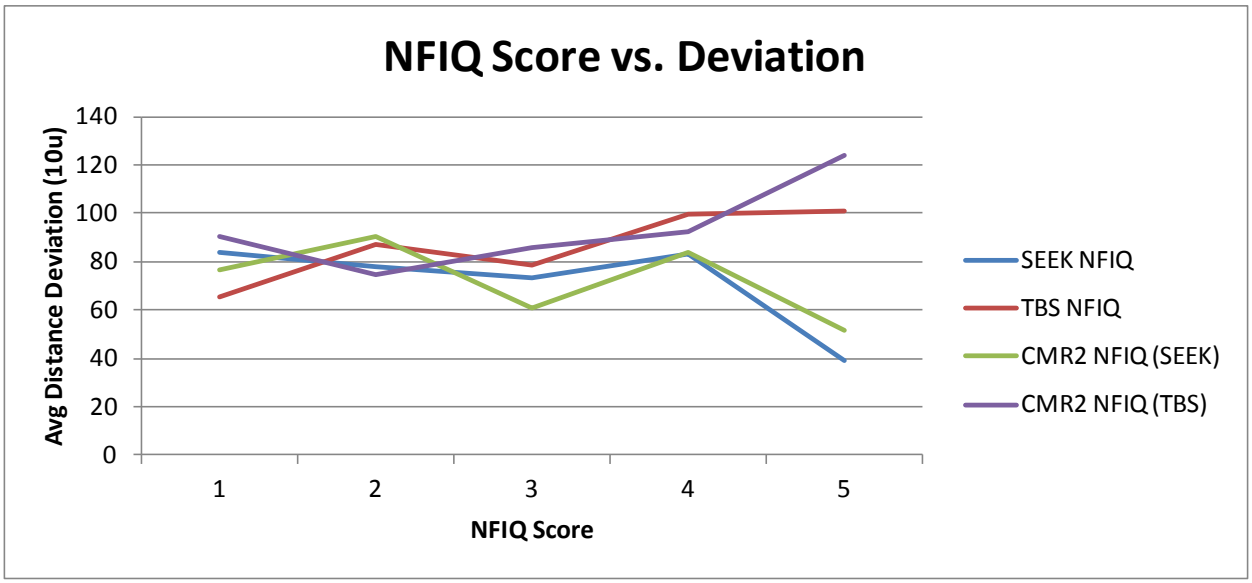

Figure 30: NFIQ Score vs. Deviation

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5.3 Matching Runs – Deviation Filtered Datasets

The result of the deviation filtered dataset matching runs provides an opportunity to directly answer the question: How is the match performance affected by probe data with lower/higher minutia deviations? The method of creating the datasets and the reasoning behind choosing ΔD = 63 as the differentiating threshold is discussed in Section 4.3 Matching Runs – Deviation Filtered Datasets. A common belief/assumption in the biometrics community is that minutia deviations are a factor in determining the similarity score (and therefore match performance) of a fingerprint match and that 2D rolled-equivalent images from contactless sensors are at a disadvantage due to this fact when submitted as probes against a legacy database.

Table 7 lists the various results and metrics of the deviation filtered datasets and matching runs. The choice of using ΔD = 63 is validated in that the average number of minutiae is almost the same between the *63low* and *63up* datasets within SEEK and TBS. The random LFFS files were created using the exact number of minutia in each subject's filtered file. As expected, the average distance deviation is lowest for *63low* datasets, with the two random datasets in each sensor set having approximately the same average deviation. Finally, the *63up* datasets have the highest average deviation.

Table 7: Deviation Filter Dataset & Match Run Results

Filter Method	SEEK TMR	SEEK TM Score (Avg)	SEEK # Minutiae (Avg)	SEEK Deviation (Avg)	TBS TMR	TBS TM Score (Avg)	TBS # Minutiae (Avg)	TBS Deviation (Avg)
63low	95%	178 ± 89	24	34	82%	102 ± 60	16	36
63low random	88%	137 ± 91	24	79	72%	80 ± 61	16	83
63up	88%	132 ± 70	22	116	82%	89 ± 50	18	114
63up random	83%	113 ± 70	22	81	79%	73 ± 50	18	85

The distribution of minutia deviations shown in Figure 31 and Figure 32 illustrates the filtering and breakdown of the various datasets. The *63low* and *63up* datasets show a clear delineation at ΔD = 63 and align with the distribution of the full datasets, both in these figures and in Figure 11. The random datasets are similar to the full dataset of all minutiae, but for both SEEK and TBS, they are separated with *63low random* having a higher frequency of low deviations and *63up random* having more high deviation minutiae. At first thought, one would assume that since they are an aggregation of randomly selected minutiae that they should mimic the full dataset distribution since they are derived from that set. If the total number of minutiae was randomly selected, then that would be true, but in this case the random files have minutiae randomly selected from a closed subset of minutiae available for that specific subject's image file. The filtering process applied to the parent file skews the random sampling towards the filtering condition. As a result, random files using subject minutiae seed numbers from *63low* will result in more low deviation minutiae than random files using seed numbers from *63up*.

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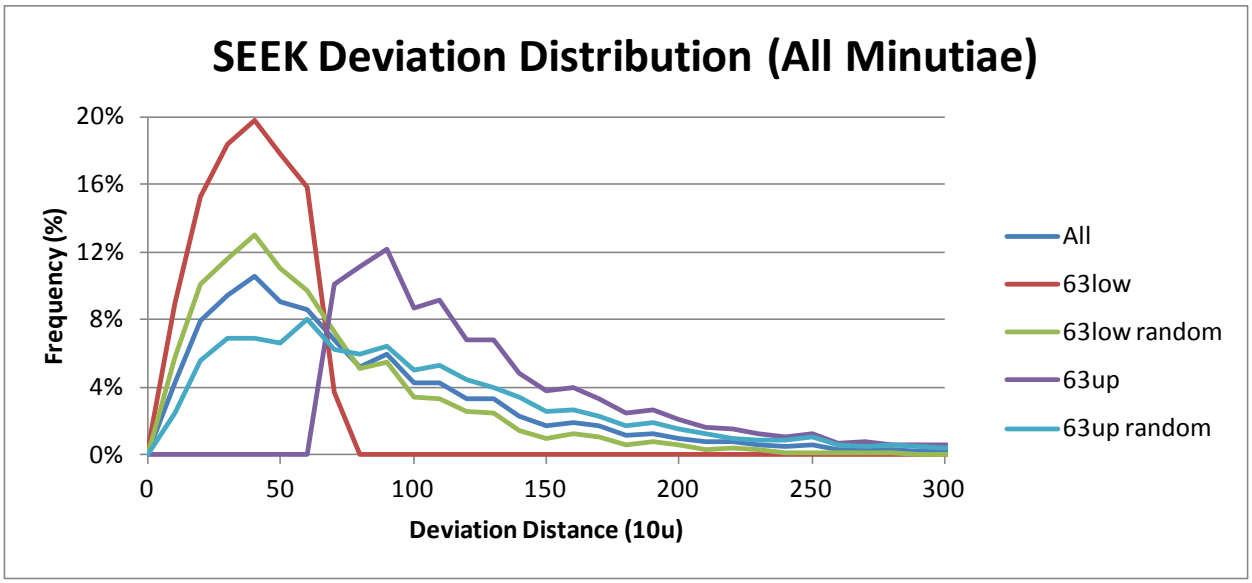

Figure 31: SEEK Filtered Deviation Distributions

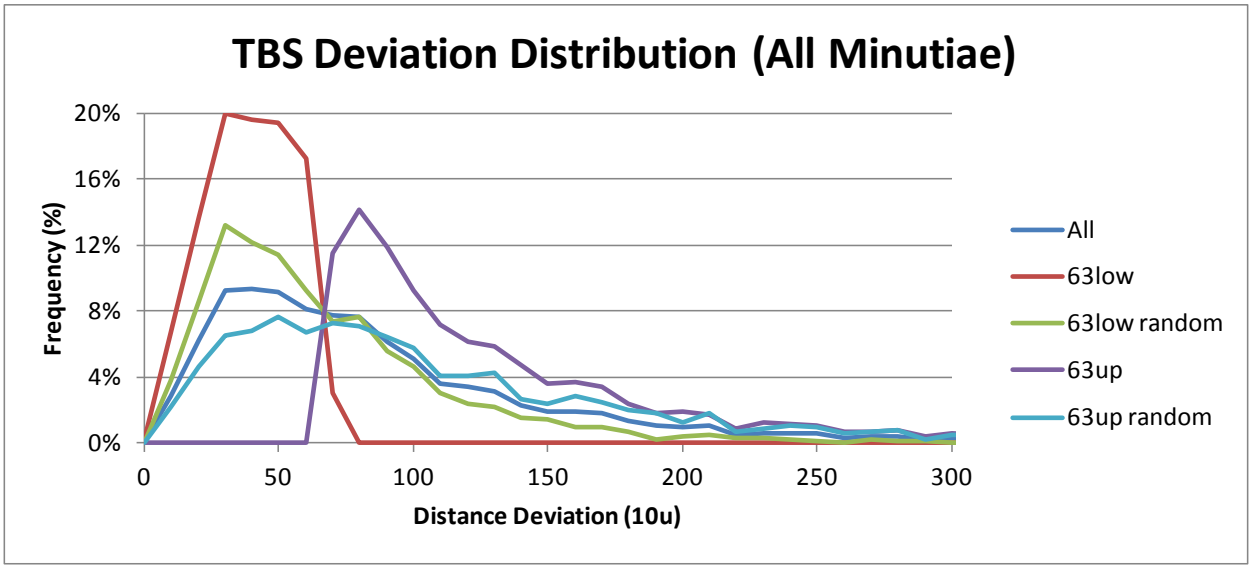

Figure 32: TBS Filtered Deviation Distributions

A comparison of the TMR at Rank 1 between the filtered and random datasets provides the most interesting results. Figure 33 shows a bar chart comparison of the TMR from

Table 7. Both SEEK and TBS have the same trend. The *63low* matching runs have the best TMR. The TMR drops when using the *63low random* dataset. The *63up* matching runs are not as good as *63low*, however they are equal or better than the *63low random* runs. Finally, the *63up random* datasets are the worse of the four runs. This does not follow the expected behavior if the minutia deviations are the primary factor for determining the similarity score. One would expect *63low random* to be worse than *63low* (which it is). However, one would expect *63up* to be worse than *63low random* due to the lower average deviation. For SEEK, *63low random* has

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an average ΔD = 79 while *63up* ΔD = 116. For TBS, *63low random* has an average ΔD = 83 while *63up* ΔD = 114. Similarly, in comparing *63up* with *63up random*, both SEEK and TBS have a higher average deviation in *63up* (116 vs. 81 and 114 vs. 85, respectively) but the TMR drops. Therefore, there is another factor(s) affecting the match performance.

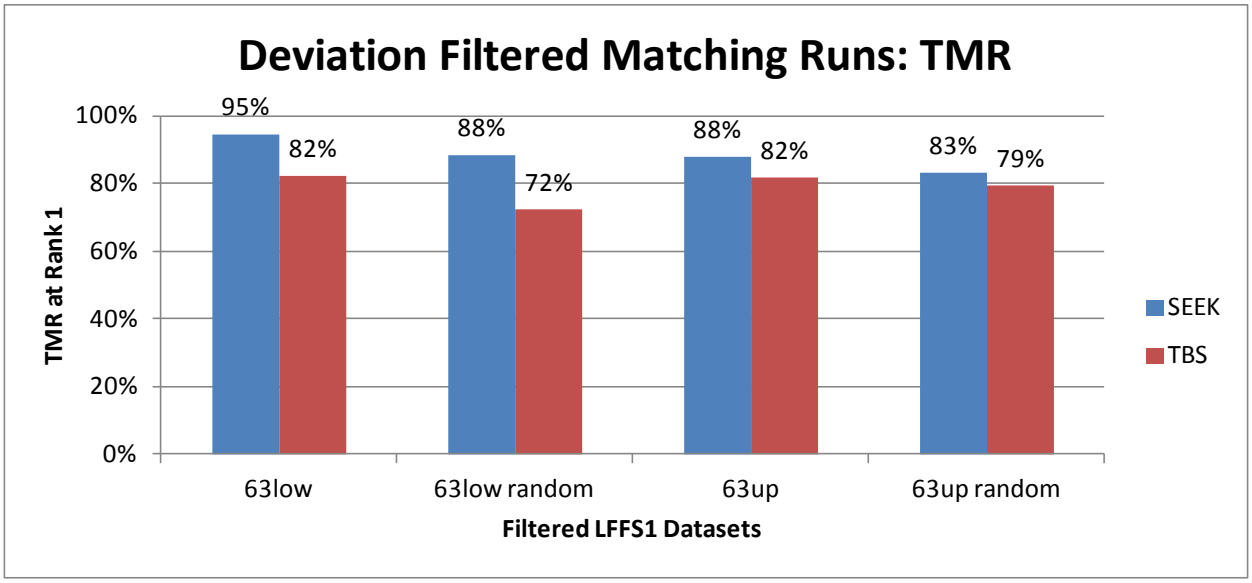

Figure 33: Deviation Filtered Matching Runs TMR

To discern what might be driving the unexpected match performances, three example subjects were selected and the MDT sessions for the *63up* and *63up random* datasets examined. The resulting images are shown side-by-side for several subjects in Figure 34 and Figure 35. One can see that in almost all cases, the minutiae in the *63up* are closer together and more clustered than the randomly selected minutia images. This supports the theory that the deviations of specific minutiae may not be as important in determining the similarity score (for the MM matching algorithm) than the network of nearest neighbors. For contactless systems, such as TBS, one could conclude from this and previous analyses that the fidelity of the image is more important for match performance than the accuracy of the unwrapping transformation applied to the contactless representation of the fingerprint.

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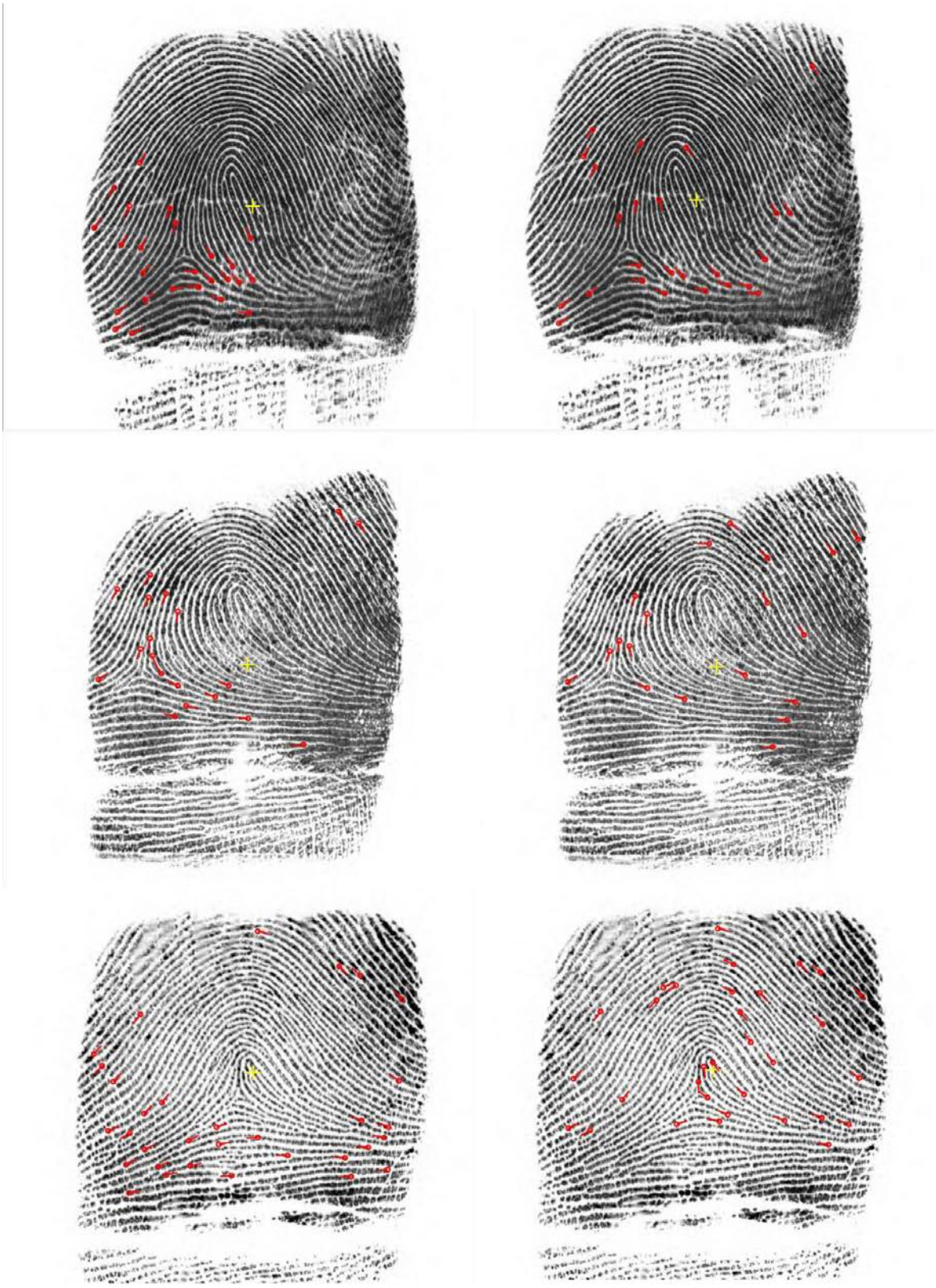

Figure 34: Comparison of Filtered Minutia SEEK Images
SEEK fingerprint images from the (left) *63up* dataset and (right) *63up random* dataset.

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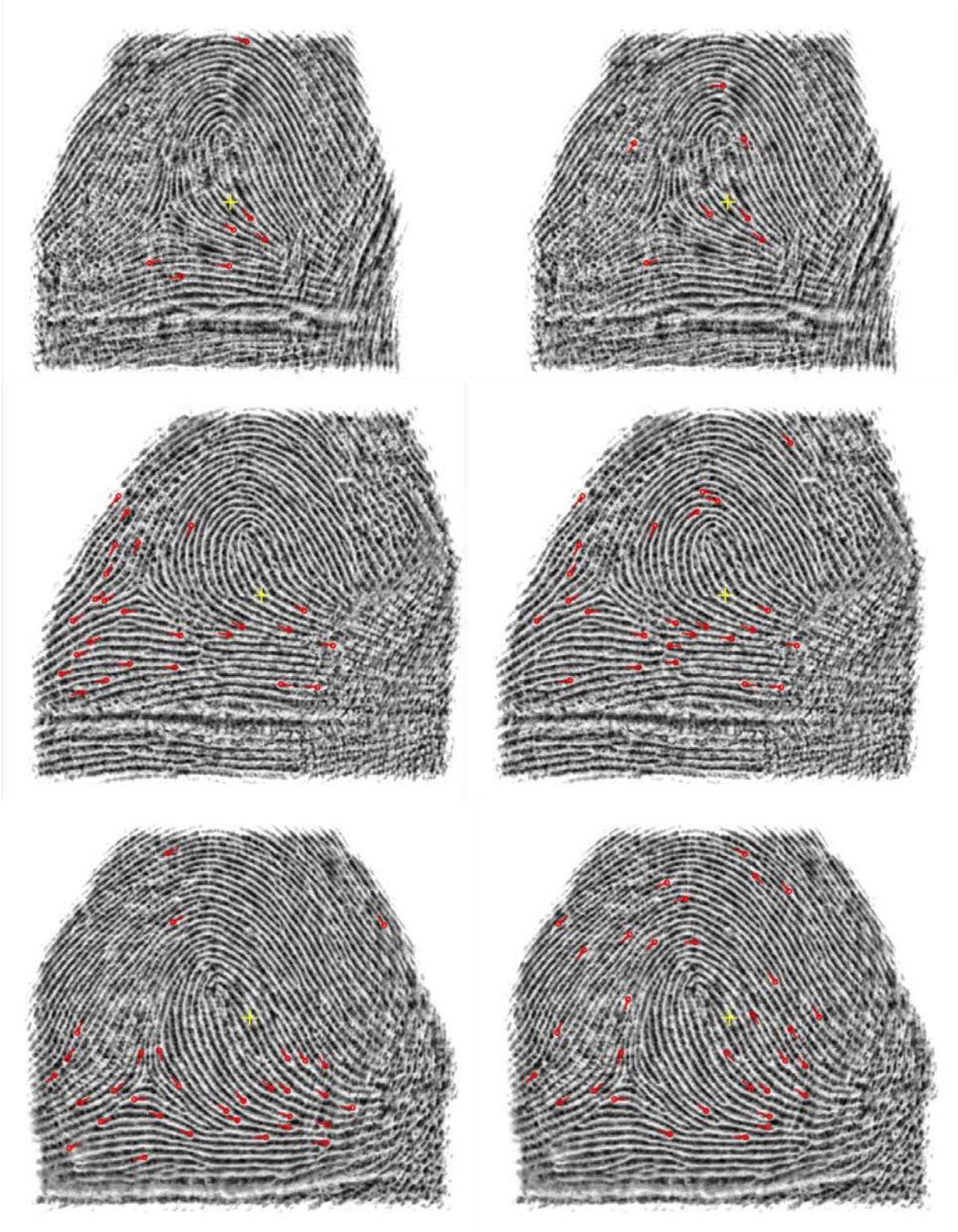

Figure 35: Comparison of Filtered Minutia TBS Images
TBS fingerprint images from the (left) *63up* dataset and (right) *63up random* dataset.

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6.0 CONCLUSIONS

In general, several key observations/conclusions were identified as a result of this analysis effort:

- The MDT allowed for categorizing, visualizing, and filtering minutiae to produce biometric data for analysis and match performance evaluation (see Section 3.1.1 Minutia Deviation Tool).
    - **Conclusion:** MDT is a useful and unique biometrics analysis tool that should be maintained and distributed to the biometrics research community.

- The process used to prepare the LFFS datasets, while necessary, introduced rounding errors when converting minutiae details from MM to EFS QSP2. The resulting biometric matching resulted in the images performing better than LFFS0, but improving when using LFFS1 vetted files (see Section 5.1.1 Comparison of TMR at Rank 1). In addition, the similarity score distributions collapsed to lowered values using LFFS files as compared to image datasets (see Section 5.1.3 Comparison of Similarity Scores).
    - **Conclusion:** Extraction algorithms should use industry standard profiles for defining minutiae to avoid rounding errors.
    - **Conclusion:** Raw images remain the best probe types for submissions and necessary for high priority applications (e.g., counterterrorism, criminal justice), but templates may be acceptable for medium-low priority applications (e.g., identity verification, access control).
    - **Conclusion:** The narrower similarity score distributions of LFFS files have implications for setting FAR/ FRR acceptance thresholds.

- Although the SEEK and TBS fingerprint images were collected using different technologies, the overall distributions of deviation magnitudes were the same (see Section 5.2.1 Magnitude Distribution of Deviations).
    - **Conclusion:** The unwrapping technique used by TBS was implemented well such that it closely mimics a contact-based rolled print capture and/or the minutia deviations from pressure deformation are not significant. This topic is deserving of additional research.

- The distributions of minutiae positions are centered on X≈0, Y≈500, R≈830 (see Section 5.2.2 Spatial Distribution of Minutiae) for all three device datasets (CMR2, SEEK, TBS).
    - **Conclusion:** The X position mean is due to the movement direction of the rolled print capture process and the unwrapping technique. The Y position mean is likely due to a decrease in feature resolution (and therefore fewer identified minutiae) at the curvature of the finger tip. This characteristic could be leveraged to improve matching algorithm speed.

- There is a linear correlation between radial distance from the image center and the magnitude of the minutiae deviation (see Section 5.2.3 Minutia Spatial Position vs. Deviation). The plots for both SEEK and TBS are identical. In comparison, there is a linear relationship between Y position and minutia deviation, but the correlation is opposite between TBS and SEEK.

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- **Conclusion:** The linear behavior suggests a uniform scaling factor between CMR2 and the comparison images. The Y position vs. deviation differences could be related to the TBS unwrapping technique. This topic is deserving of additional research.

- There is a direct, but weak correlation between similarity score and minutiae deviations for both SEEK and TBS datasets (see Section 5.2.4 Similarity Score). The average similarity score decreases with increasing deviation.
  - **Conclusion:** This is a reasonable and expected result. The less in register a set of minutiae are between probe and gallery image, the less similar the images are to the matcher.
  - **Conclusion:** There is significant variation (i.e., noise) in the data. Combined with the weak dependency, this suggests that minutia deviations are not the primary factor for the MM algorithm when determining similarity during biometric matching processes.

- The average minutia deviation does affect the NFIQ score, but the correlation is different for SEEK and TBS datasets (see Section 5.2.5 NFIQ Score). The CMR2-TBS NFIQ scores increase with increasing minutia deviations, but the CMR2-SEEK scores decrease.
  - **Conclusion:** It is possible that the CLPE vetting process allowed a greater degree of error in the position and direction of minutiae when examining TBS images due to their atypical overall appearance. Alternatively, the TBS and SEEK images possess different quality discrepancies that affect the calculation of the NFIQ score to differing degrees.

- Datasets with lower average minutia deviations did not inherently produce better matching performance than those with higher average deviations. The deviation filtered dataset matching runs resulted in *63up* out performing *63up random* for both SEEK and TBS (see Section

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- 5.3 Matching Runs – Deviation Filtered Datasets).
    - **Conclusion:** Minutia deviations are not the primary factor for the MM algorithm when determining similarity during biometric matching processes.
    - **Conclusion:** A qualitative examination of images with minutia marks suggests that the clustering of minutiae or the effective network of nearest neighbors may play a larger role in the MM algorithm in determining similarity during biometric matching processes.
    - **Conclusion:** For contactless systems, the fidelity of the image is likely more important for match performance than the accuracy of the unwrapping transformation applied to the contactless representation of the fingerprint.

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6.1 Future RDT&E Directions

Included here are follow-on RDT&E topics that build upon this work, explore topics discussed here in more detail, or pursue complimentary experiments. Resource limitations have precluded the SSBT CoE team from pursuing these, but given the general availability of the WVU collection datasets and the MDT, it would be easy to continue the work.

- **Expand the MDT mated sessions to cover the entire WVU dataset so as to improve analysis results and reduce statistical variations.** Due to resource limitations, the SSBT CoE processed 130 subjects using the MDT to produce paired minutia sets and their resulting deviations. There are an additional 468 subjects in the CLPE vetted dataset with data for all three devices, as well as FS3D.

- **Investigate the match performance of deviation filtered datasets using different algorithms with known mechanics for processing and handling minutia features and maps.** The results from deviation filtered datasets contained herein were hindered by the MM being treated as a black box with respect to how it handled minutiae. There were interesting outcomes from the deviation filtered experiments that warrant further research to better understand the role of deviations and/or minutia networks, and therefore improve the rolled-equivalent images produced by contactless systems.

- **Apply the MDT and minutia characterization approach developed here to 2D rolled-equivalent images produced using a variety of 3D transformation algorithms.** Understanding how unwrapping directly effects minutia and subsequent match performance will allow more accurate transformation methods to be developed and thereby improving the output of contactless systems when submitting against legacy gallery databases.

- **Conduct similar deviation analyses with datasets from other devices to identify similarities and differences and connect them to fundamental image processing and biometric characteristics.** Several experiments conducted in this research produced similar results for both TBS and SEEK (e.g., magnitude distribution of deviations, radial position vs. minutia deviations). Given the different capture approaches and image processing, this is an unlikely coincidence that warrants repeated experiments with other data sources to ascertain true behaviors.

- **Enhance the MDT with additional functionality to improve its value to the biometrics community.** The software is a unique and useful tool. Some additional features that might aid researchers include the ability to update the GUI display after filtering with only minutia that satisfied filtering conditions. This would allow for visualization by the user as well as more useful multi-staged filtering. A second enhancement would be the introduction of a nearest neighbor or minutiae network metric that could be used for filtering. This would allow for further research into the role of minutia clustering as well as allow for that metric to be a filter criterion to produce controlled datasets.

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APPENDIX A: MATCHING RUN DETAILS

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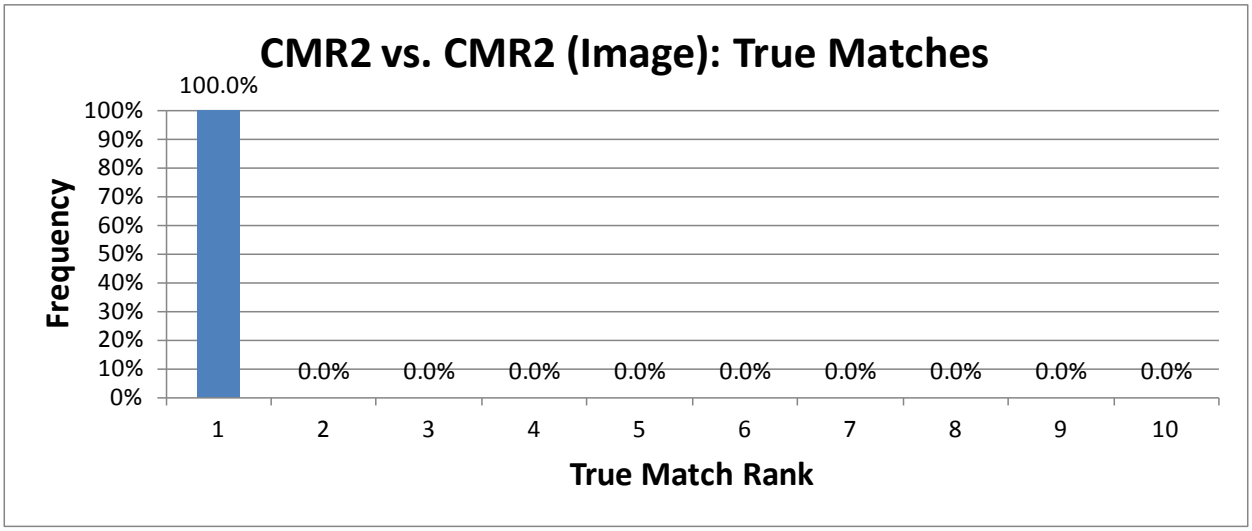
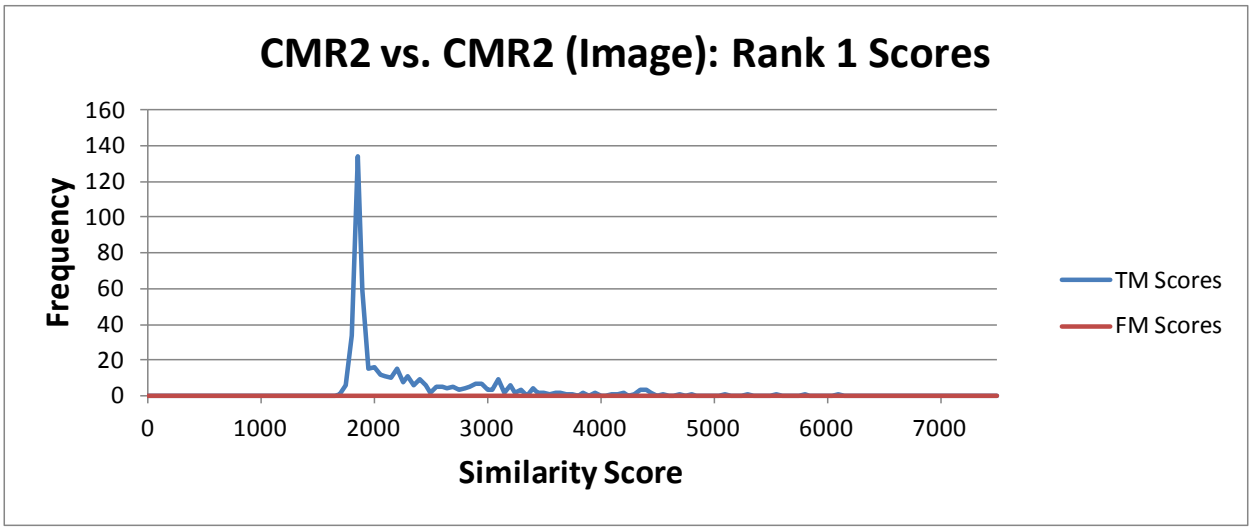
A.1 Gallery Matching Runs

A.1.2 Matching Runs: Image, Original

A.1.1.1 CMR2 Gallery

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 Image Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
CMR2 Image Original	**Unique Subjects**	468			
Matches	**True Matches**	468	100%	2276	717
	False Matches	0	0%	#DIV/0!	#DIV/0!
	Total Matches	219024			





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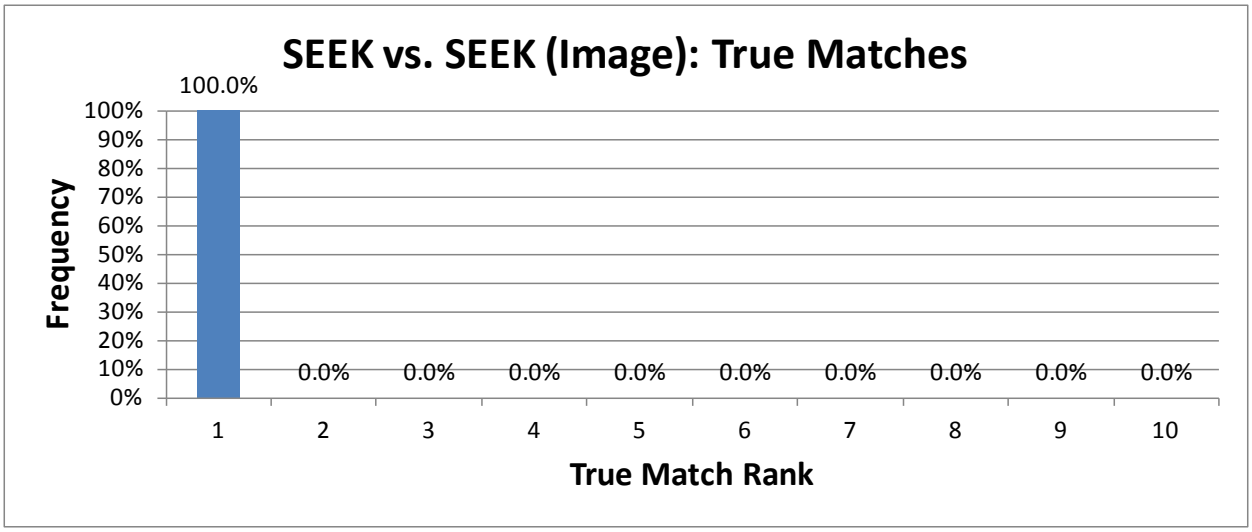
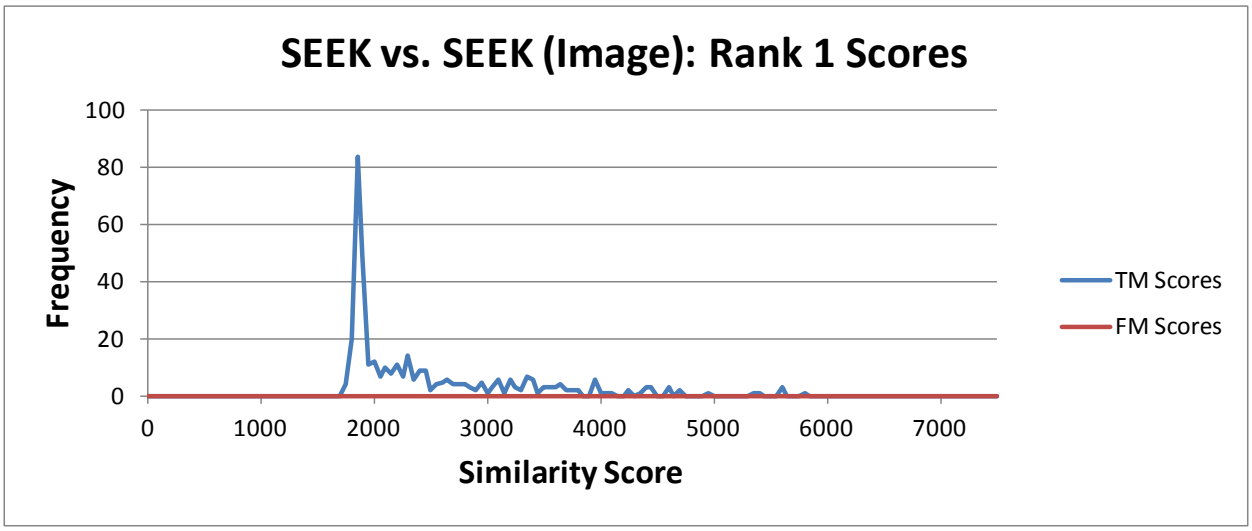
A.1.1.2 SEEK Gallery

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
SEEK Image Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
SEEK Image Original	**Unique Subjects**	468			
Matches	**True Matches**	468	100%	2441	834
	False Matches	0	0%	#DIV/0!	#DIV/0!
	Total Matches	219024			





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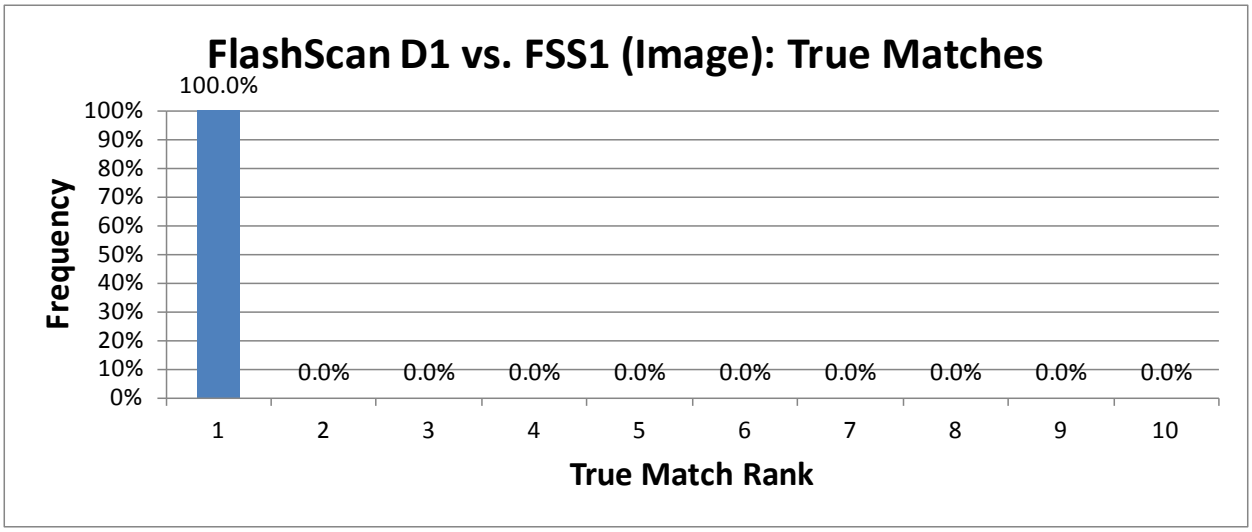
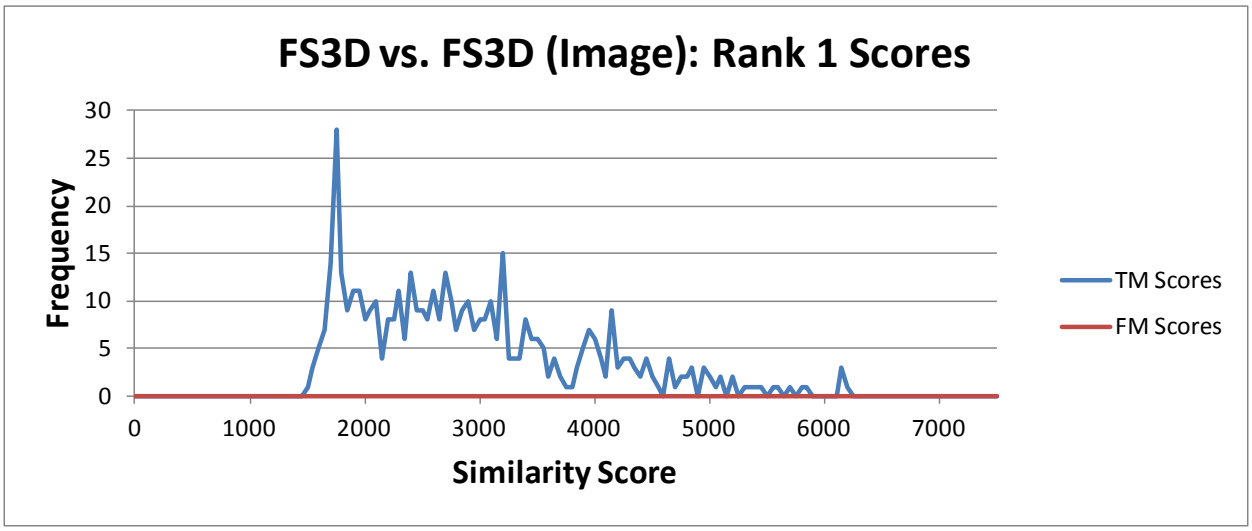
A.1.1.3 FS3D Gallery

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
FS3D Image Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
FS3D Image Original	**Unique Subjects**	468			
Matches	**True Matches**	468	100%	2883	1014
	False Matches	0	0%	#DIV/0!	#DIV/0!
	Total Matches	219024			





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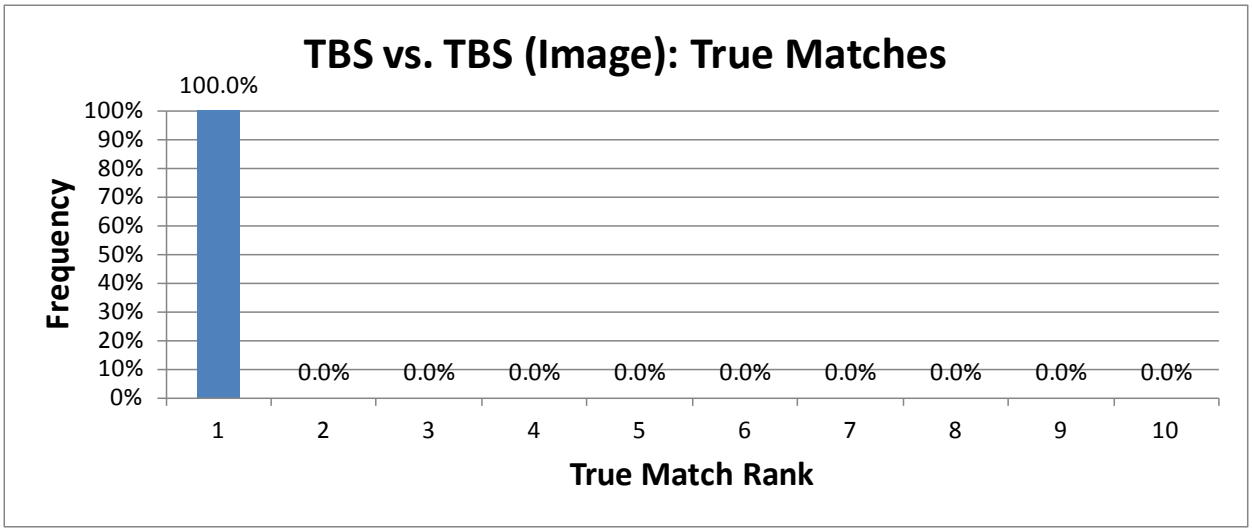
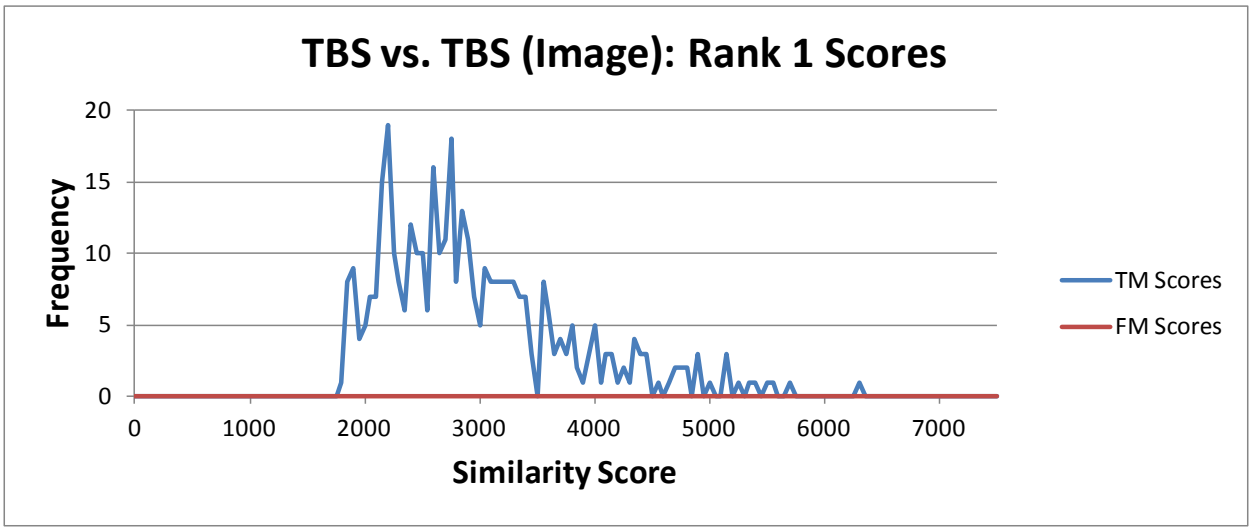
A.1.1.4 TBS Gallery

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
TBS Image Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
TBS Image Original	**Unique Subjects**	468			
Matches	**True Matches**	468	100%	2938	815
	False Matches	0	0%	#DIV/0!	#DIV/0!
	Total Matches	219024			





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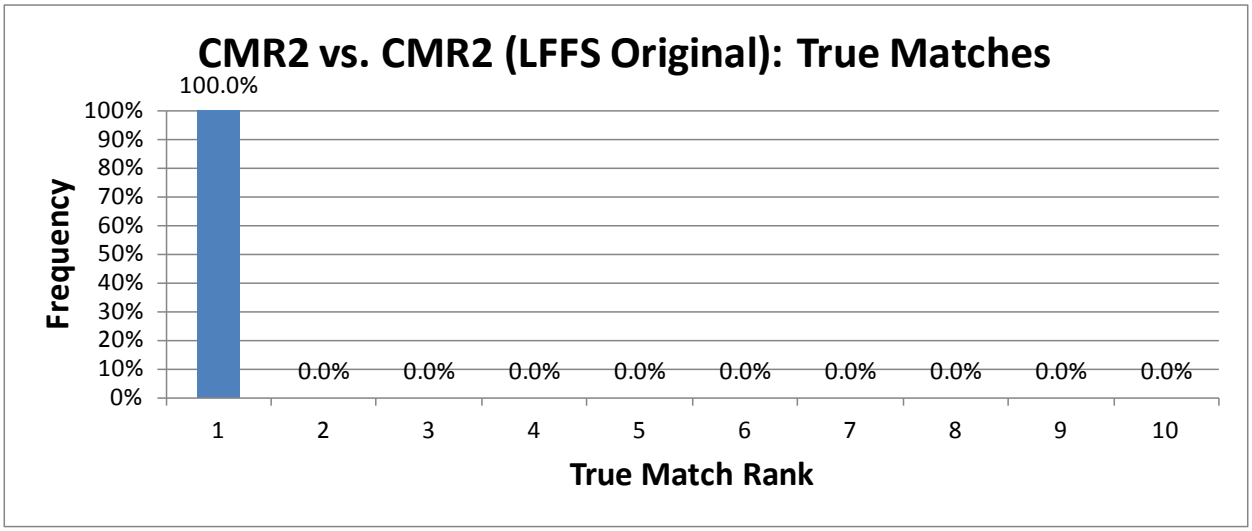
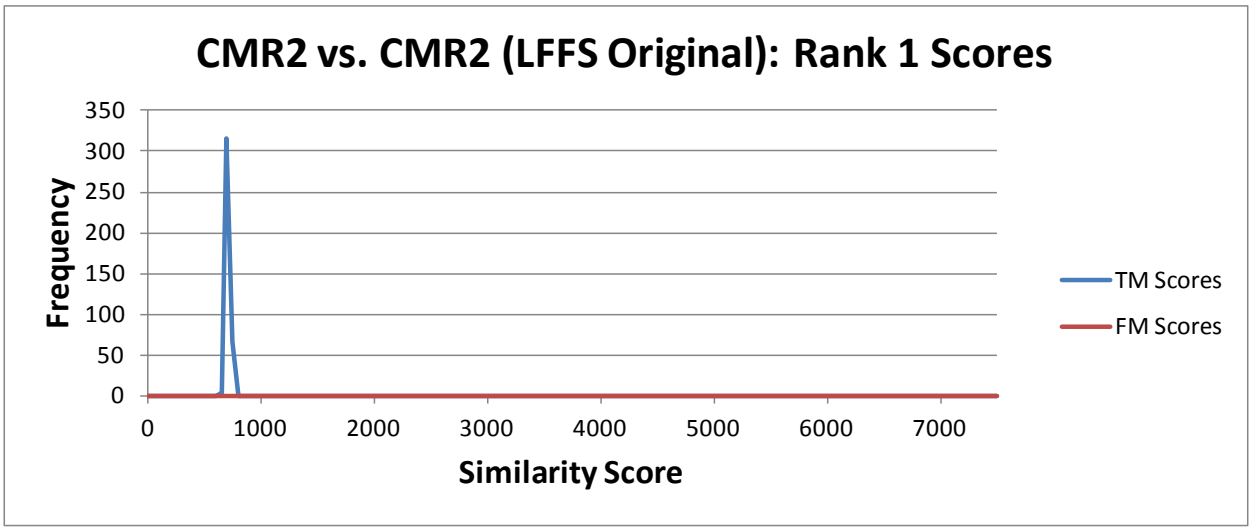
A.1.3 Matching Runs: LFFS, Original

A.1.2.1 CMR2 Gallery

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
CMR2 LFFS Original	**Unique Subjects**	468			
Matches	**True Matches**	468	100%	693	13
	False Matches	0	0%	#DIV/0!	#DIV/0!
	Total Matches	219024			





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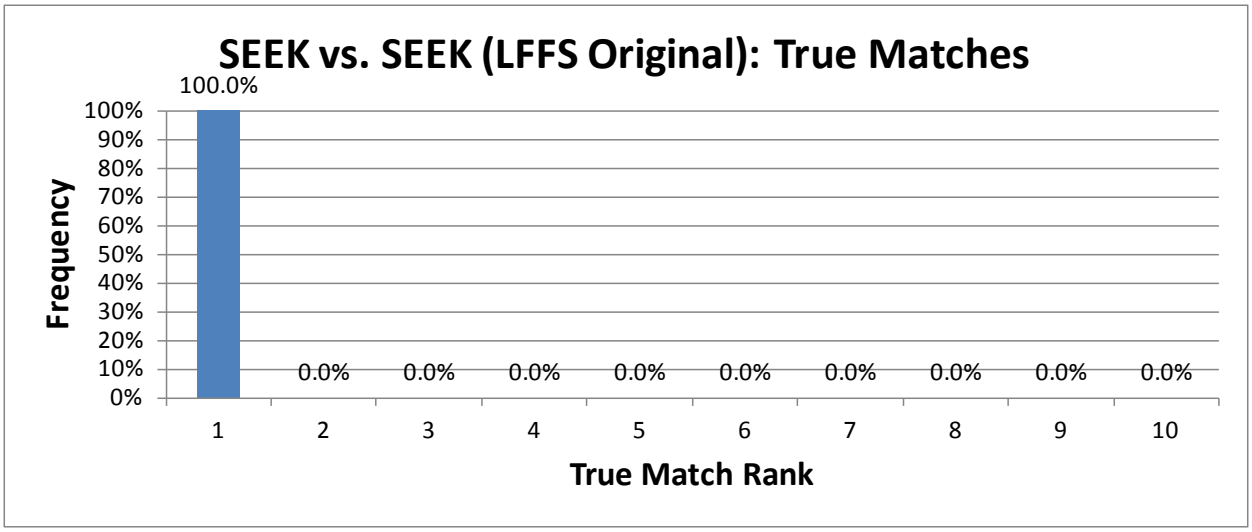
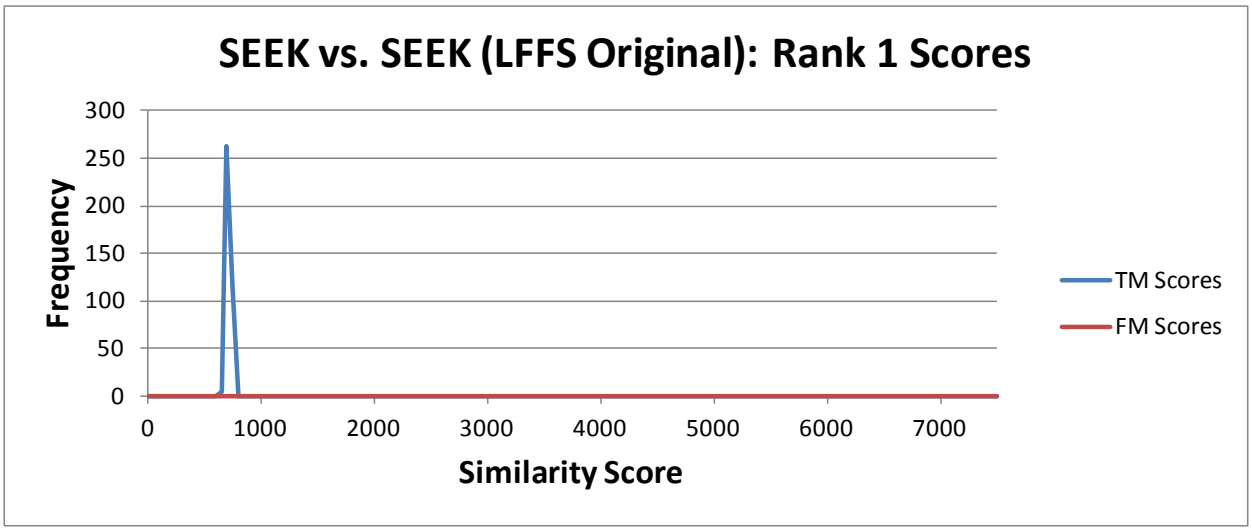
A.1.2.2 SEEK Gallery

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
SEEK LFFS Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
SEEK LFFS Original	**Unique Subjects**	468			
Matches	**True Matches**	468	100%	697	15
	False Matches	0	0%	#DIV/0!	#DIV/0!
	Total Matches	219024			





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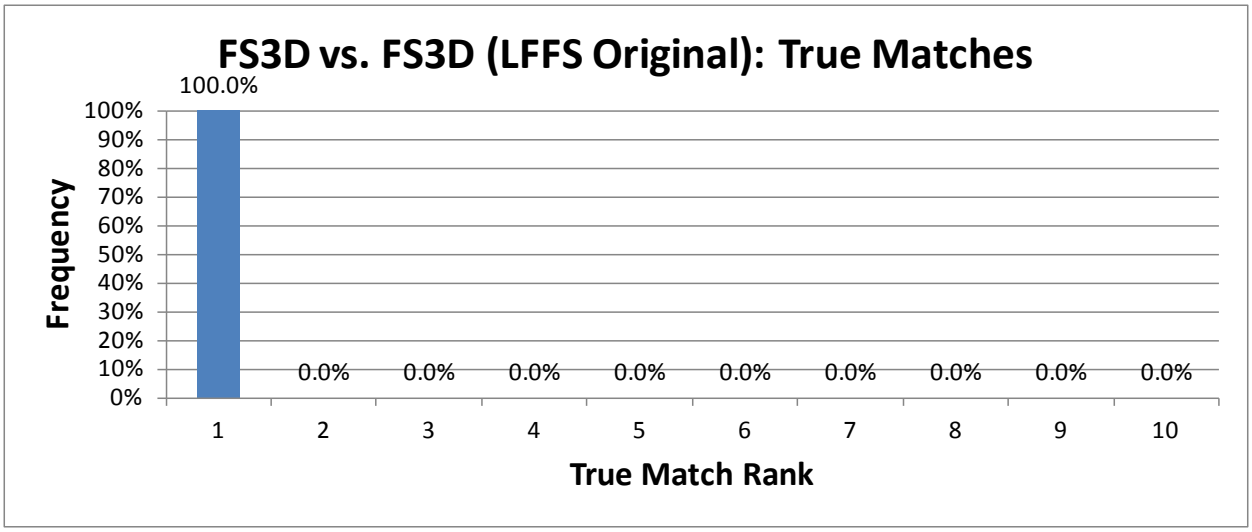
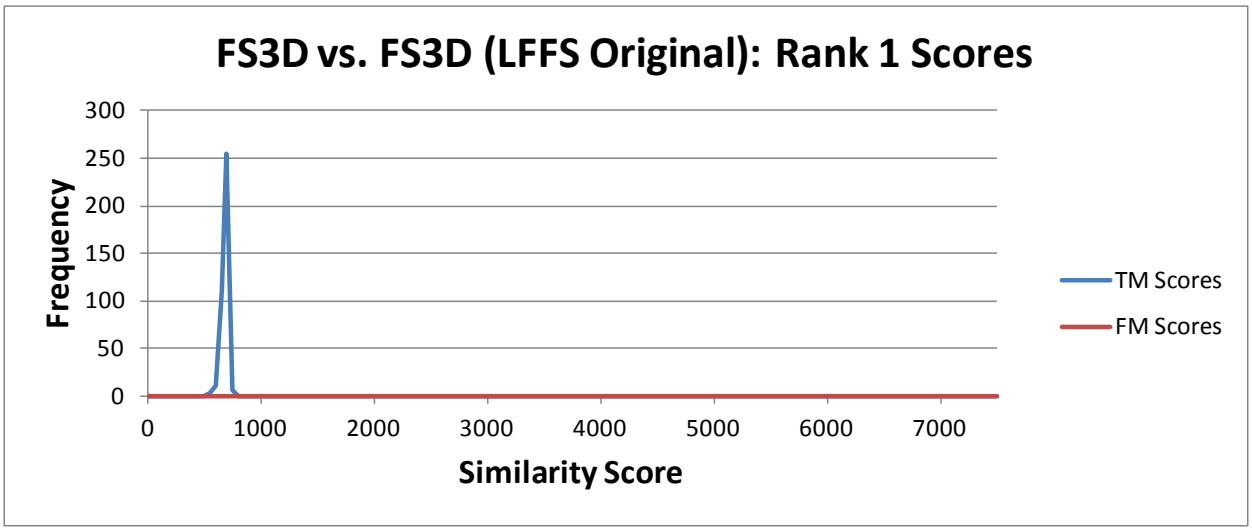
A.1.2.3 FS3D Gallery

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
FS3D LFFS Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
FS3D LFFS Original	**Unique Subjects**	468			
Matches	**True Matches**	468	100%	662	27
	False Matches	0	0%	#DIV/0!	#DIV/0!
	Total Matches	219024			





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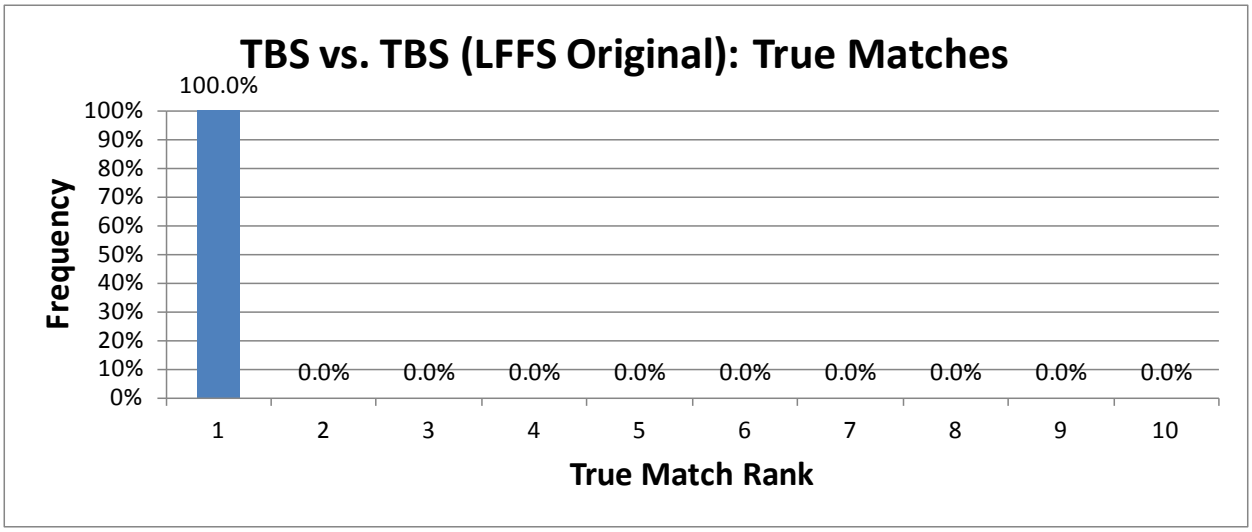
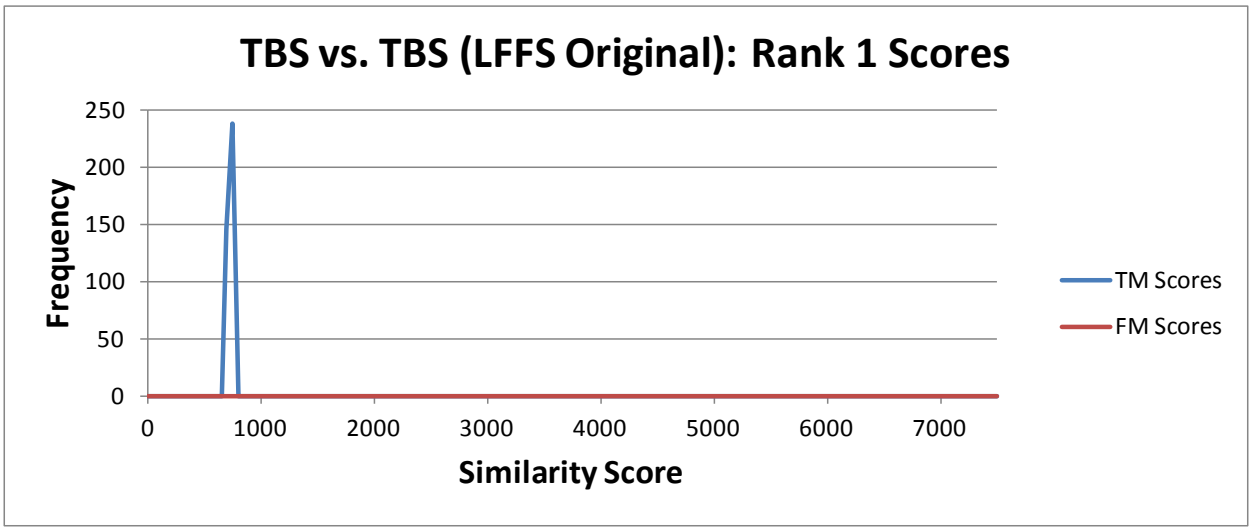
A.1.2.4 TBS Gallery

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
TBS LFFS Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
TBS LFFS Original	**Unique Subjects**	468			
Matches	**True Matches**	468	100%	707	10
	False Matches	0	0%	#DIV/0!	#DIV/0!
	Total Matches	219024			





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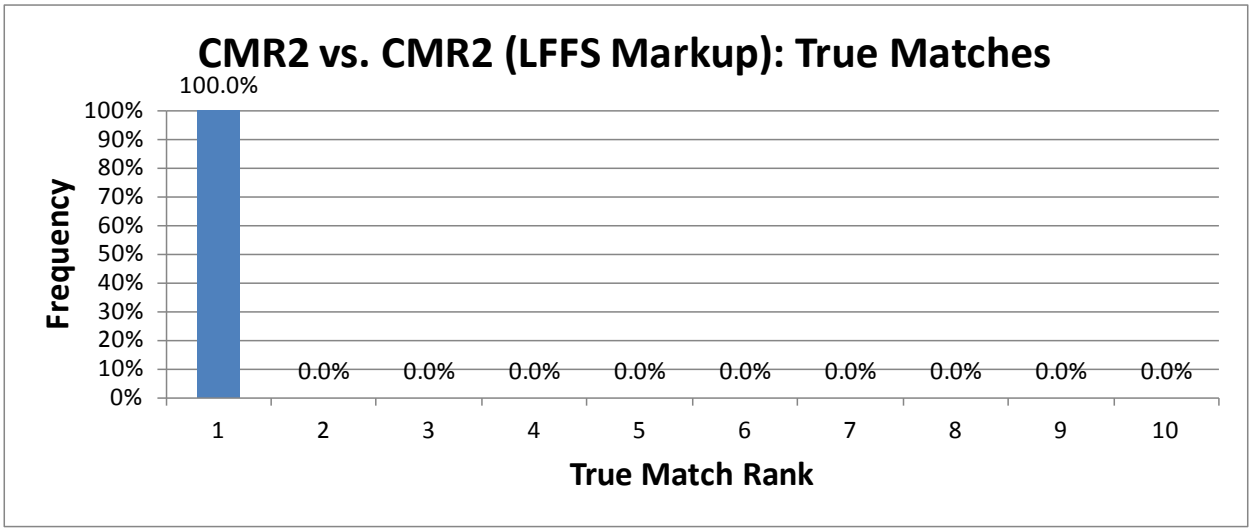
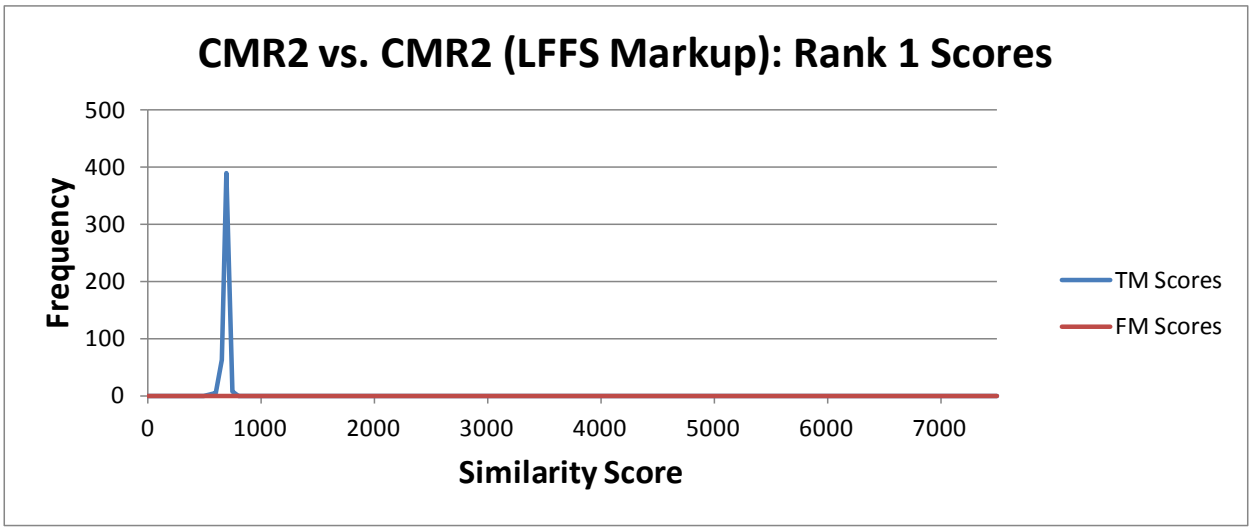
A.1.4 Matching Runs: LFFS, Markup

A.1.3.1 CMR2 Gallery

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Markup	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
CMR2 LFFS Markup	**Unique Subjects**	468			
Matches	**True Matches**	468	100%	672	22
	False Matches	0	0%	#DIV/0!	#DIV/0!
	Total Matches	219024			





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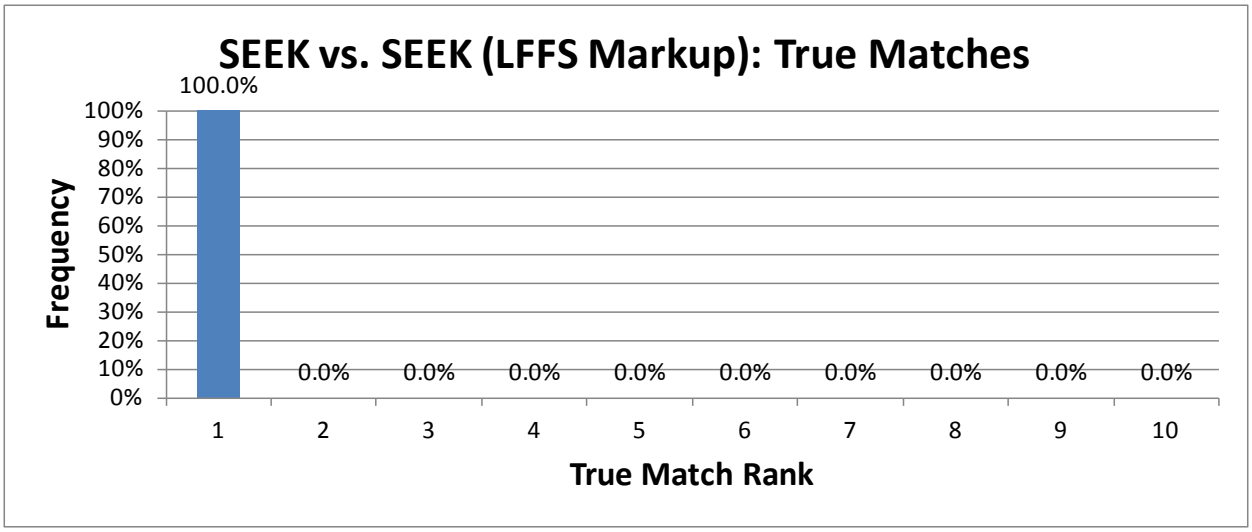
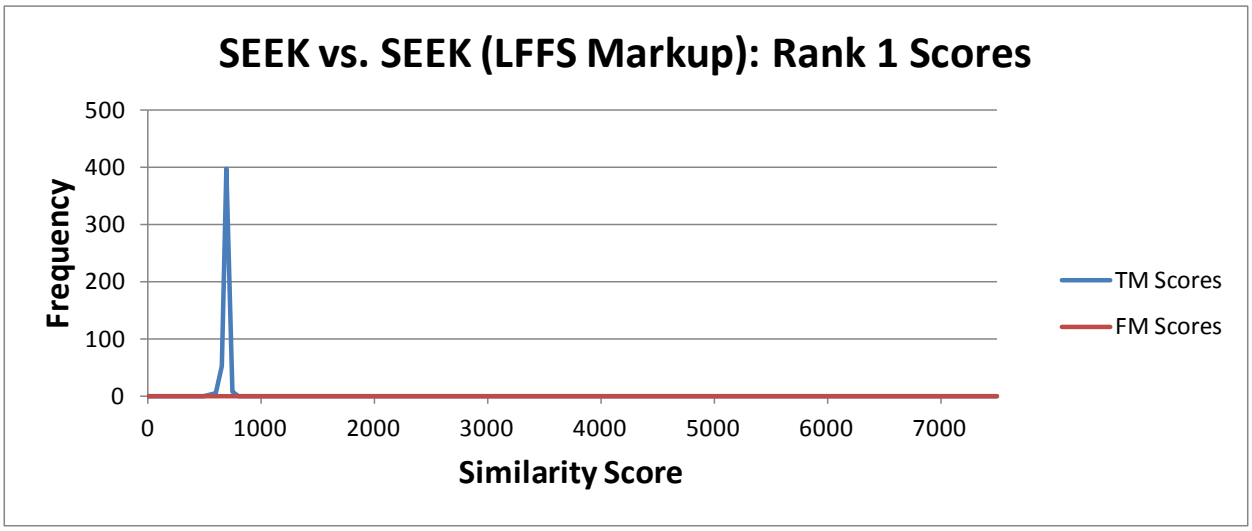
A.1.3.2 SEEK Gallery

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
SEEK LFFS Markup	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
SEEK LFFS Markup	**Unique Subjects**	468			
Matches	**True Matches**	468	100%	674	27
	False Matches	0	0%	#DIV/0!	#DIV/0!
	Total Matches	219024			





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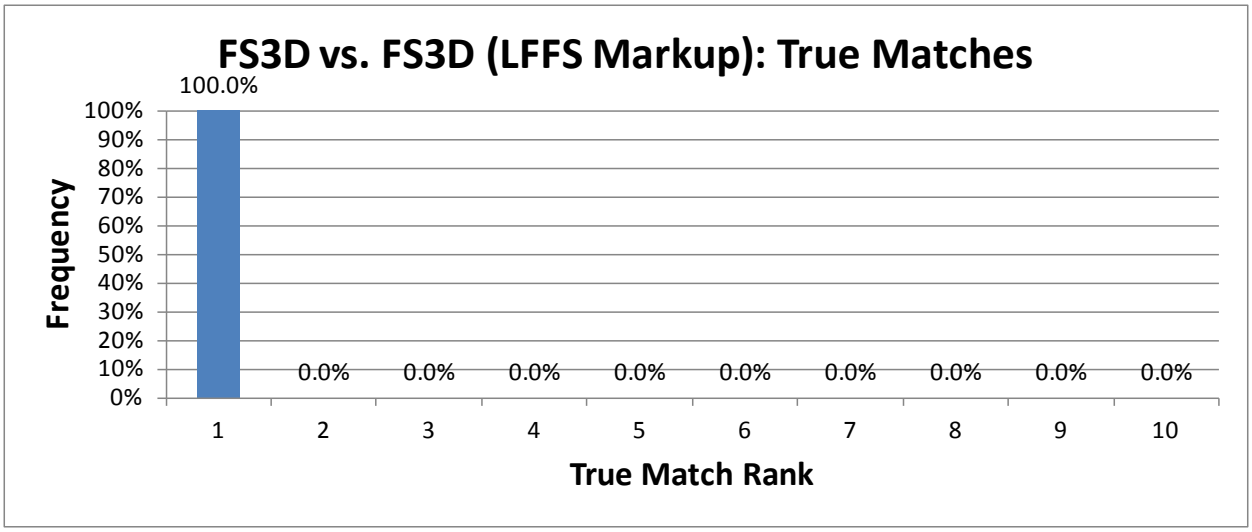
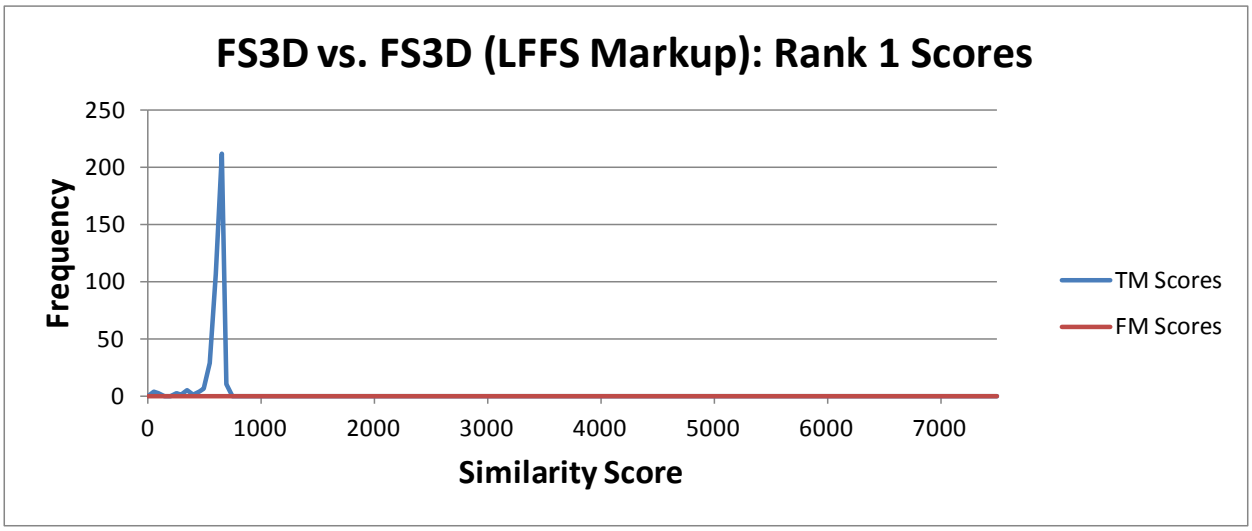
A.1.3.3 FS3D Gallery

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
FS3D LFFS Markup	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
FS3D LFFS Markup	**Unique Subjects**	468			
Matches	**True Matches**	468	100%	588	90
	False Matches	0	0%	#DIV/0!	#DIV/0!
	Total Matches	219024			





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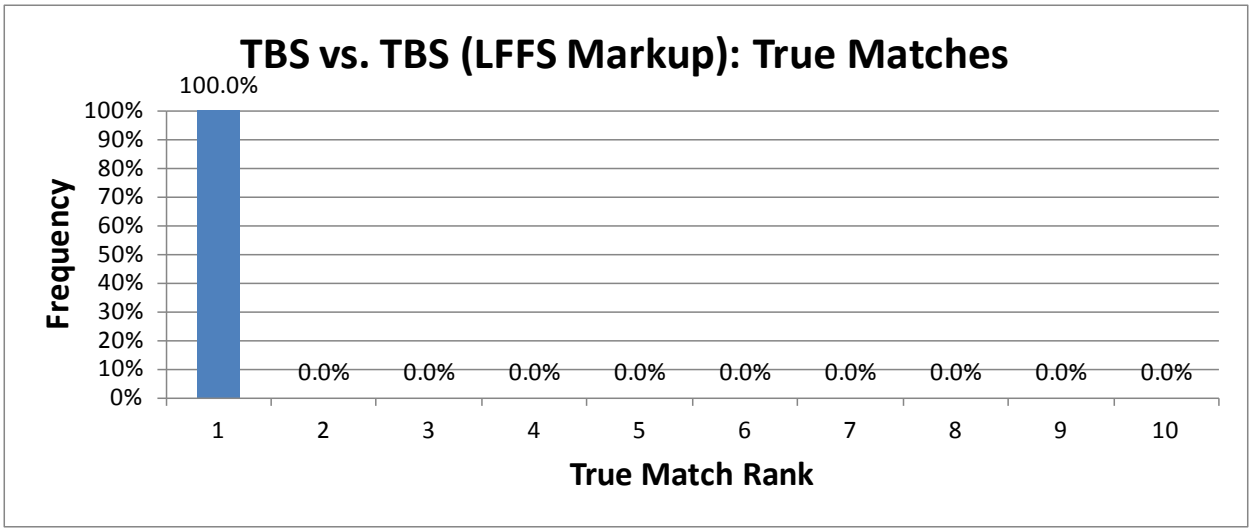
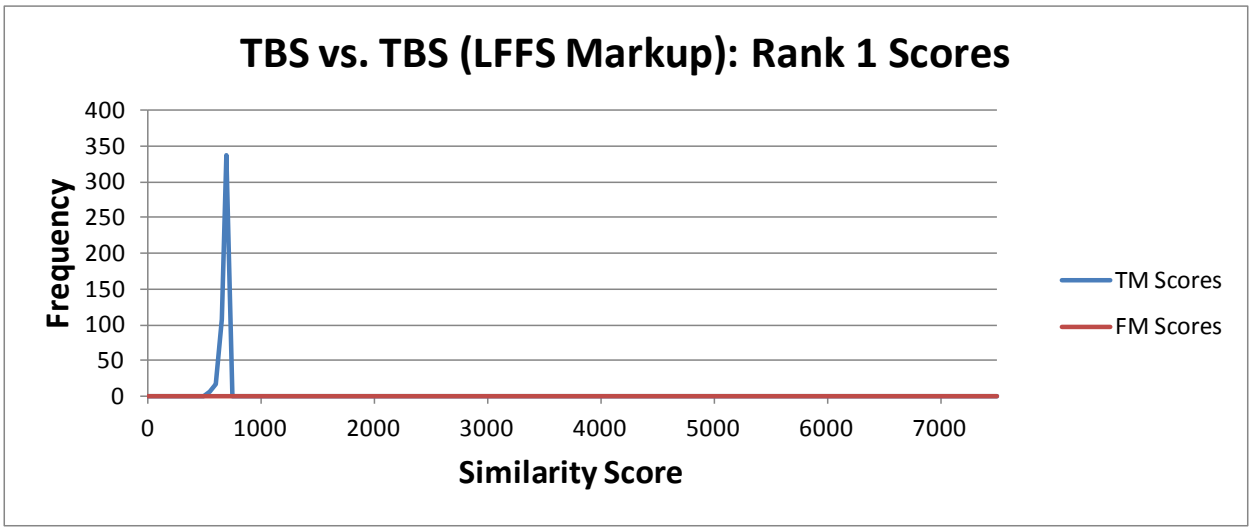
A.1.3.4 TBS Gallery

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
TBS LFFS Markup	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
TBS LFFS Markup	**Unique Subjects**	468			
Matches	**True Matches**	468	100%	661	31
	False Matches	0	0%	#DIV/0!	#DIV/0!
	Total Matches	219024			





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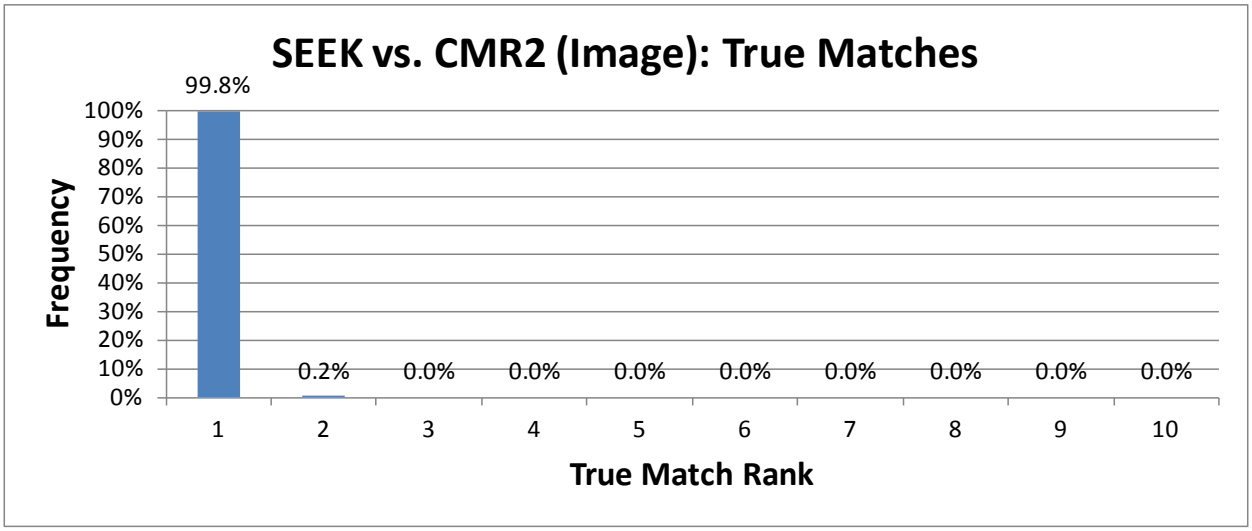
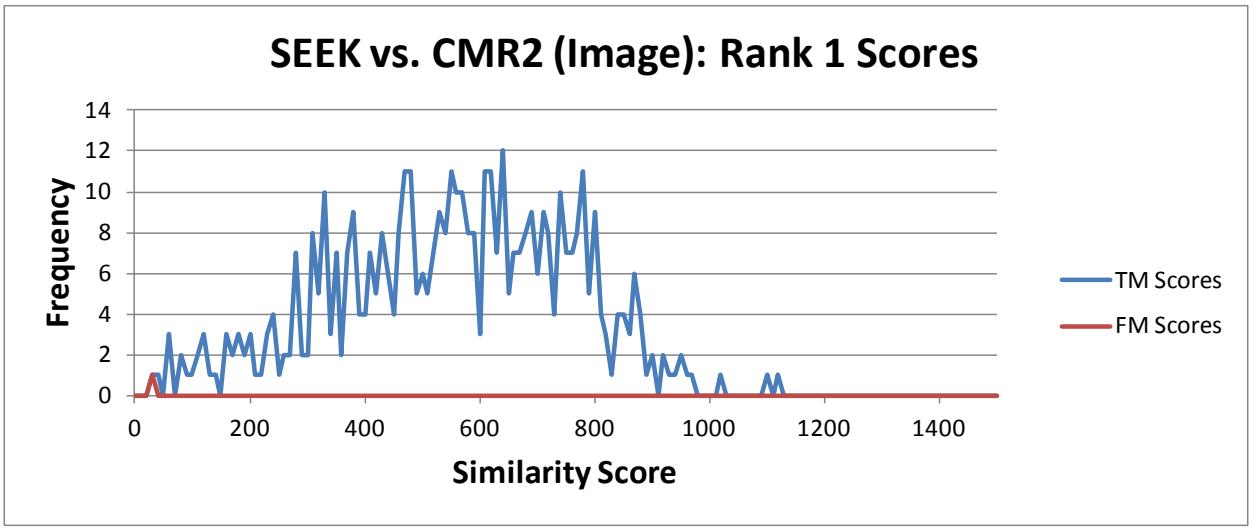
A.2 Matching Runs: Image, Original

A.2.1 CMR2 Gallery

A.2.1.1 SEEK Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 Image Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
SEEK Image Original	**Unique Subjects**	468			
Matches	**True Matches**	467	100%	553	205
	False Matches	1	0%	29	#DIV/0!
	Total Matches	219024			





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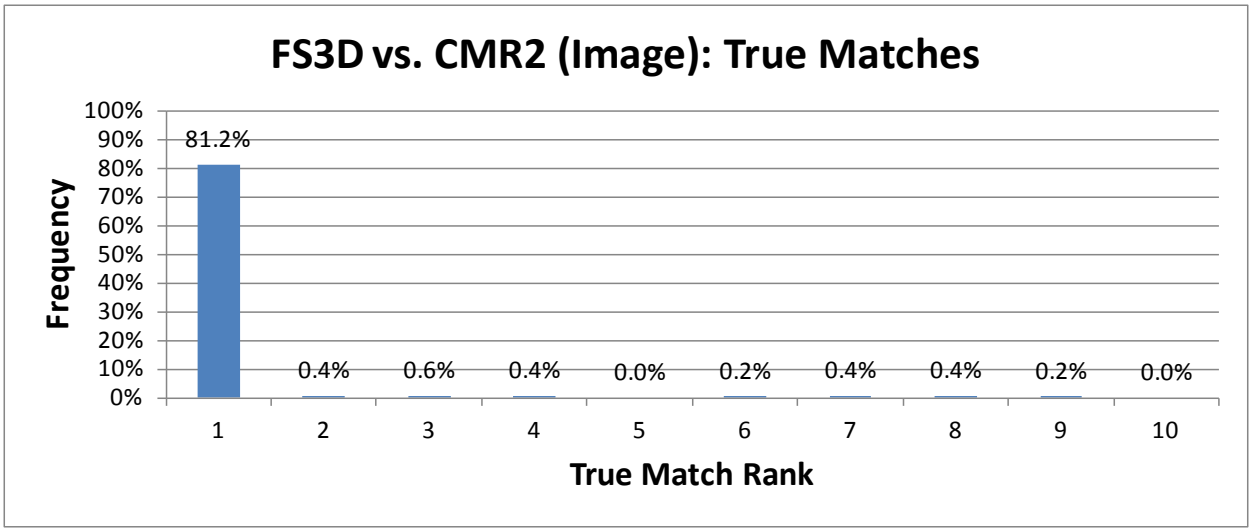
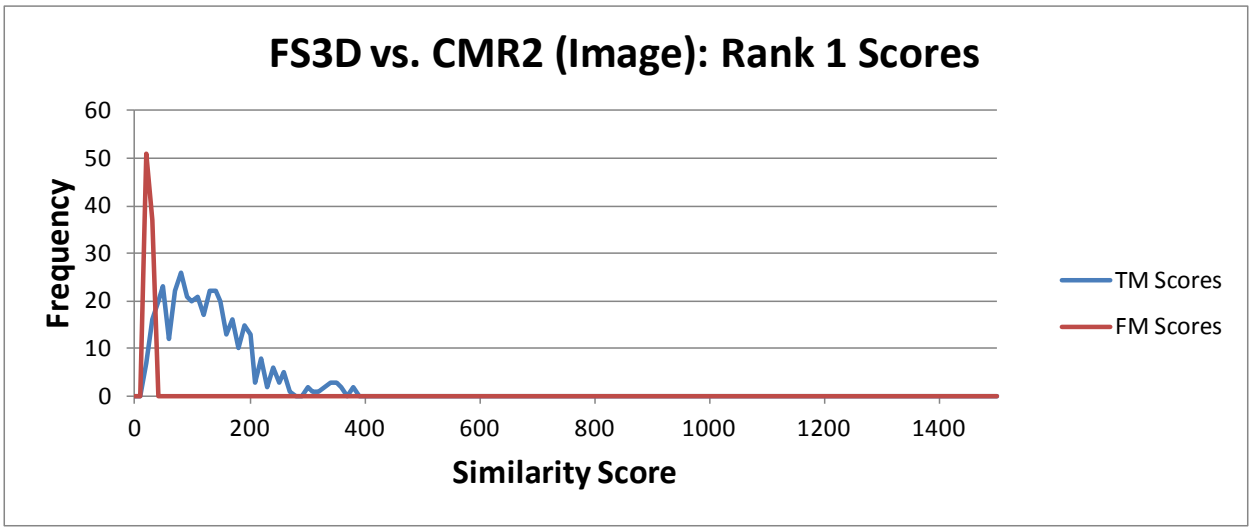
A.2.1.2 FS3D Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 Image Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
FS3D Image Original	**Unique Subjects**	468			
Matches	**True Matches**	380	81%	126	73
	False Matches	88	19%	24	4
	Total Matches	219024			





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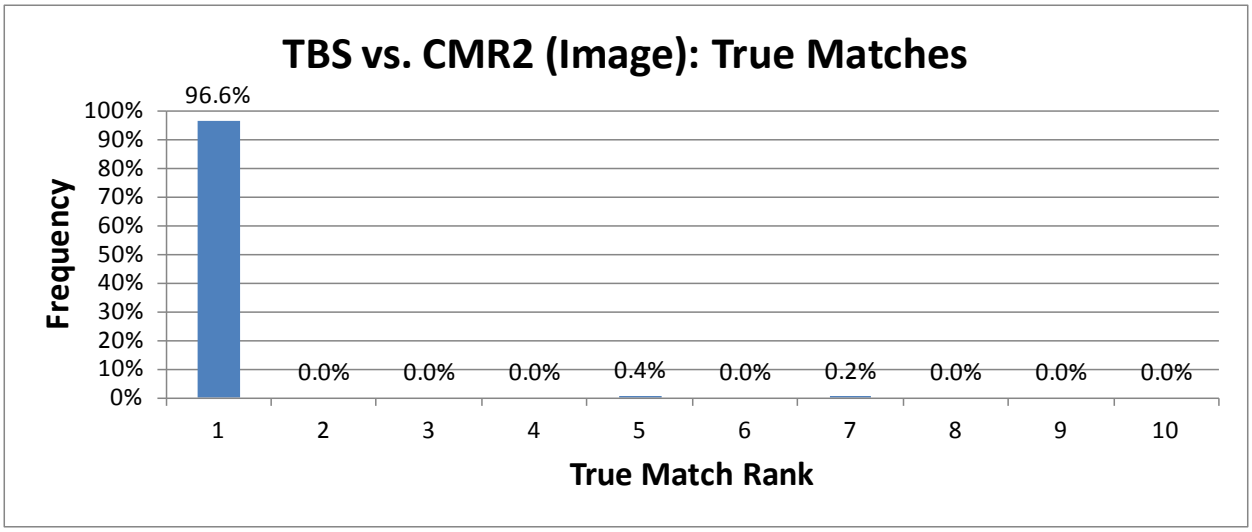
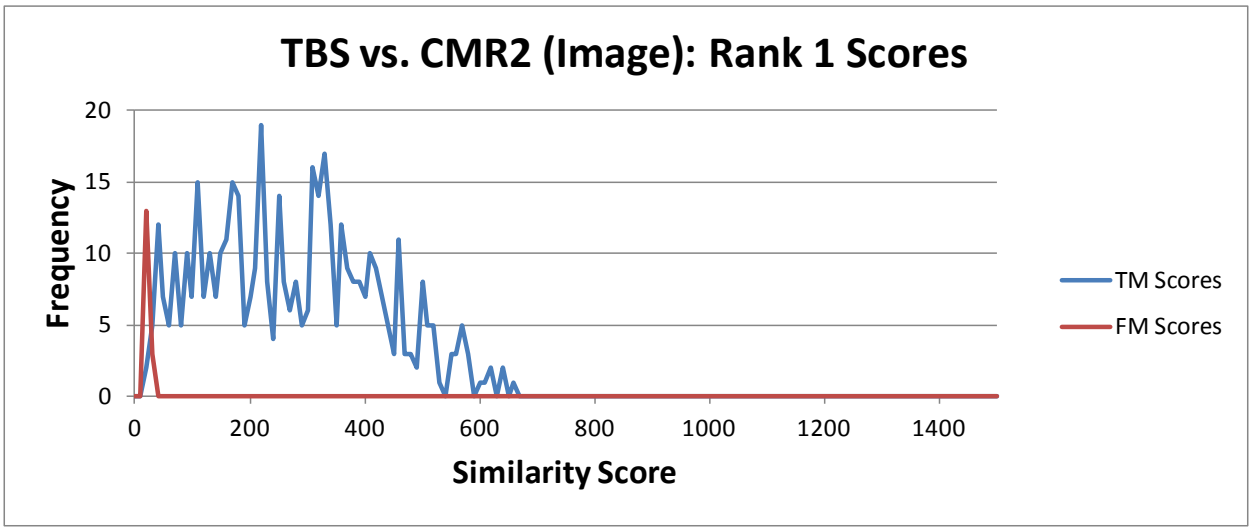
A.2.1.3 TBS Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 Image Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
TBS Image Original	**Unique Subjects**	468			
Matches	**True Matches**	452	97%	273	147
	False Matches	16	3%	22	3
	Total Matches	219024			





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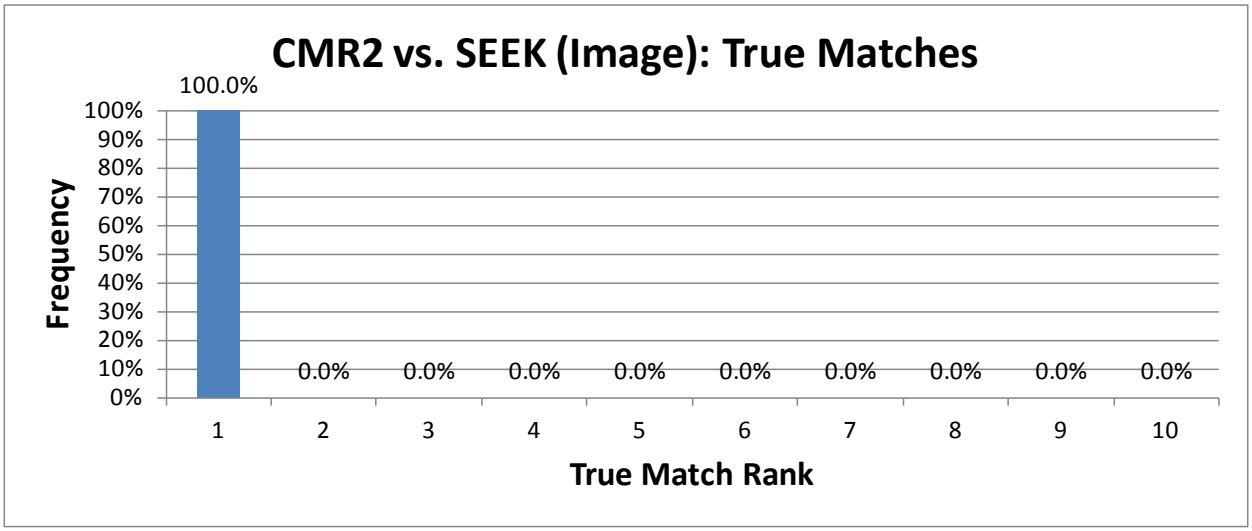
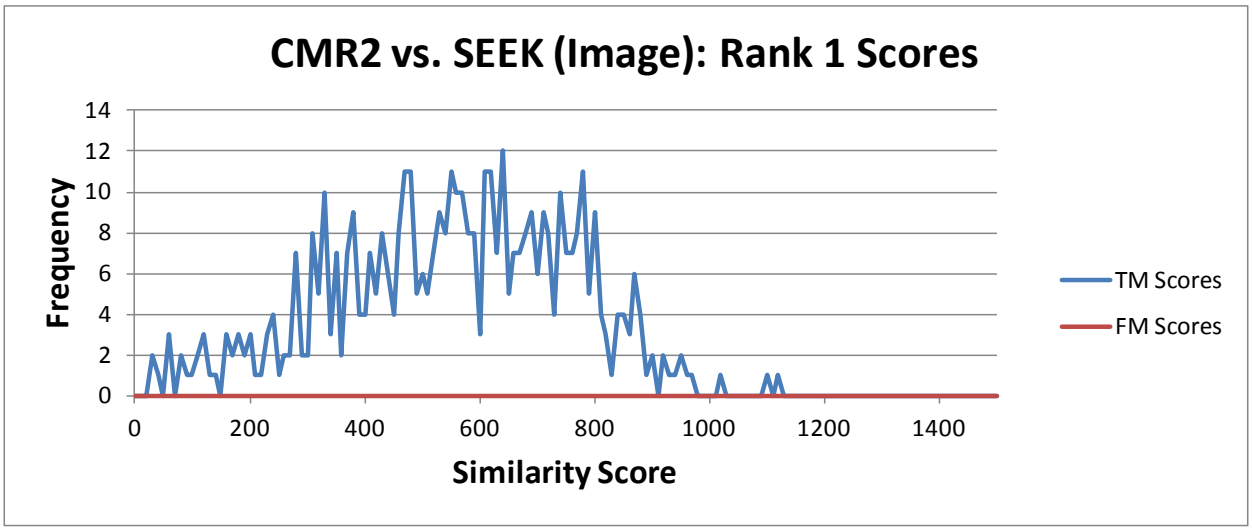
A.2.2 SEEK Gallery

A.2.2.1 CMR2 Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
SEEK Image Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
CMR2 Image Original	**Unique Subjects**	468			
Matches	**True Matches**	468	100%	552	207
	False Matches	0	0%	#DIV/0!	#DIV/0!
	Total Matches	219024			





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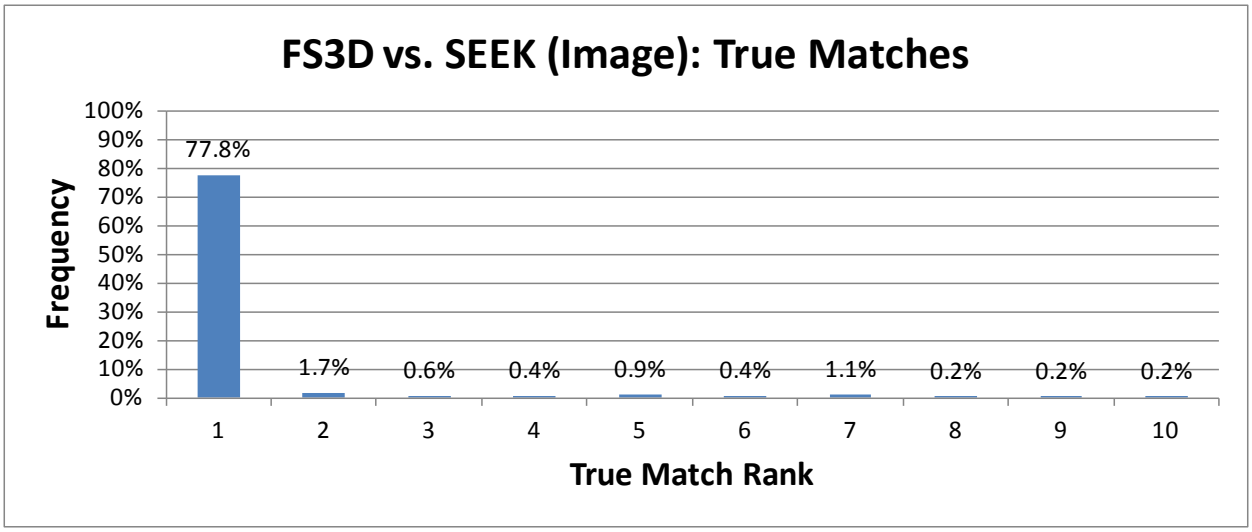
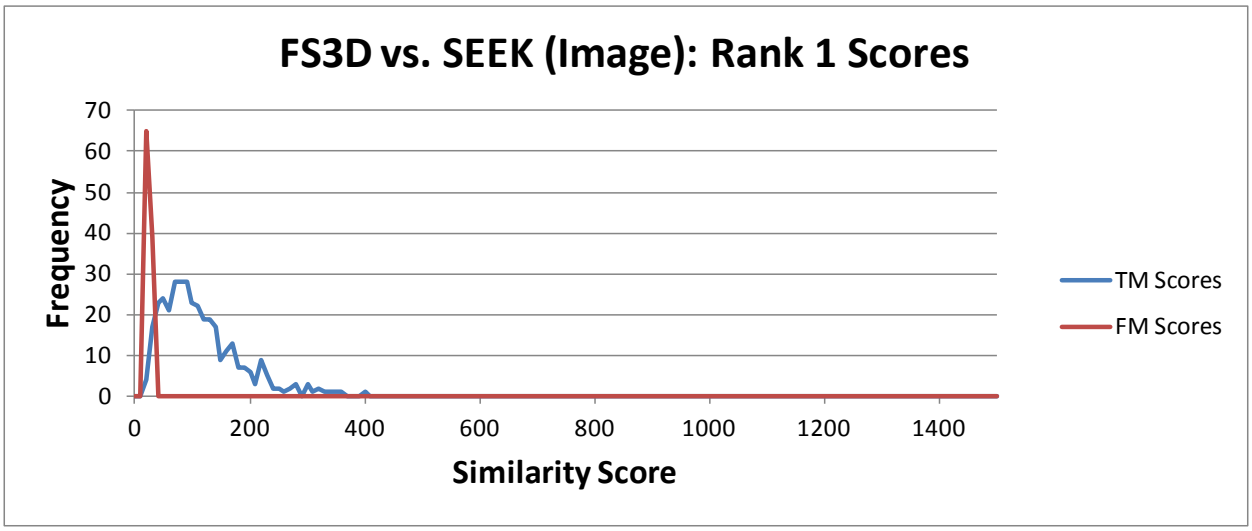
A.2.2.2 FS3D Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
SEEK Image Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
FS3D Image Original	**Unique Subjects**	468			
Matches	**True Matches**	364	78%	114	68
	False Matches	104	22%	24	3
	Total Matches	219024			





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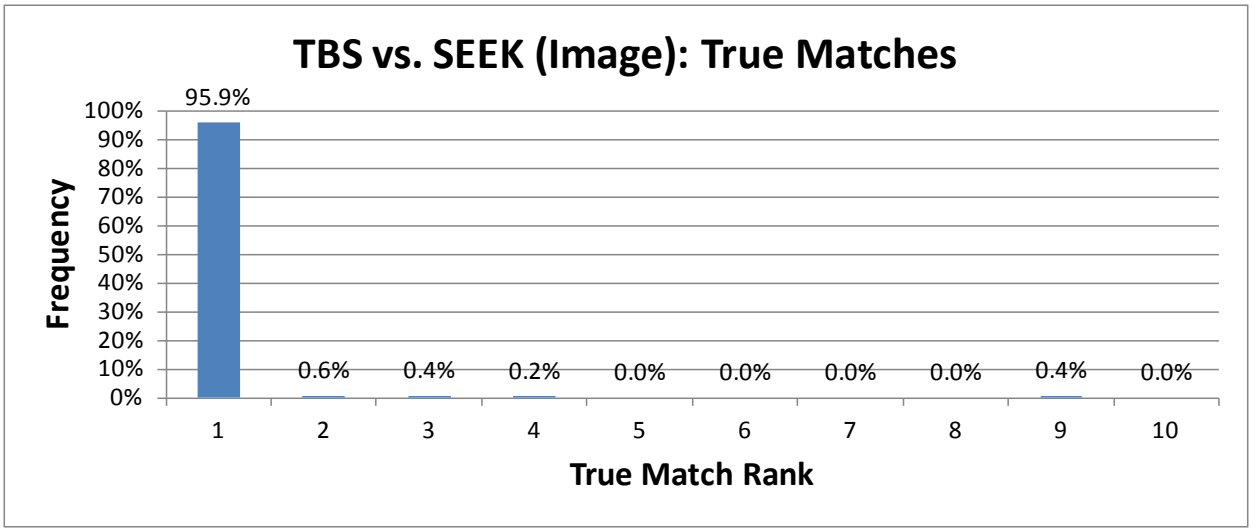
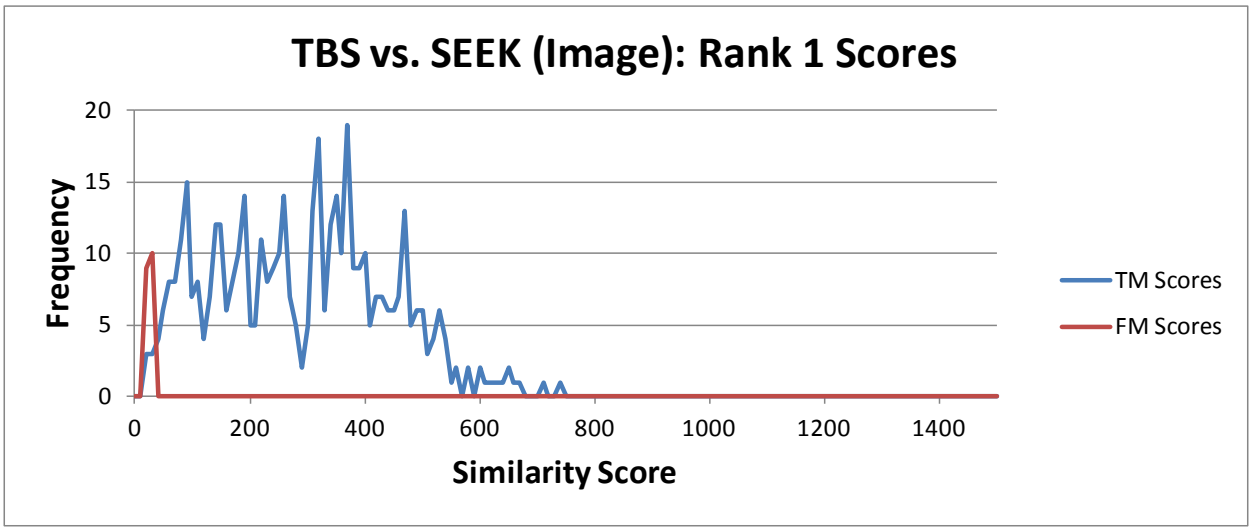
A.2.2.3 TBS Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
SEEK Image Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
TBS Image Original	**Unique Subjects**	468			
Matches	**True Matches**	449	96%	289	152
	False Matches	19	4%	25	4
	Total Matches	219024			





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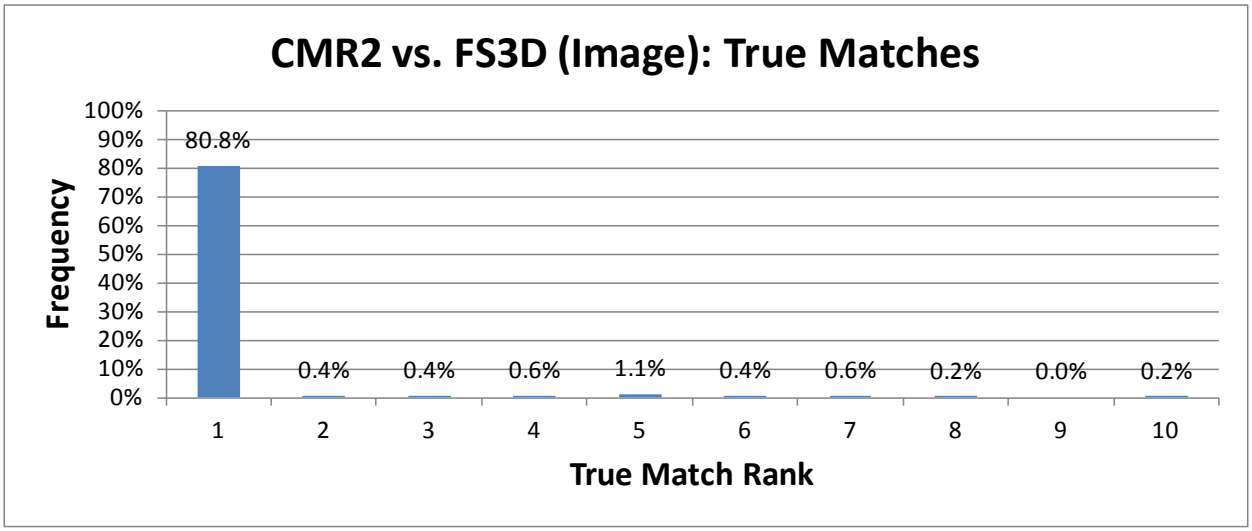
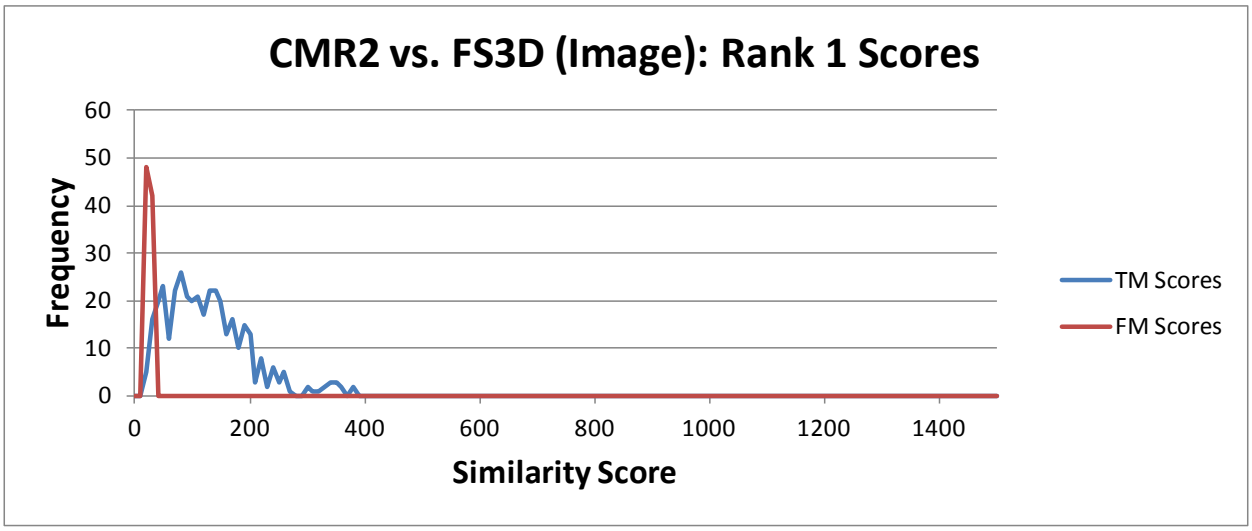
A.2.3 FS3D Gallery

A.2.3.1 CMR2 Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
FS3D Image Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
CMR2 Image Original	**Unique Subjects**	468			
Matches	**True Matches**	378	81%	127	73
	False Matches	90	19%	24	3
	Total Matches	219024			





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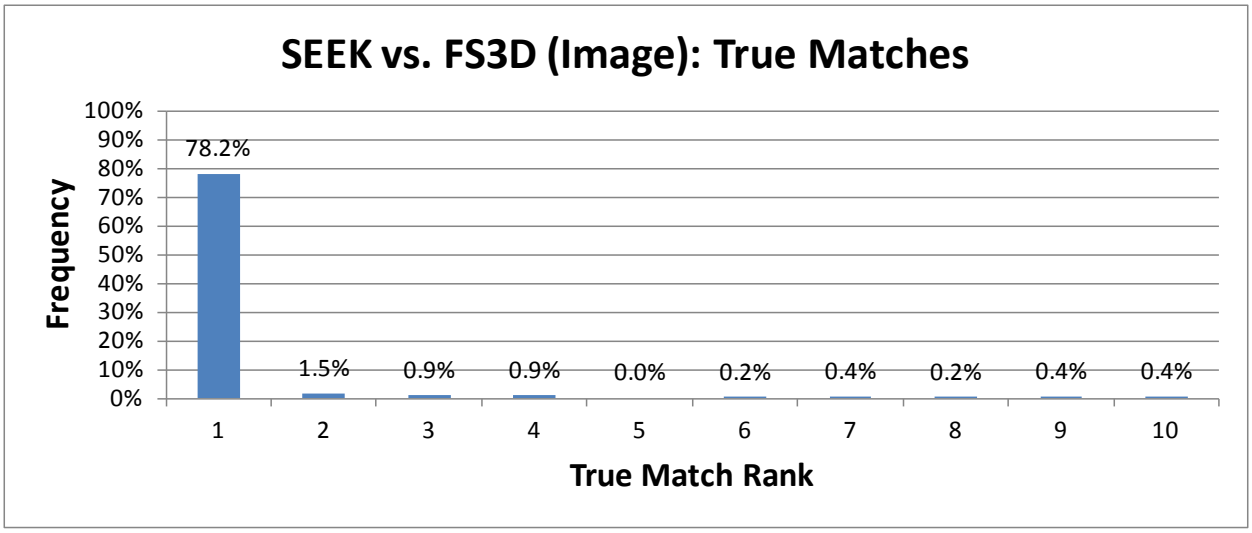
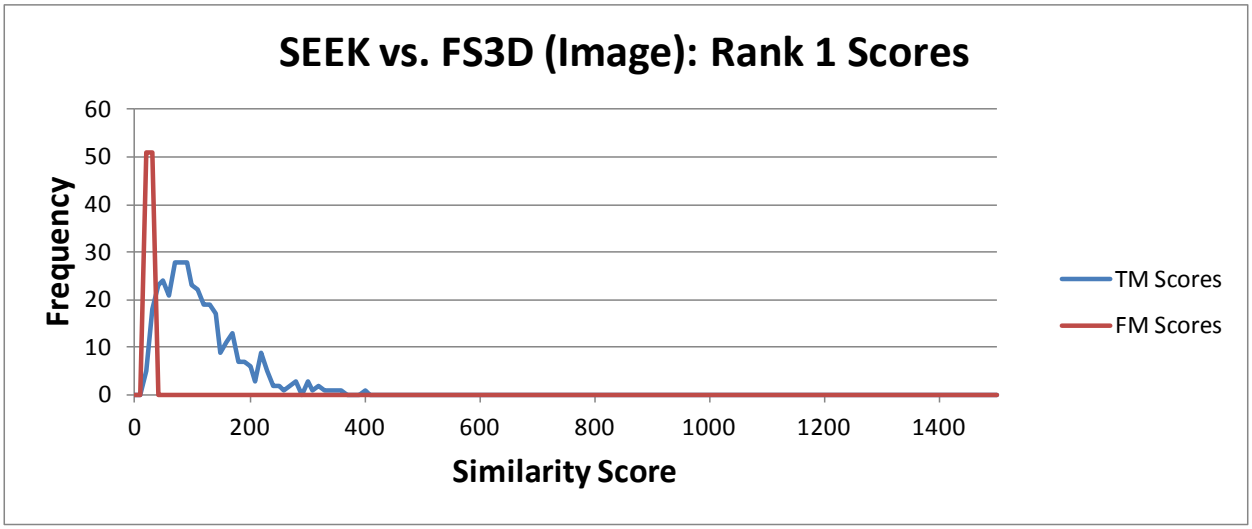
A.2.3.2 SEEK Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
FS3D Image Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
SEEK Image Original	**Unique Subjects**	468			
Matches	**True Matches**	366	78%	114	69
	False Matches	102	22%	24	3
	Total Matches	219024			





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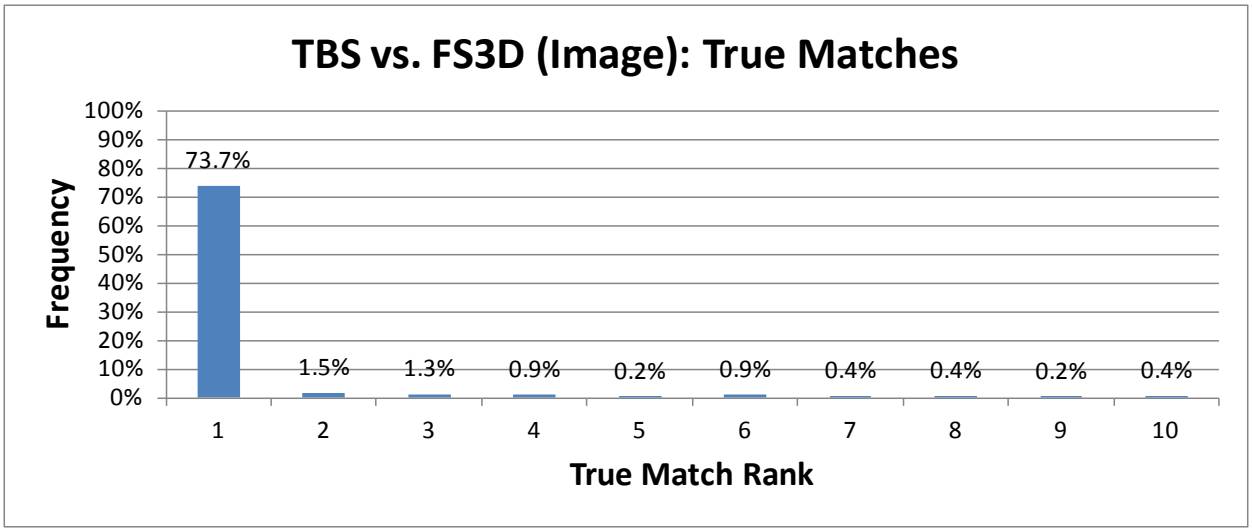
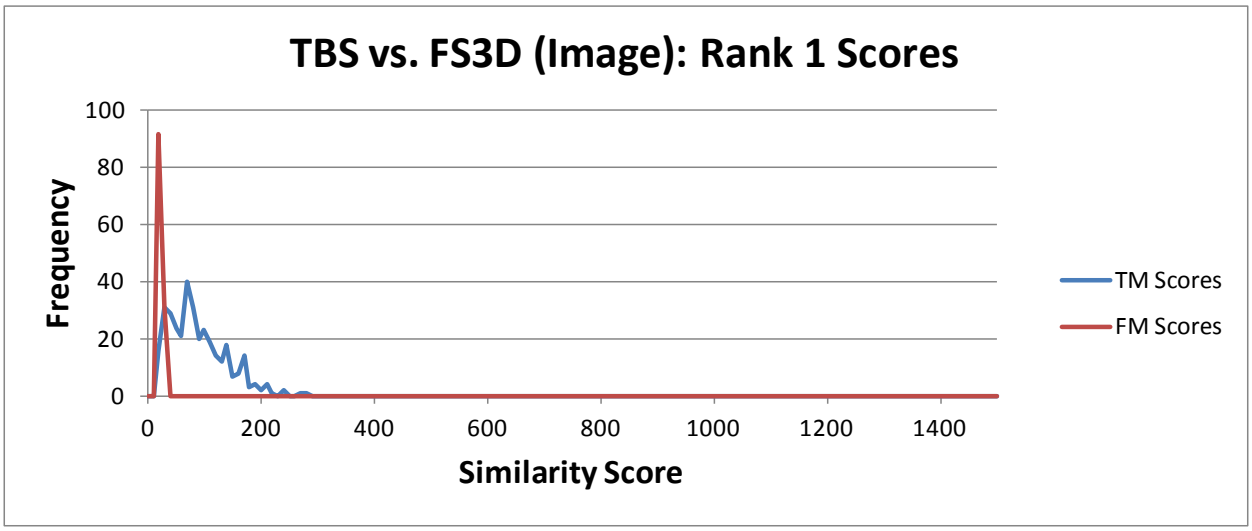
A.2.3.3 TBS Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
FS3D Image Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
TBS Image Original	**Unique Subjects**	468			
Matches	**True Matches**	345	74%	88	50
	False Matches	123	26%	23	3
	Total Matches	219024			





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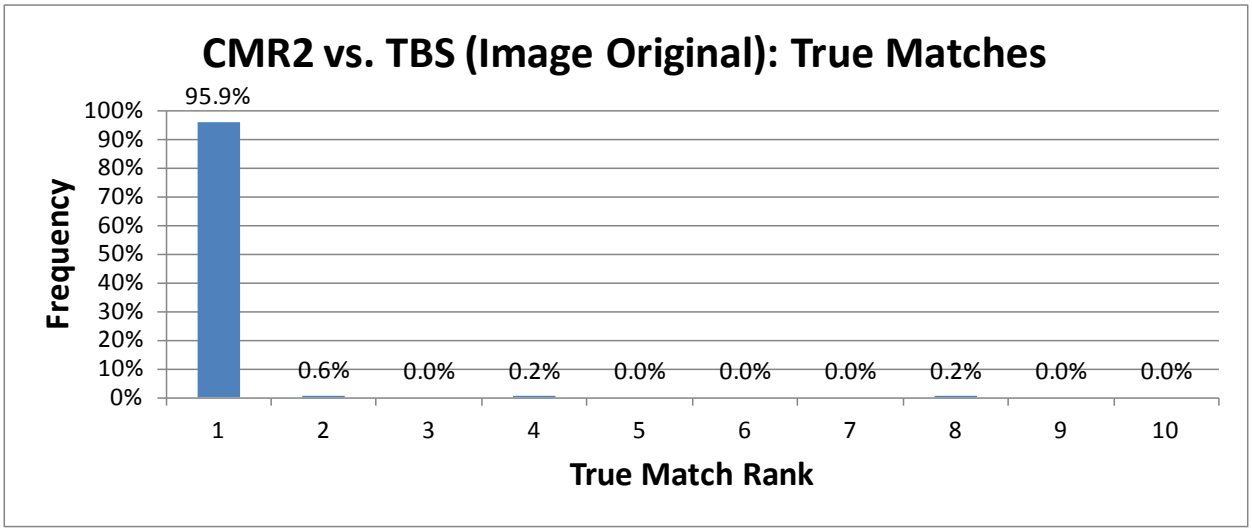
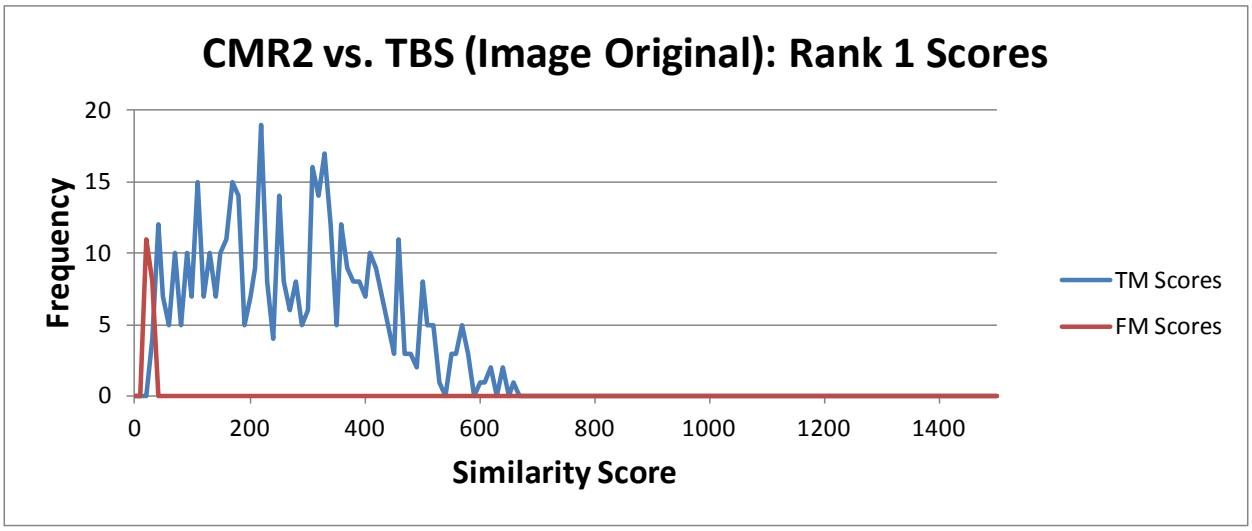
A.2.4 TBS Gallery

A.2.4.1 CMR2 Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
TBS Image Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
CMR2 Image Original	**Unique Subjects**	468			
Matches	**True Matches**	449	96%	275	146
	False Matches	19	4%	24	3
	Total Matches	219024			





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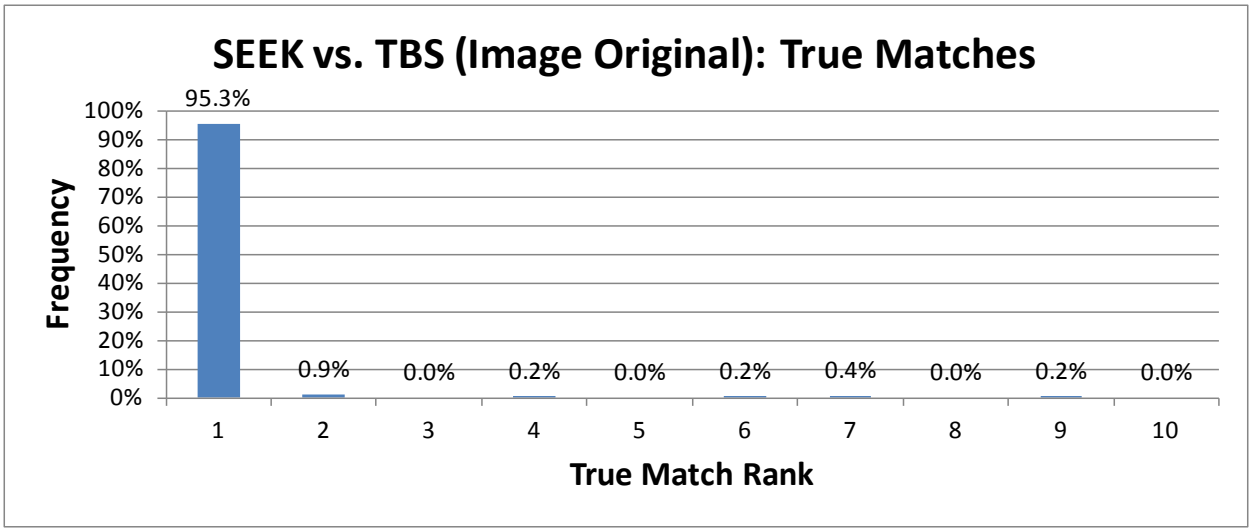
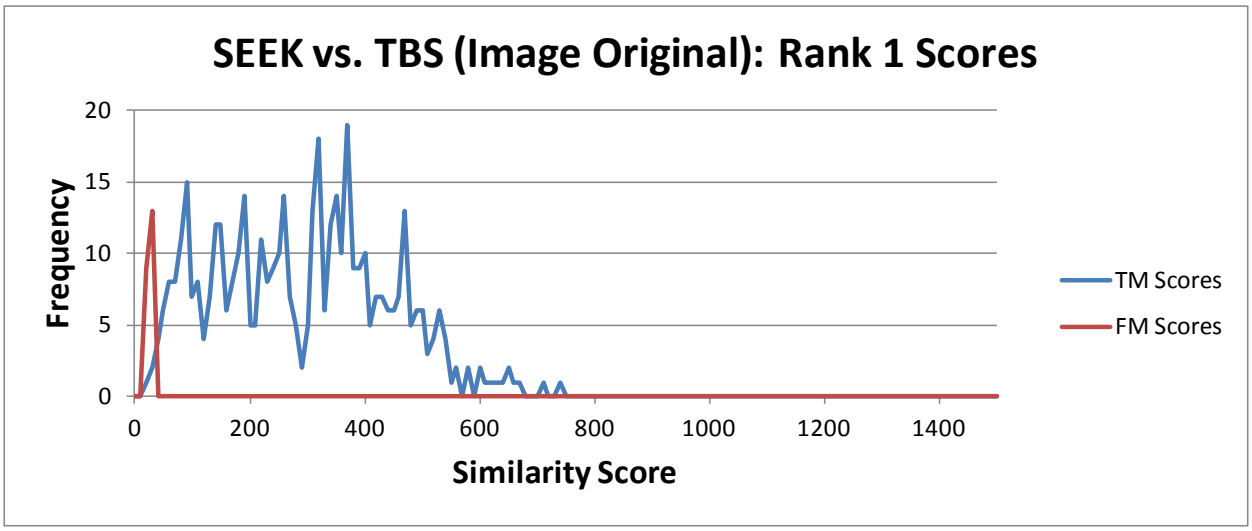
A.2.4.2 SEEK Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
TBS Image Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
SEEK Image Original	**Unique Subjects**	468			
Matches	**True Matches**	446	95%	291	150
	False Matches	22	5%	26	3
	Total Matches	219024			





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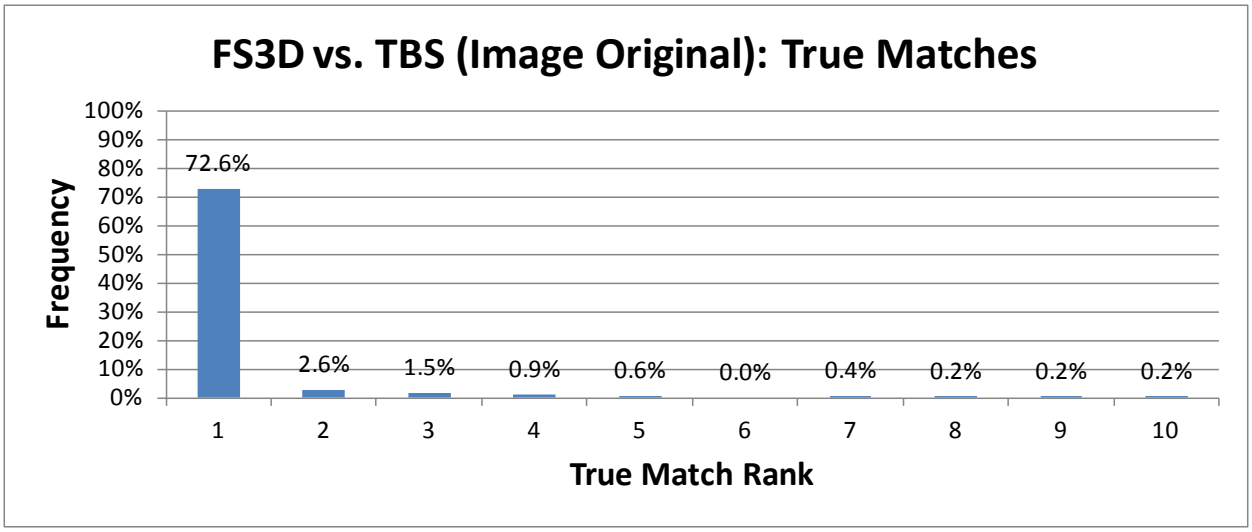
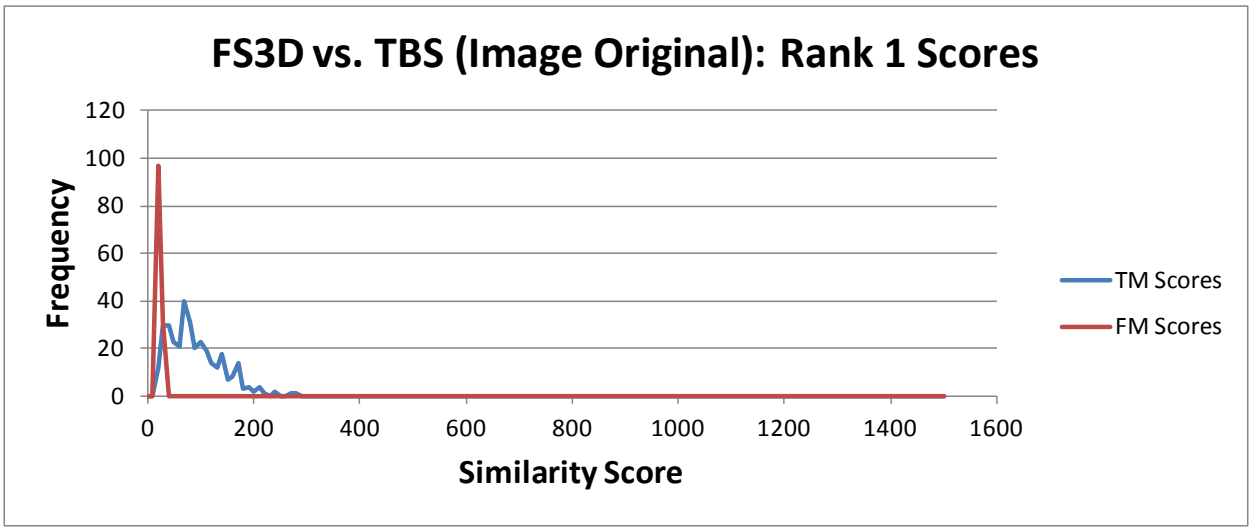
A.2.4.3 FS3D Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
TBS Image Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
FS3D Image Original	**Unique Subjects**	468			
Matches	**True Matches**	340	73%	89	49
	False Matches	128	27%	23	3
	Total Matches	219024			





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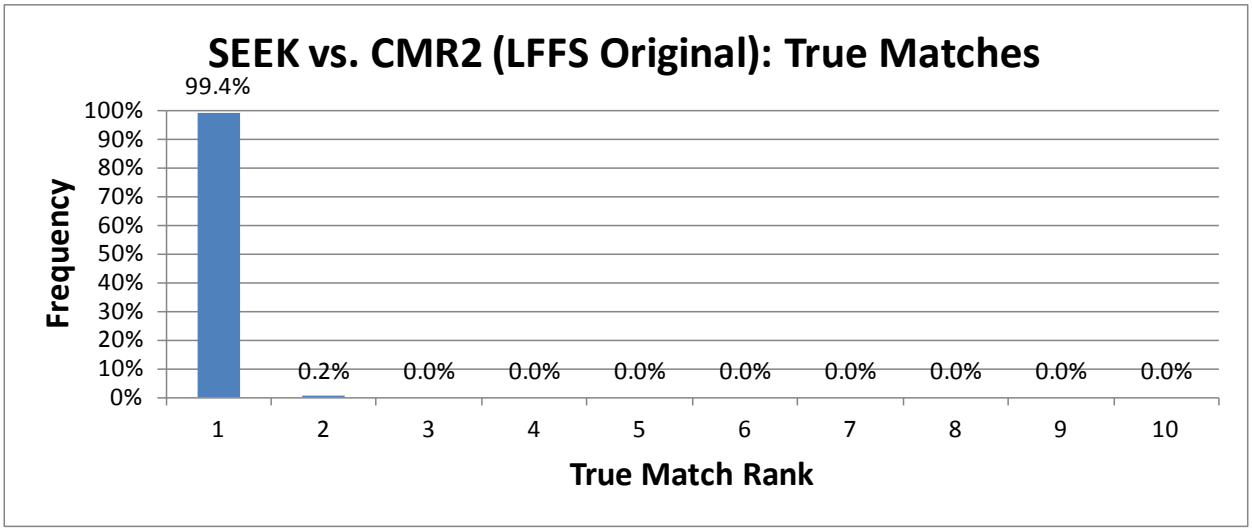
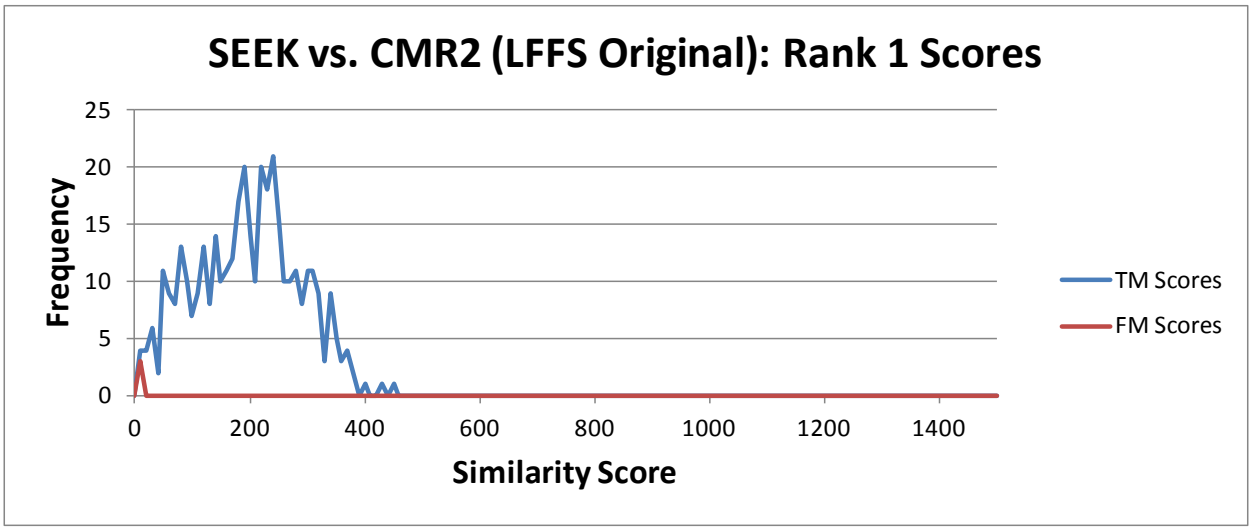
A.3 Matching Runs: LFFS, Original

A.3.1 CMR2 Gallery

A.3.1.1 SEEK Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
SEEK LFFS Original	**Unique Subjects**	468			
Matches	**True Matches**	465	99%	197	90
	False Matches	3	1%	7	2
	Total Matches	219024			





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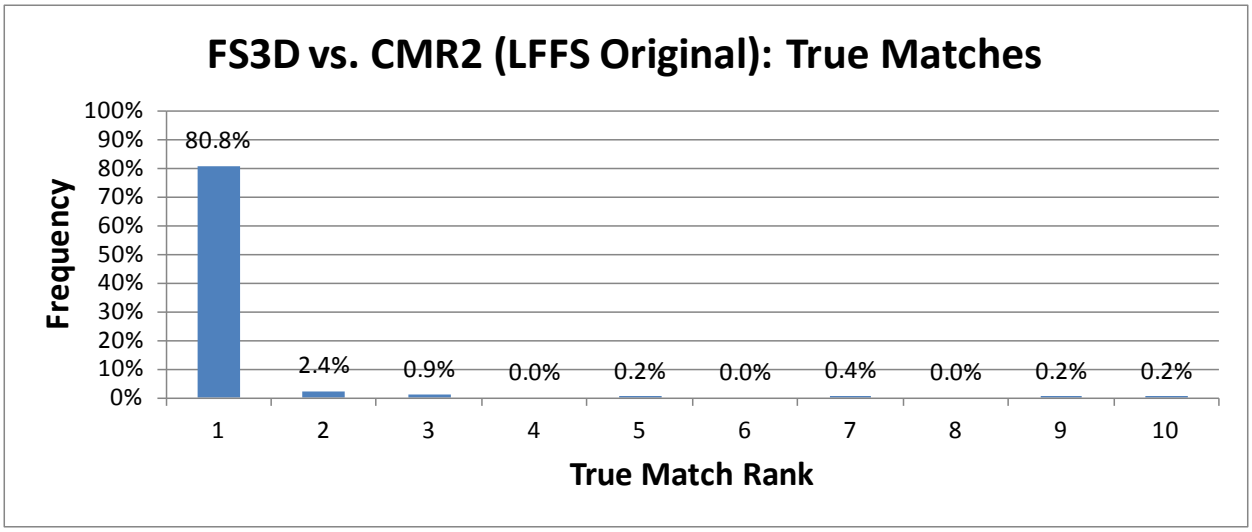
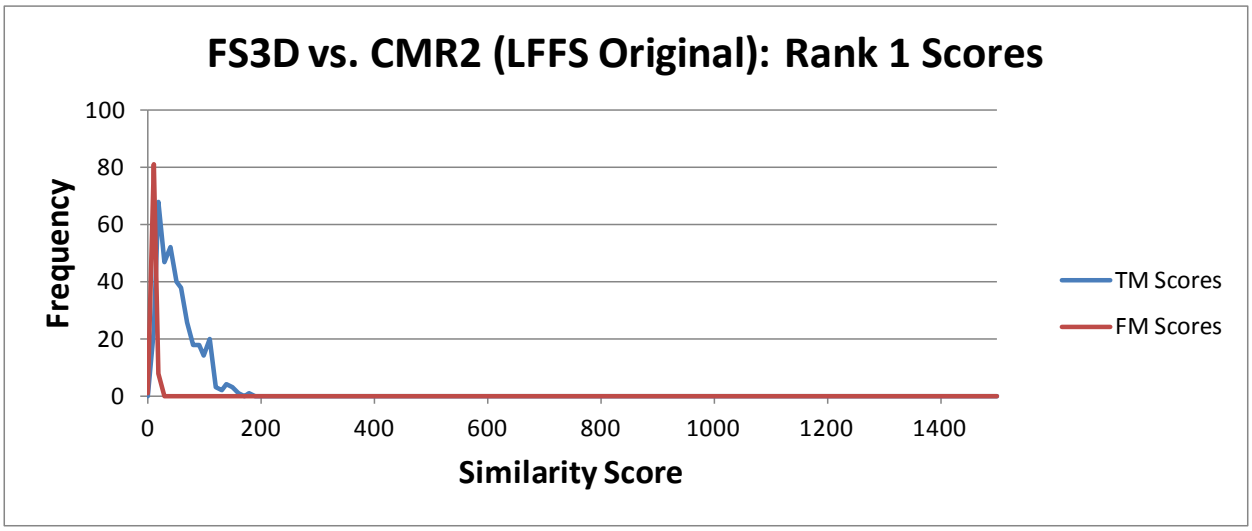
A.3.1.2 FS3D Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
FS3D LFFS Original	**Unique Subjects**	468			
Matches	**True Matches**	378	81%	52	33
	False Matches	90	19%	10	4
	Total Matches	219024			





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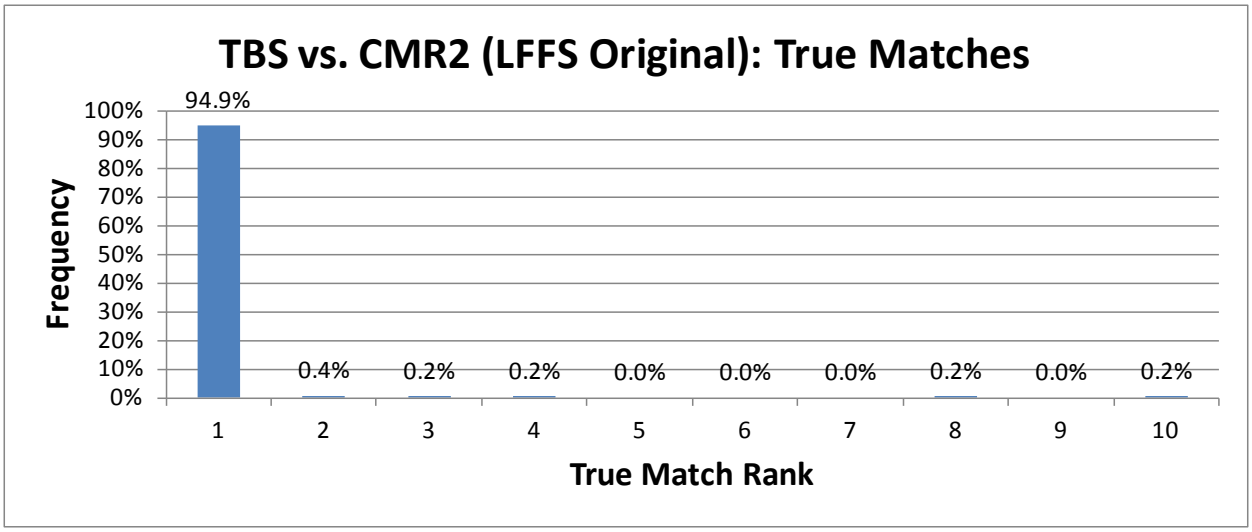
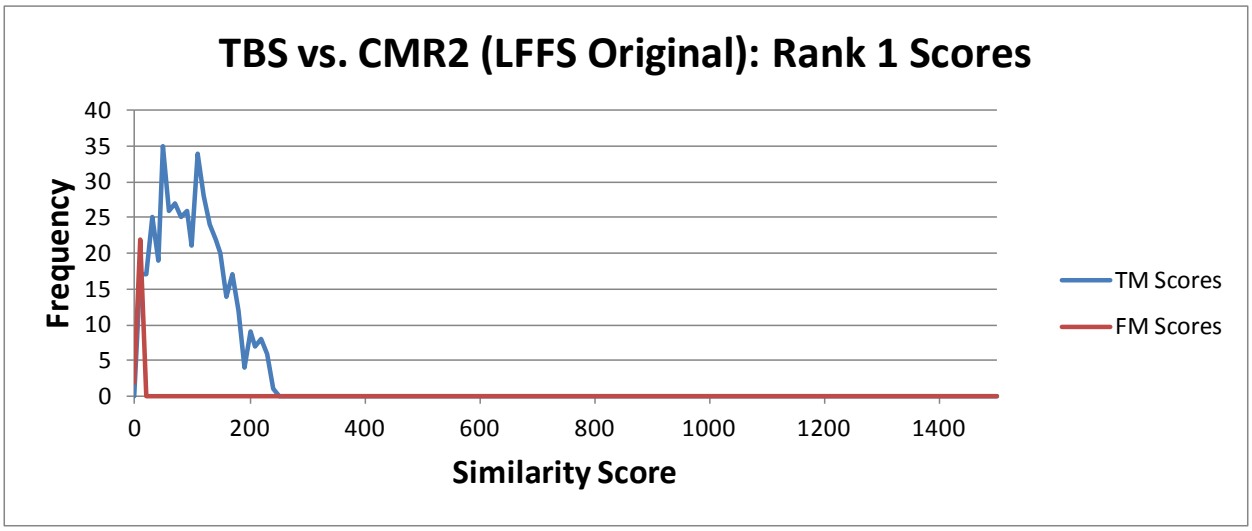
A.3.1.3 TBS Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
TBS LFFS Original	**Unique Subjects**	468			
Matches	**True Matches**	444	95%	100	56
	False Matches	24	5%	7	2
	Total Matches	219024			





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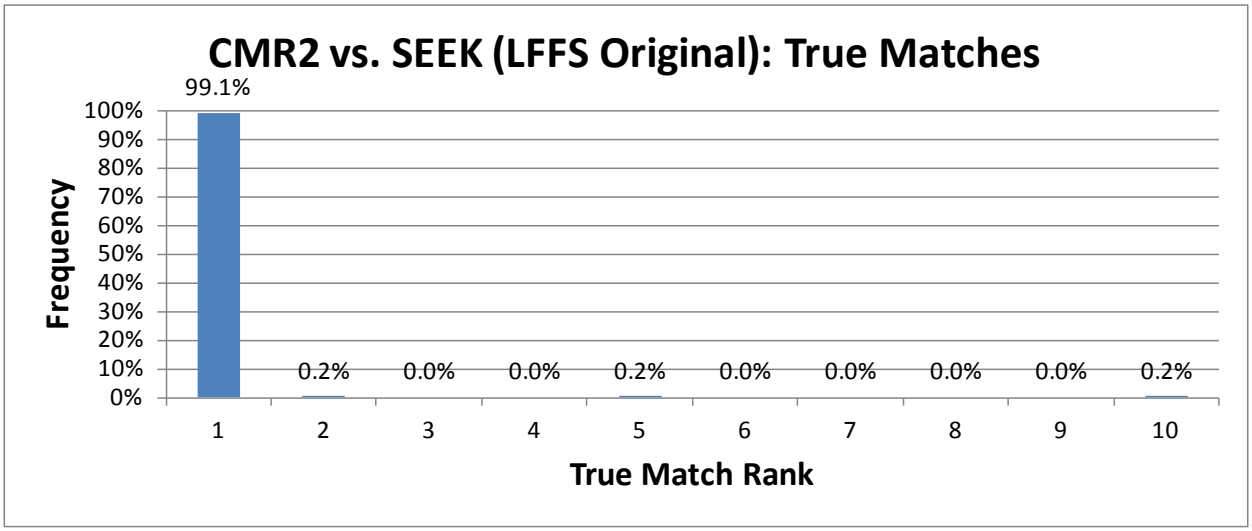
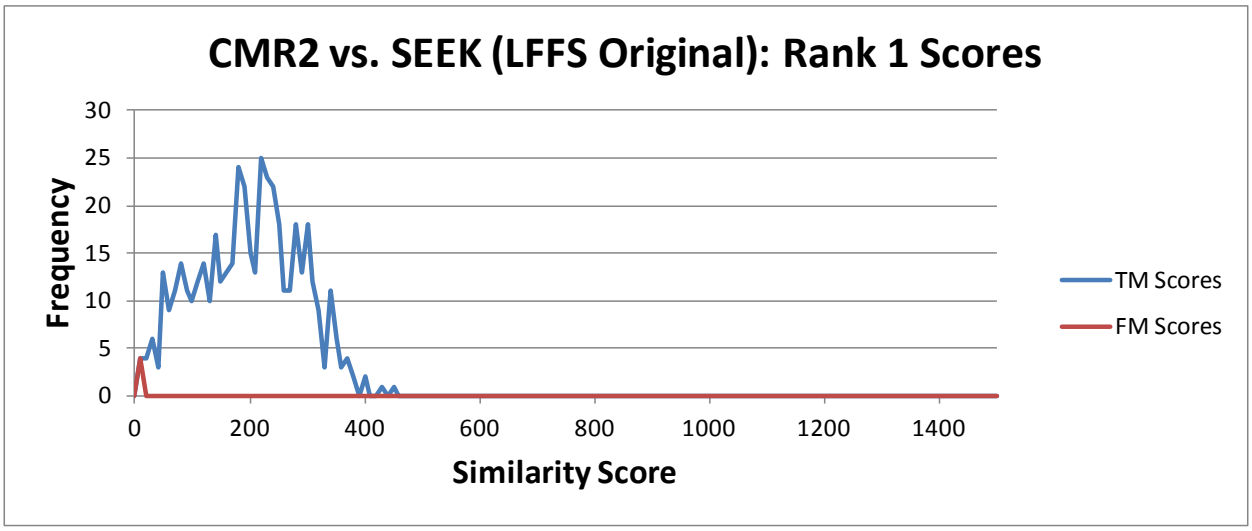
A.3.2 SEEK Gallery

A.3.2.1 CMR2 Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
SEEK LFFS Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
CMR2 LFFS Original	**Unique Subjects**	468			
Matches	**True Matches**	464	99%	197	89
	False Matches	4	1%	8	2
	Total Matches	219024			





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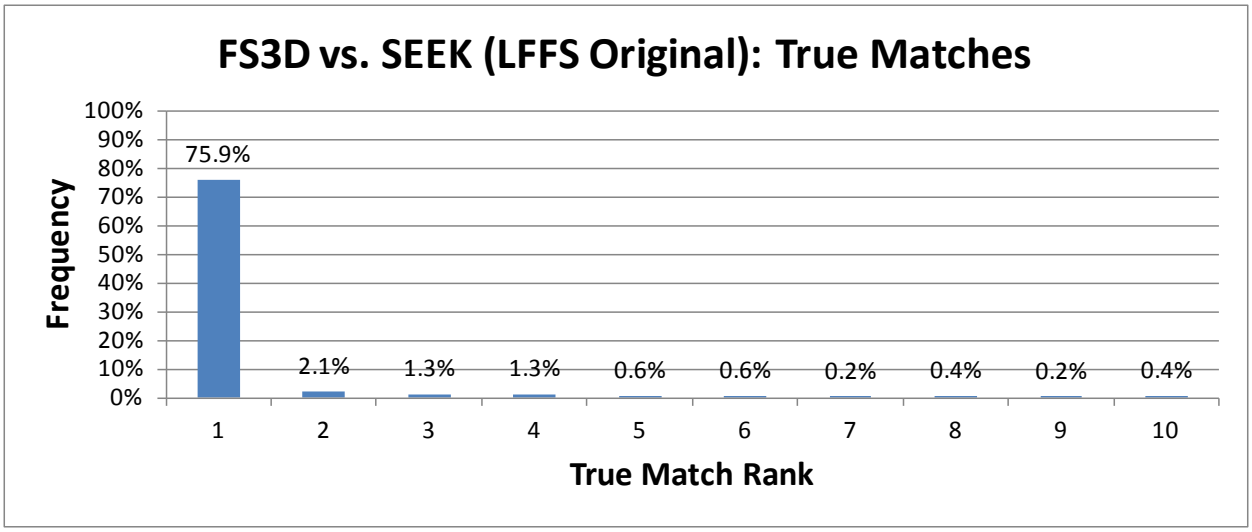
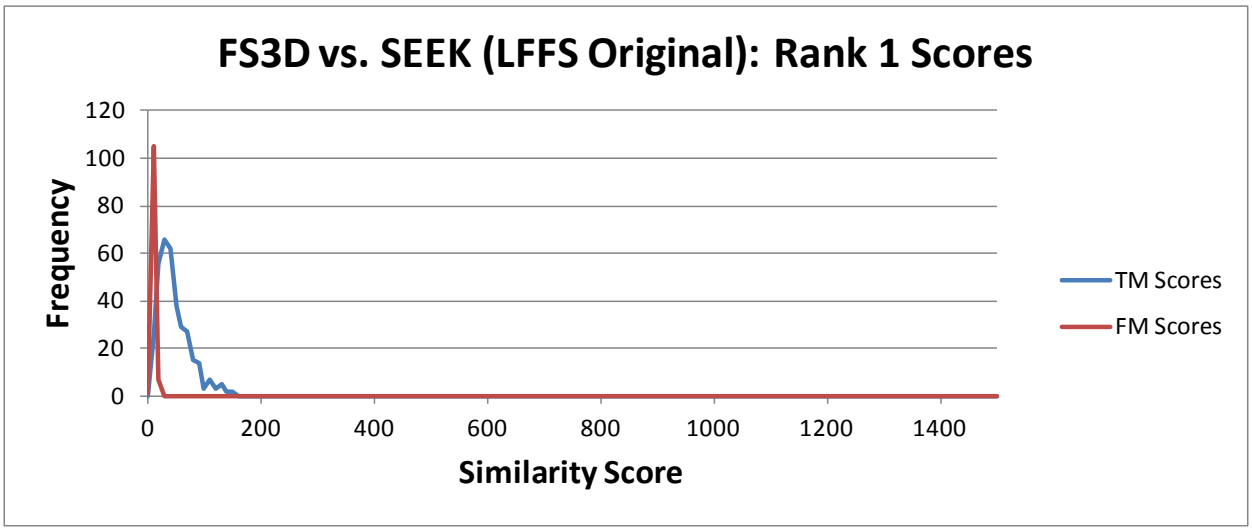
A.3.2.2 FS3D Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
SEEK LFFS Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
FS3D LFFS Original	**Unique Subjects**	468			
Matches	**True Matches**	355	76%	46	29
	False Matches	113	24%	9	3
	Total Matches	219024			





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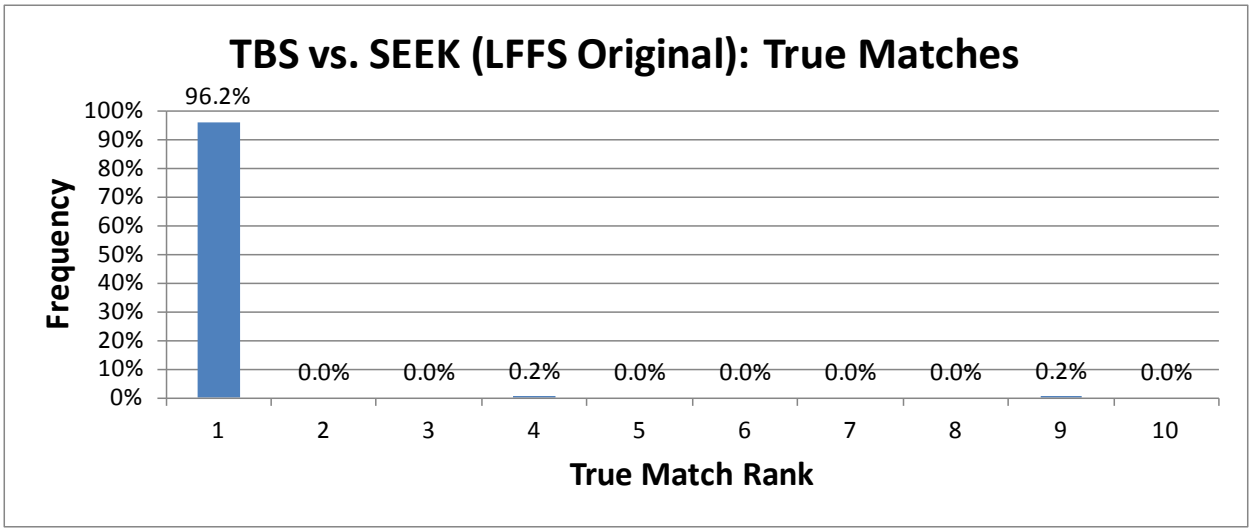
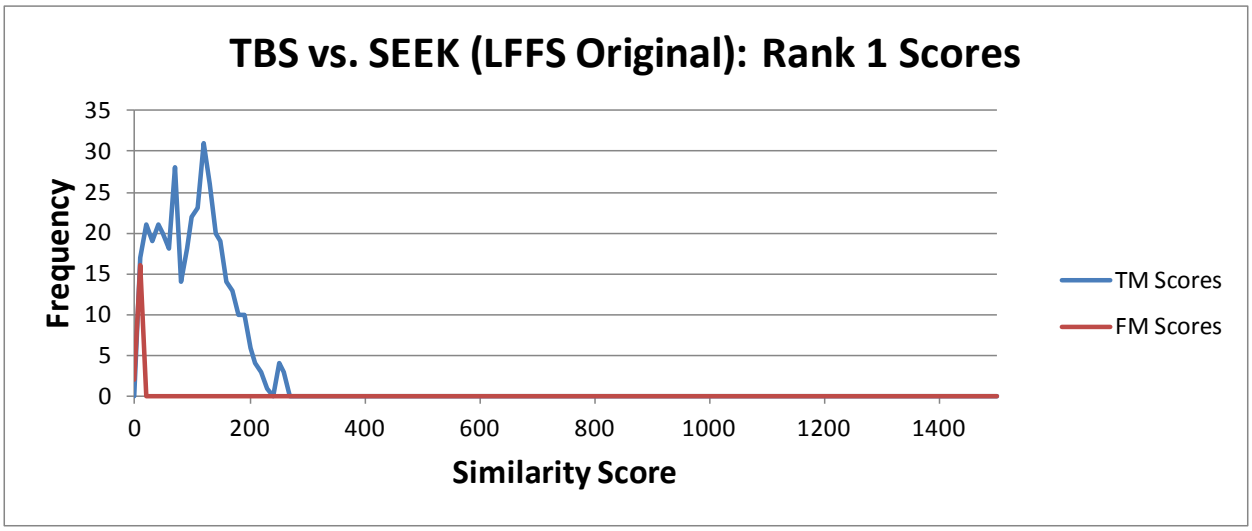
A.3.2.3 TBS Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
SEEK LFFS Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
TBS LFFS Original	**Unique Subjects**	468			
Matches	**True Matches**	450	96%	101	58
	False Matches	18	4%	7	2
	Total Matches	219024			





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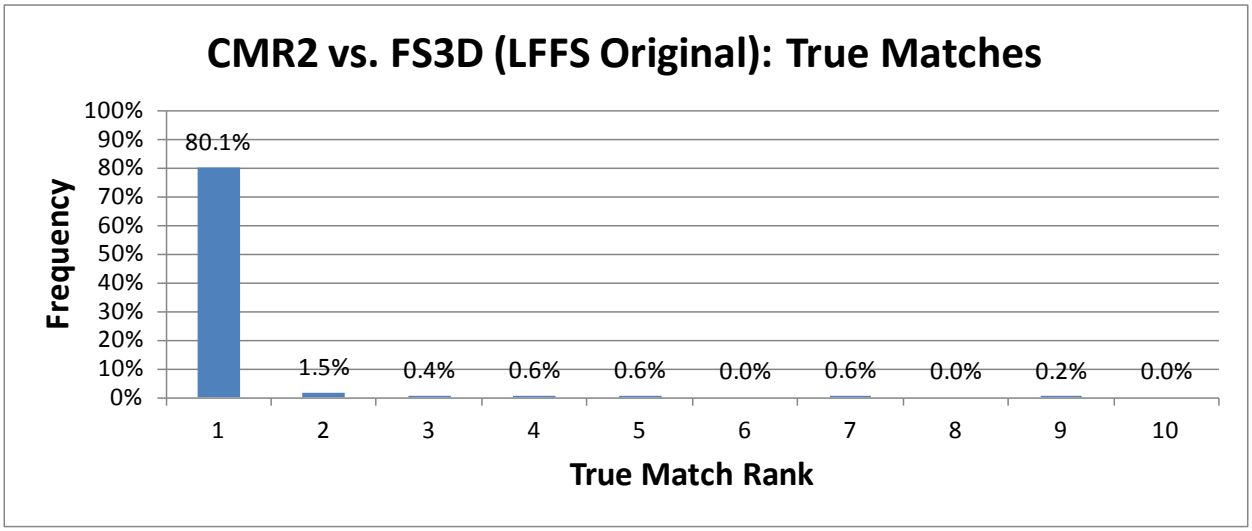
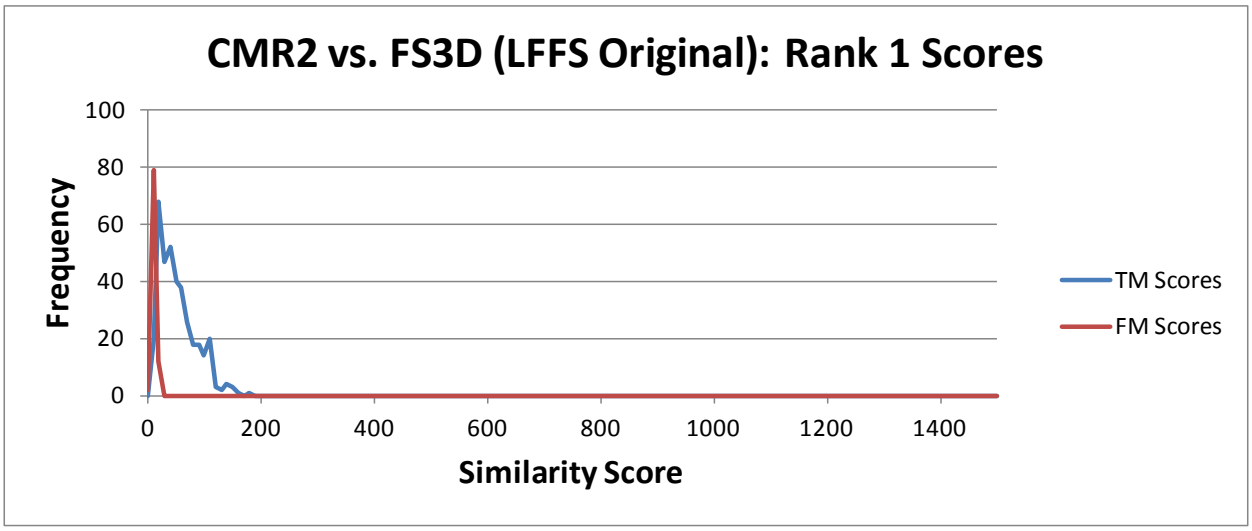
A.3.3 FS3D Gallery

A.3.3.1 CMR2 Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
FS3D LFFS Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
CMR2 LFFS Original	**Unique Subjects**	468			
Matches	**True Matches**	375	80%	52	33
	False Matches	93	20%	11	3
	Total Matches	219024			





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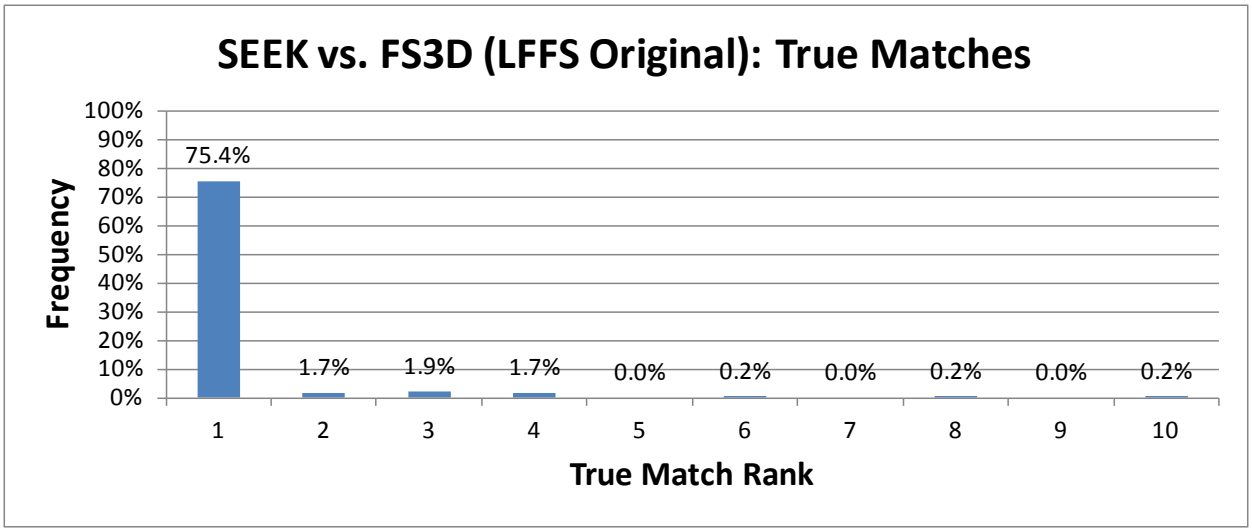
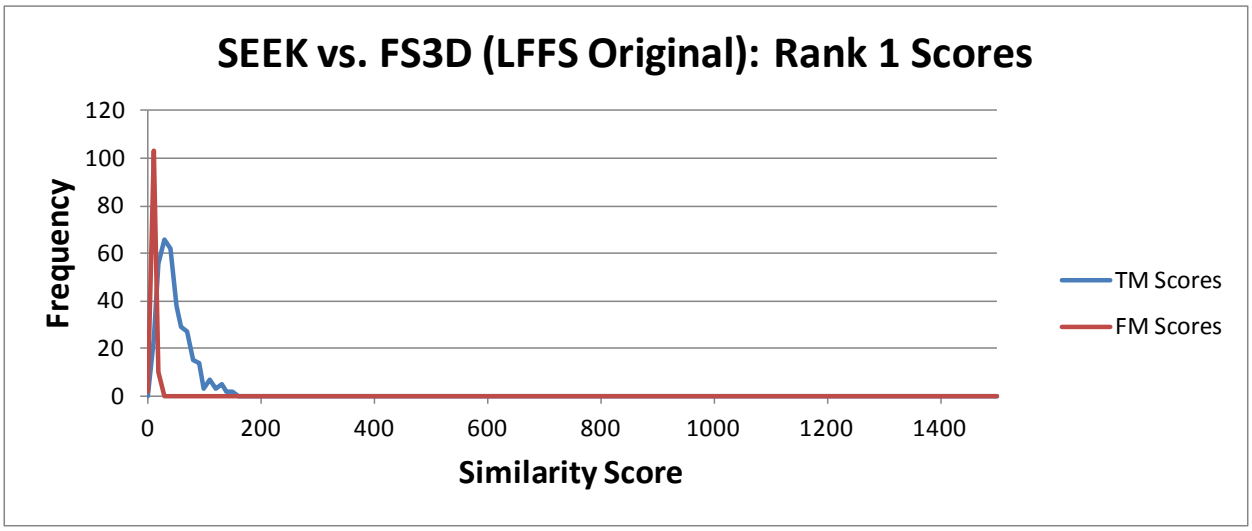
A.3.3.2 SEEK Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
FS3D LFFS Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
SEEK LFFS Original	**Unique Subjects**	468			
Matches	**True Matches**	353	75%	46	29
	False Matches	115	25%	10	3
	Total Matches	219024			





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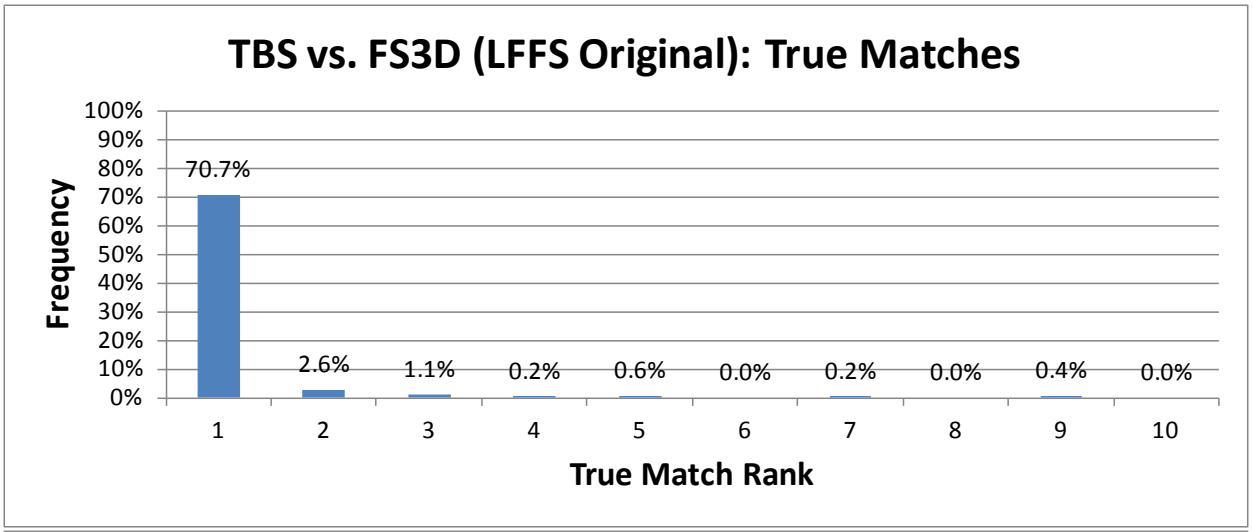
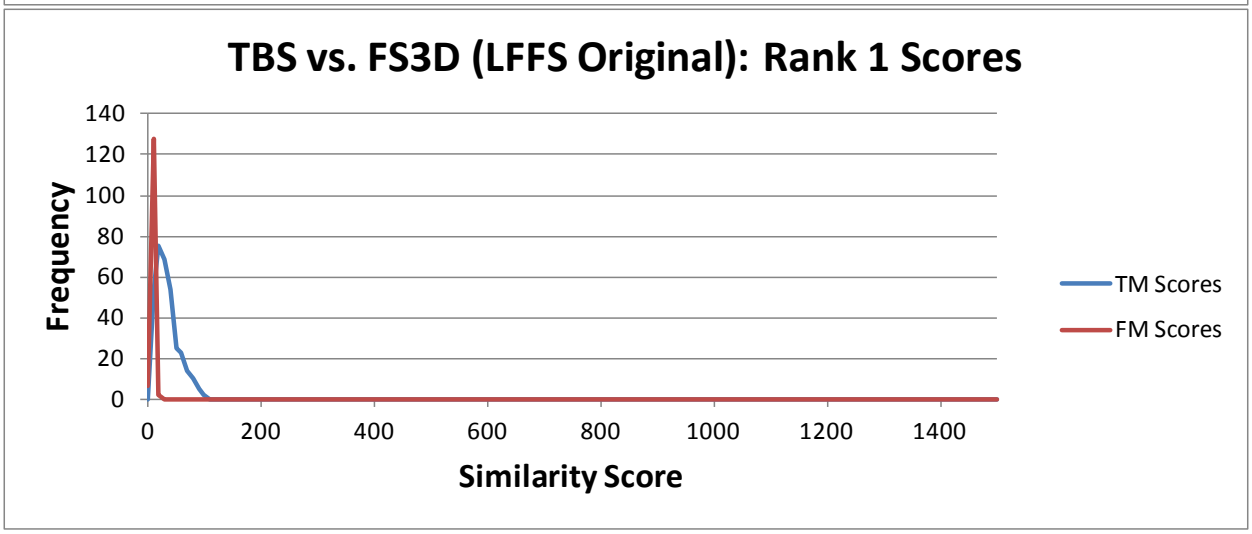
A.3.3.3 TBS Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
FS3D LFFS Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
TBS LFFS Original	**Unique Subjects**	468			
Matches	**True Matches**	331	71%	34	20
	False Matches	137	29%	8	2
	Total Matches	219024			





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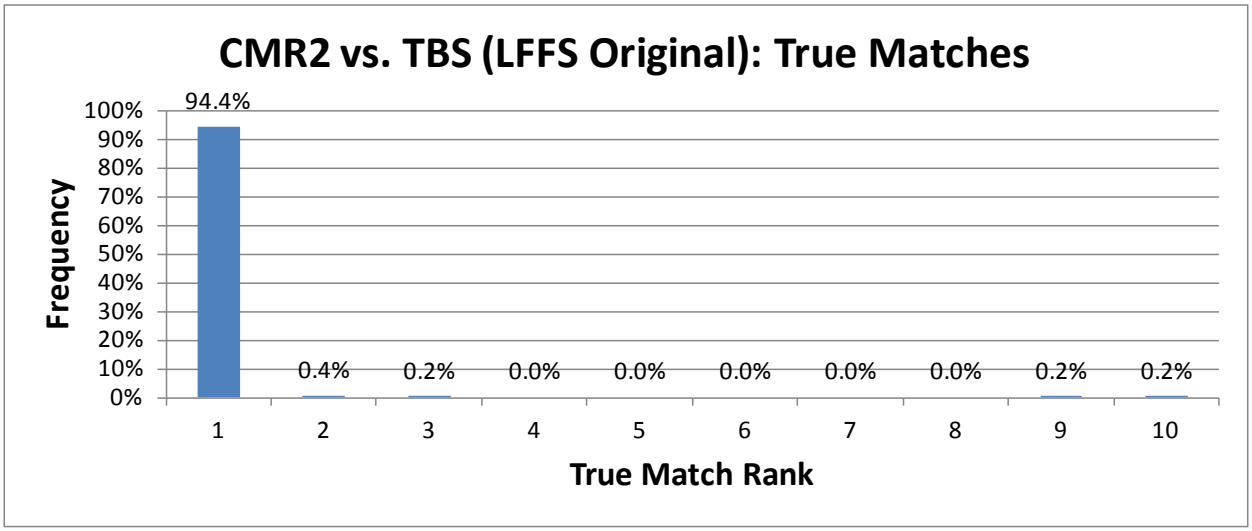
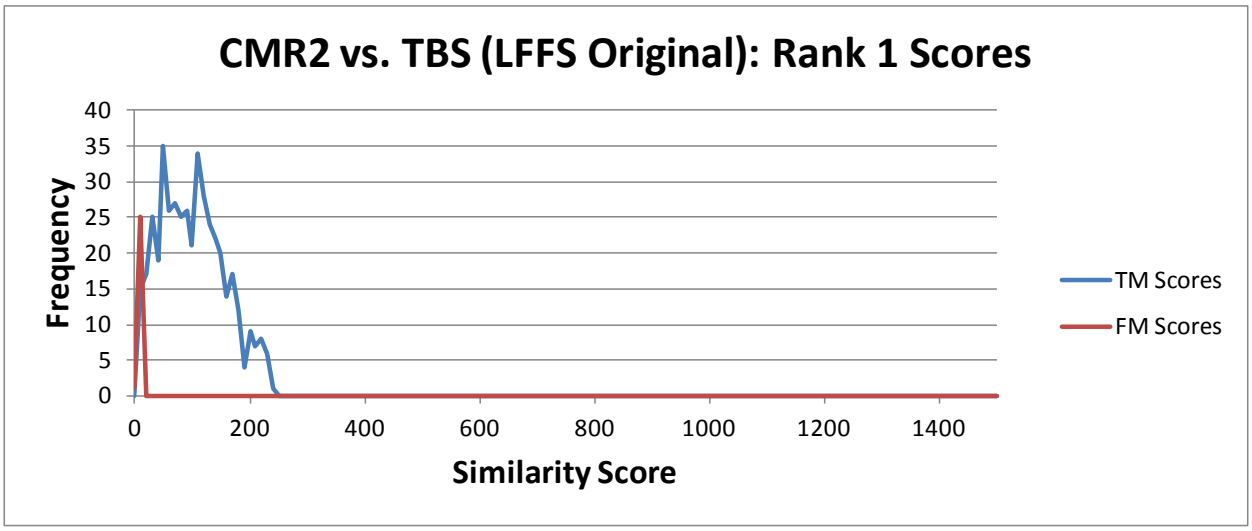
A.3.4 TBS Gallery

A.3.4.1 CMR2 Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
TBS LFFS Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
CMR2 LFFS Original	**Unique Subjects**	468			
Matches	**True Matches**	442	94%	101	56
	False Matches	26	6%	9	2
	Total Matches	219024			





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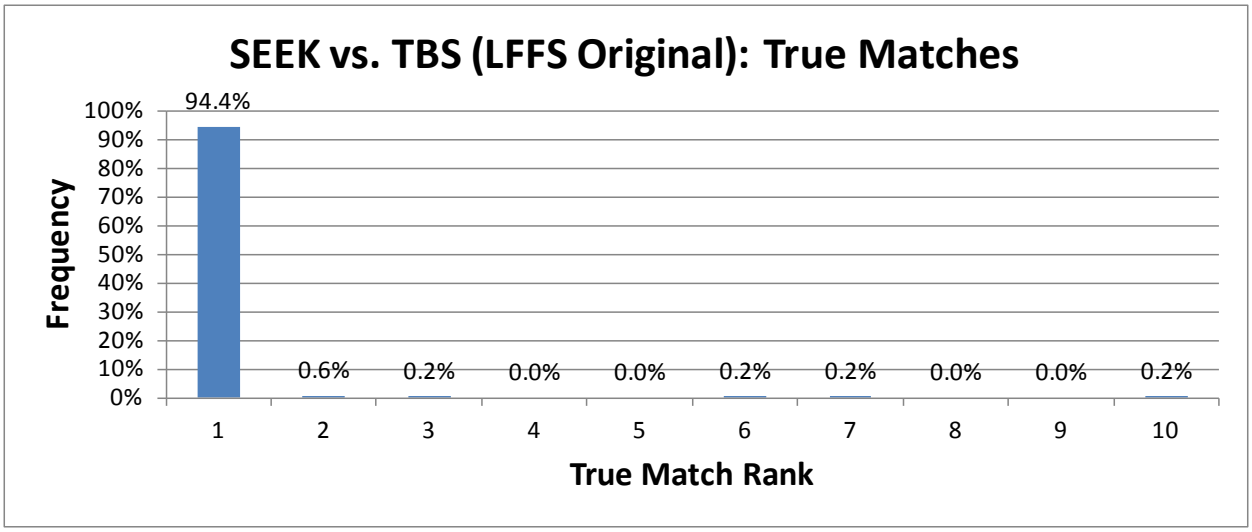
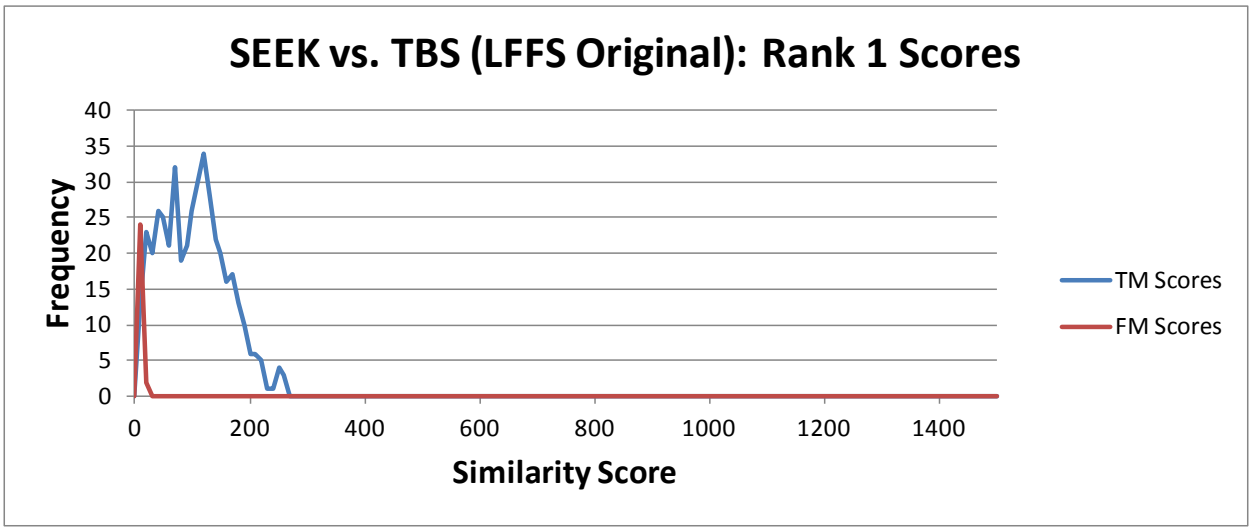
A.3.4.2 SEEK Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
TBS LFFS Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
SEEK LFFS Original	**Unique Subjects**	468			
Matches	**True Matches**	442	94%	103	57
	False Matches	26	6%	10	3
	Total Matches	219024			





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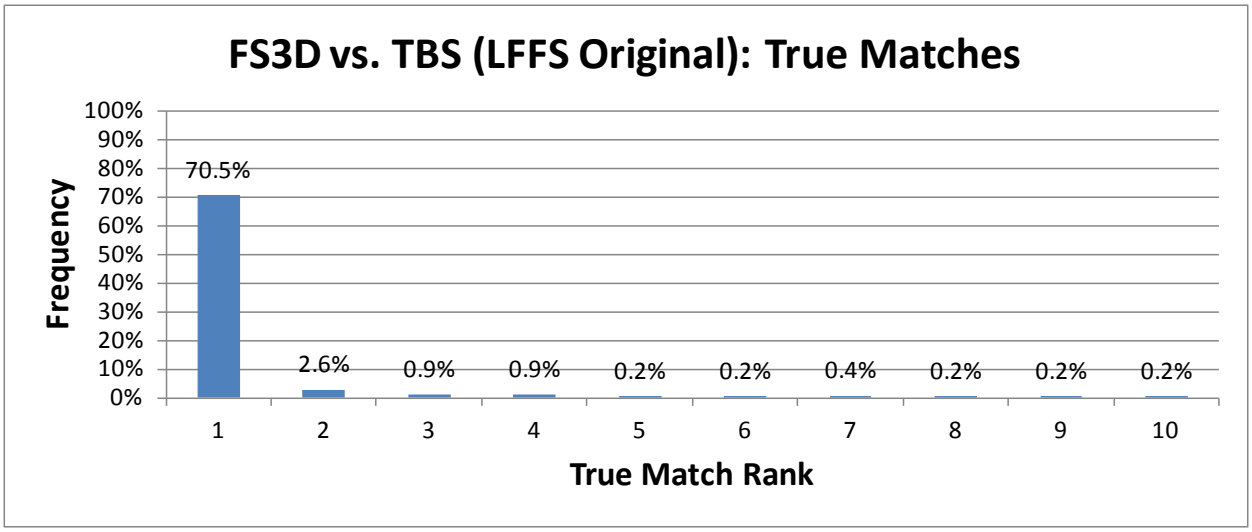
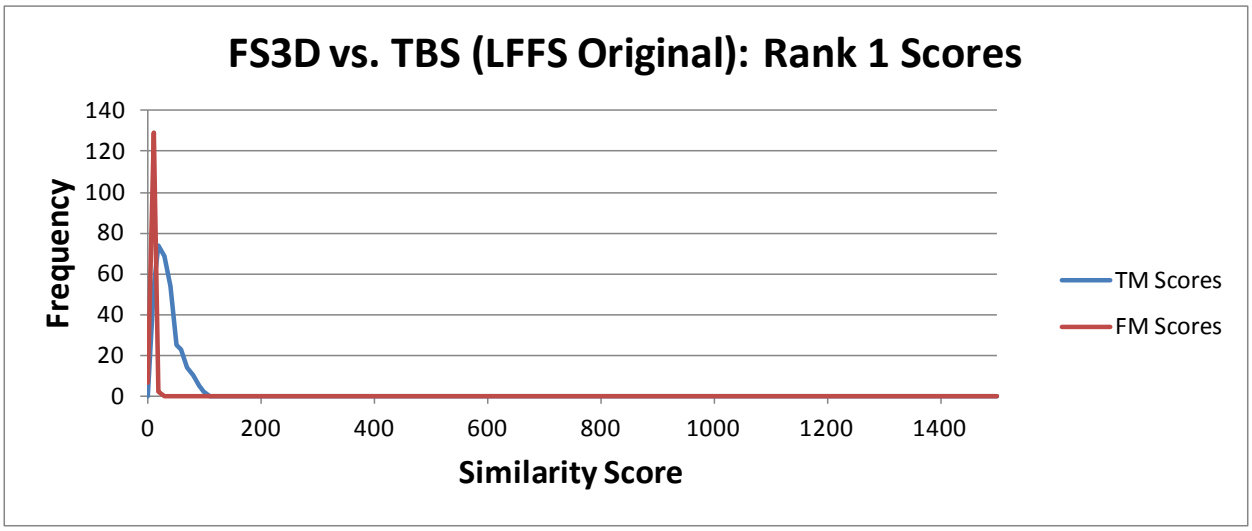
A.3.4.3 FS3D Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
TBS LFFS Original	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
FS3D LFFS Original	**Unique Subjects**	468			
Matches	**True Matches**	330	71%	34	20
	False Matches	138	29%	8	2
	Total Matches	219024			





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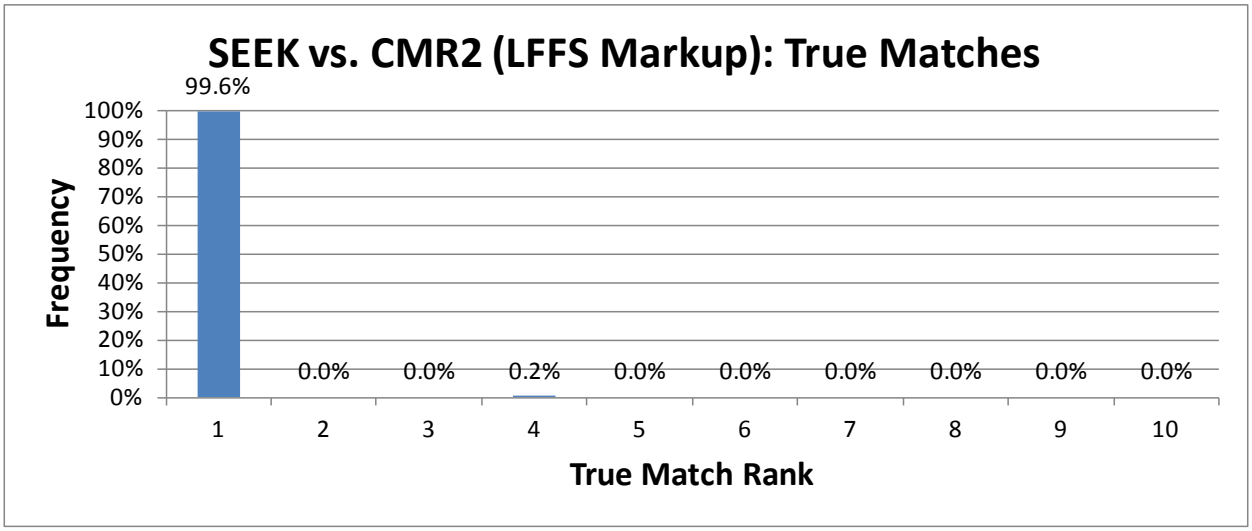
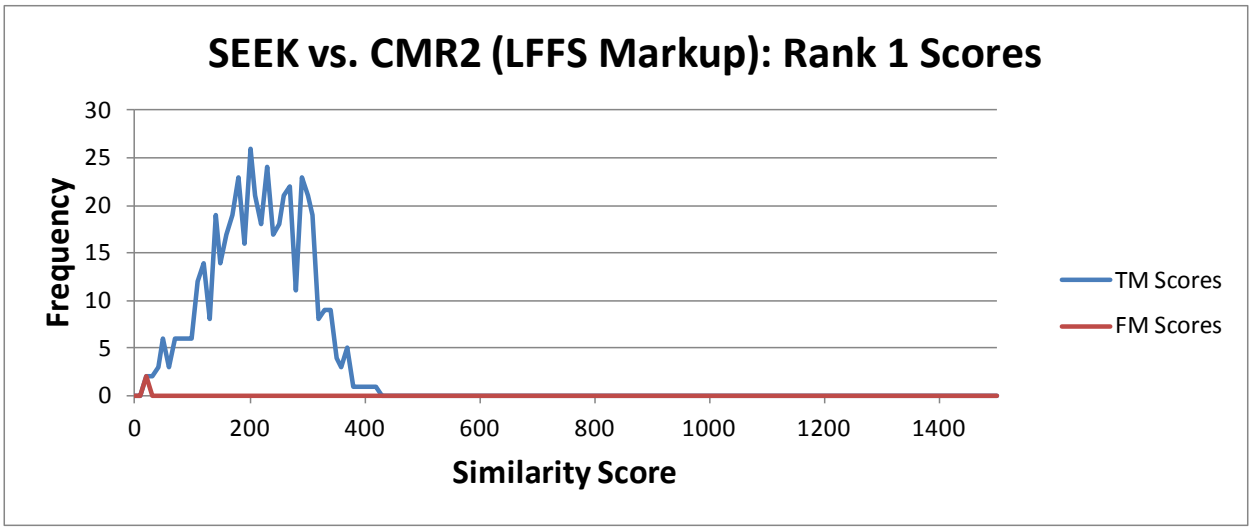
A.4 Matching Runs: LFFS, Markup

A.4.1 CMR2 Gallery

A.4.1.1 SEEK Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Markup	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
SEEK LFFS Markup	**Unique Subjects**	468			
Matches	**True Matches**	466	100%	215	79
	False Matches	2	0%	18	4
	Total Matches	219024			





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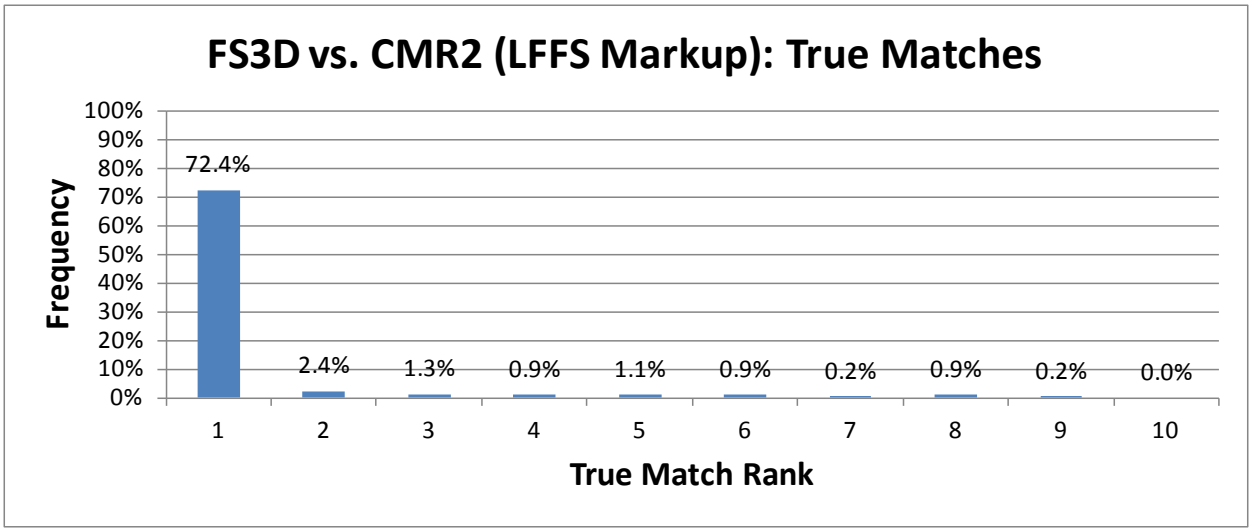
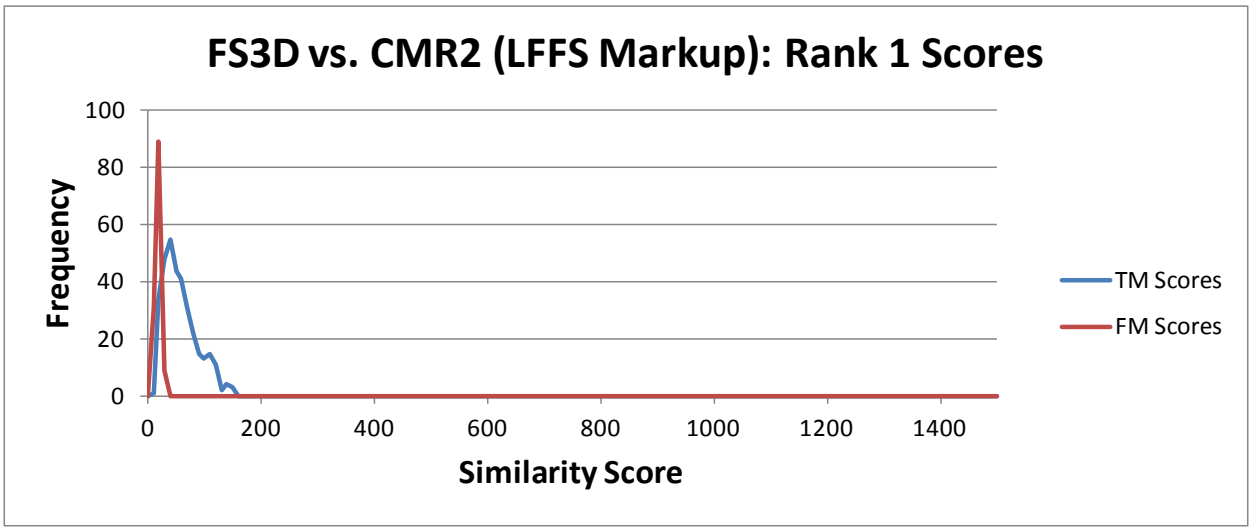
A.4.1.2 FS3D Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Markup	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
FS3D Markup	**Unique Subjects**	468			
Matches	**True Matches**	339	72%	58	30
	False Matches	129	28%	17	5
	Total Matches	219024			





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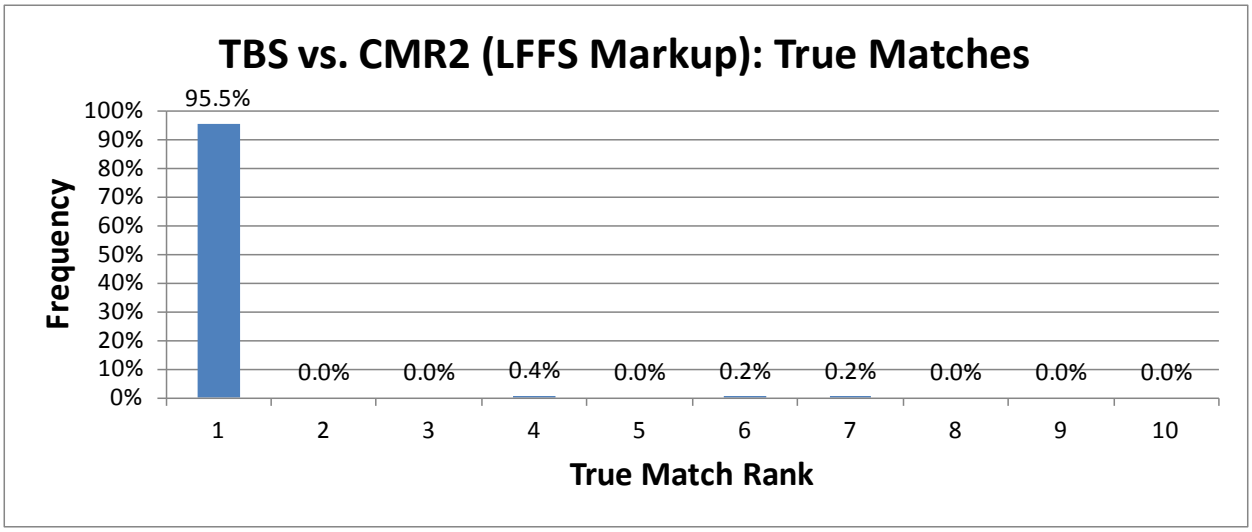
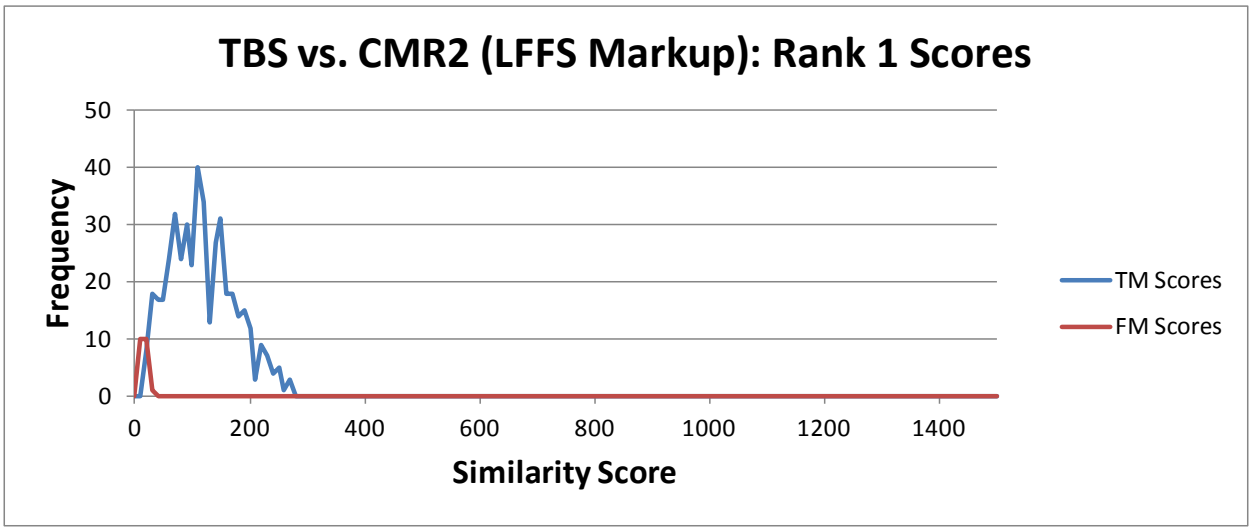
A.4.1.3 TBS Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 LFFS Markup	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
TBS LFFS Markup	**Unique Subjects**	468			
Matches	**True Matches**	447	96%	117	56
	False Matches	21	4%	16	5
	Total Matches	219024			





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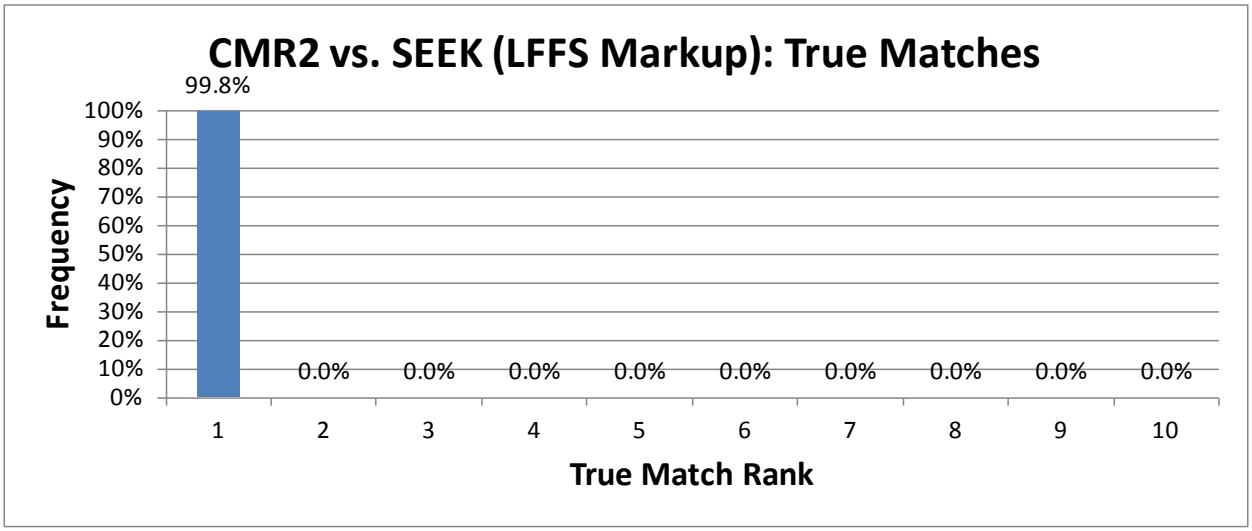
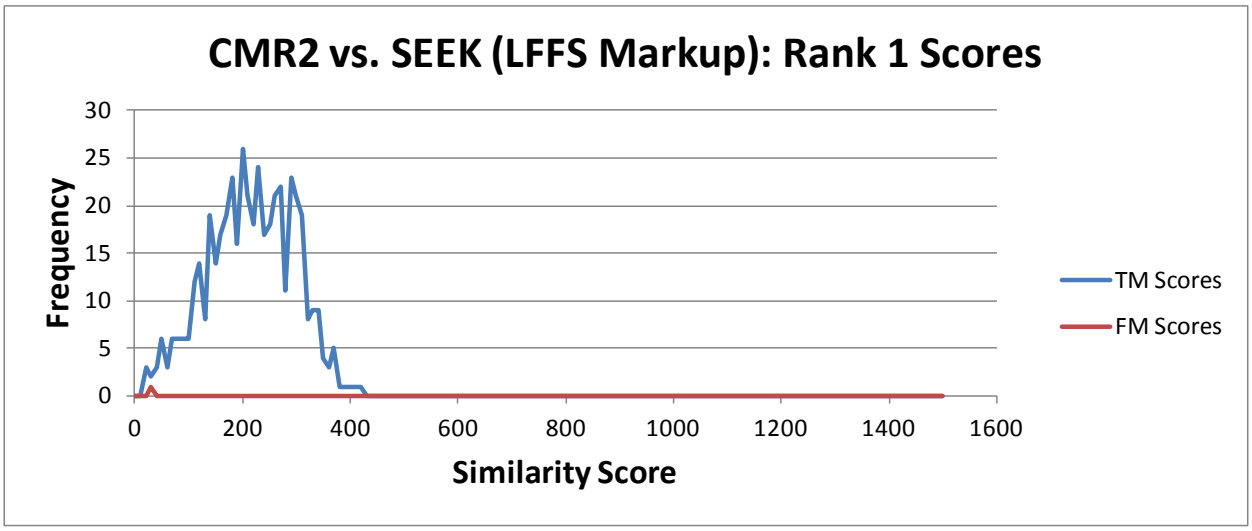
A.4.2 SEEK Gallery

A.4.2.1 CMR2 Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
SEEK LFFS Markup	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
CMR2 LFFS Markup	**Unique Subjects**	468			
Matches	**True Matches**	467	100%	215	80
	False Matches	1	0%	27	#DIV/0!
	Total Matches	219024			





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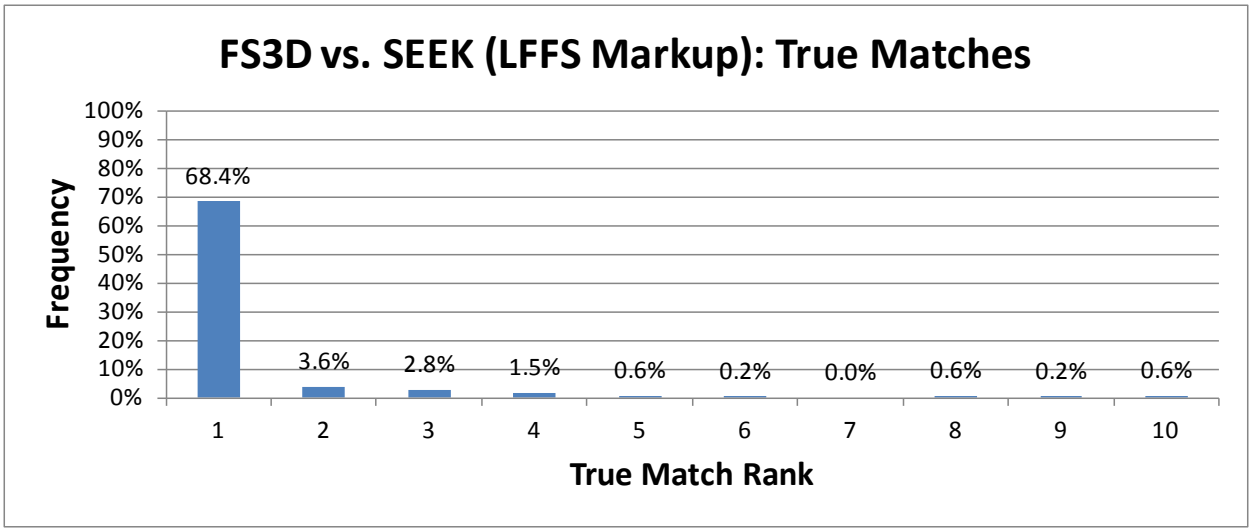
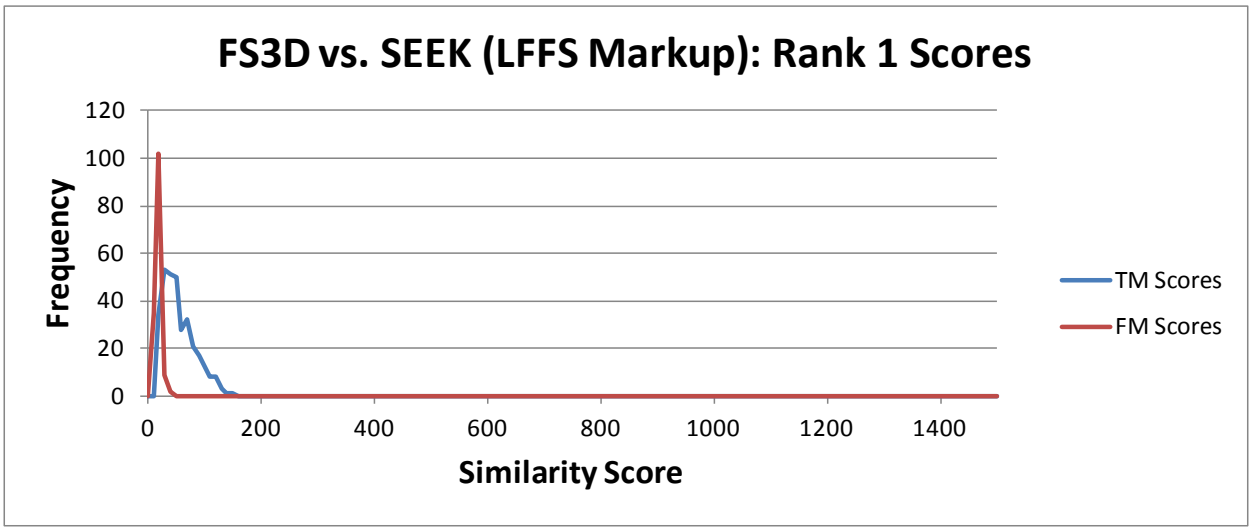
A.4.2.2 FS3D Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
SEEK LFFS Markup	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
FS3D LFFS Markup	**Unique Subjects**	468			
Matches	**True Matches**	320	68%	55	28
	False Matches	148	32%	17	5
	Total Matches	219024			





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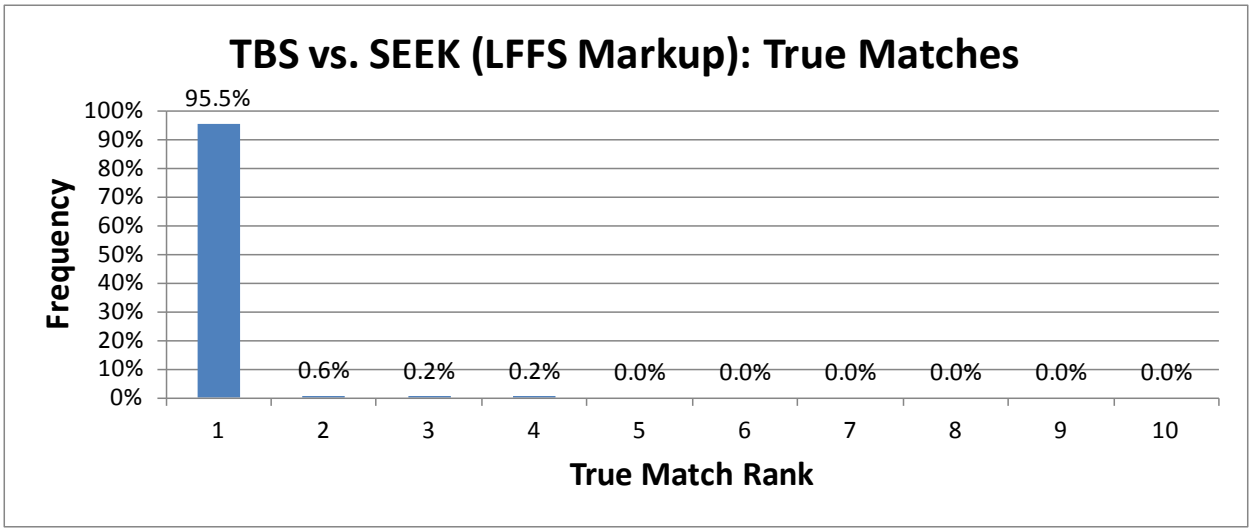
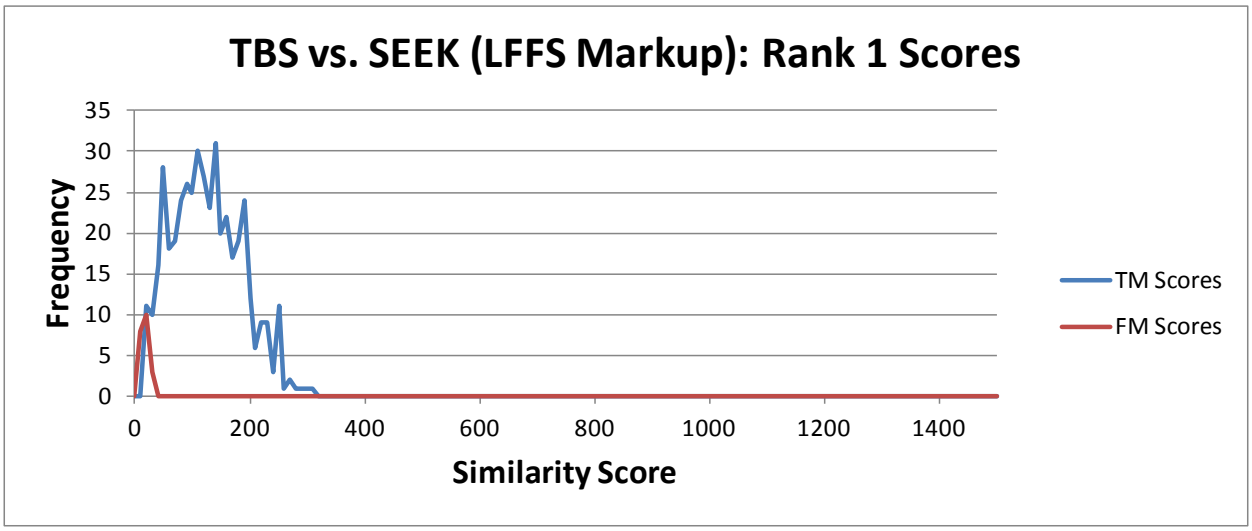
A.4.2.3 TBS Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
SEEK LFFS Markup	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
TBS LFFS Markup	**Unique Subjects**	468			
Matches	**True Matches**	447	96%	125	61
	False Matches	21	4%	17	6
	Total Matches	219024			





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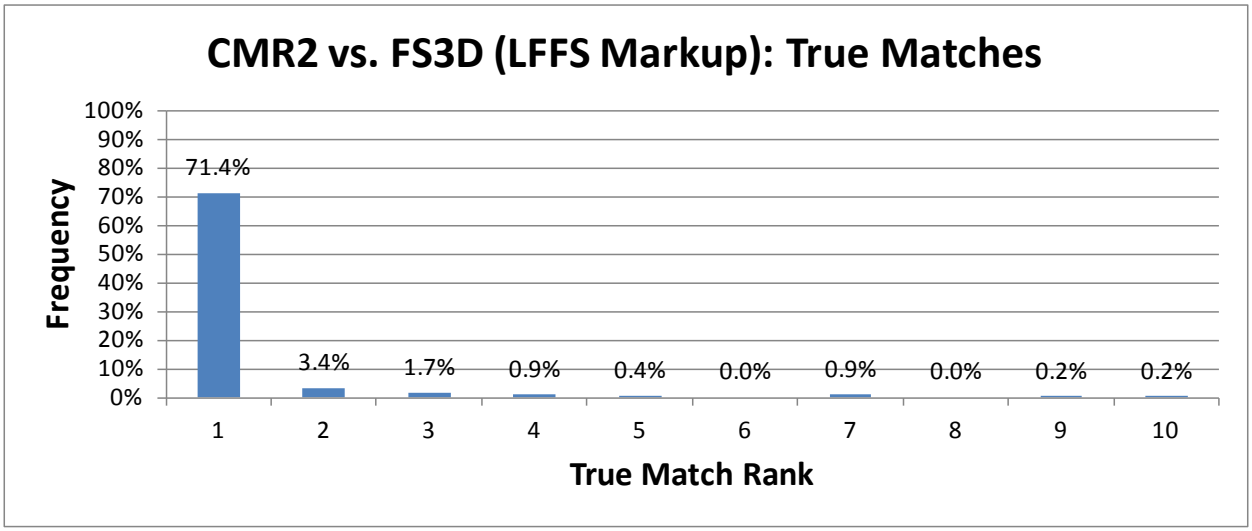
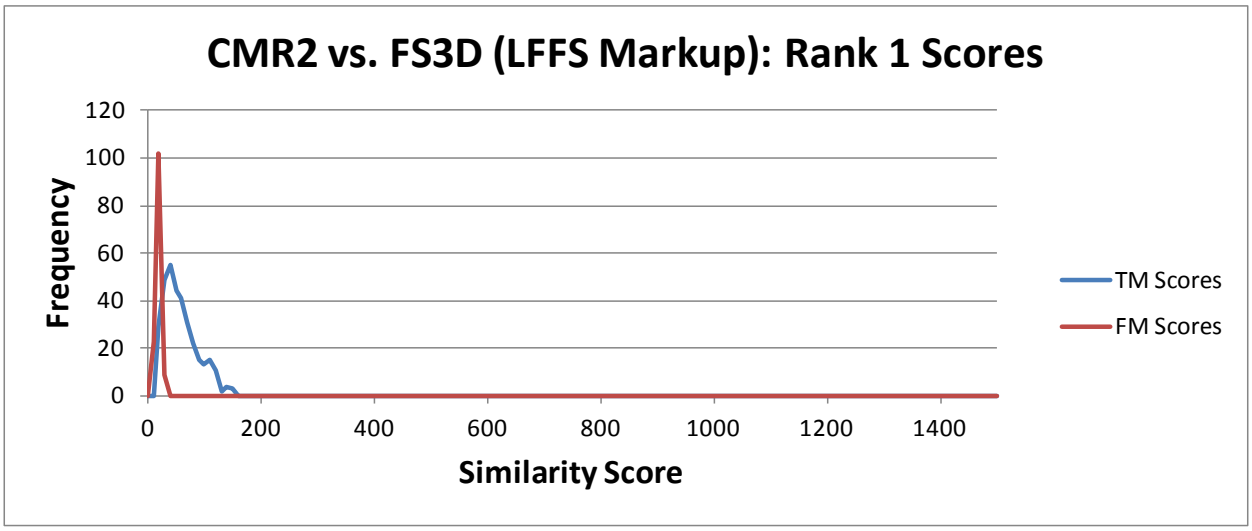
A.4.3 FS3D Gallery

A.4.3.1 CMR2 Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
FS3D LFFS Markup	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
CMR2 LFFS Markup	**Unique Subjects**	468			
Matches	**True Matches**	334	71%	59	30
	False Matches	134	29%	18	4
	Total Matches	219024			





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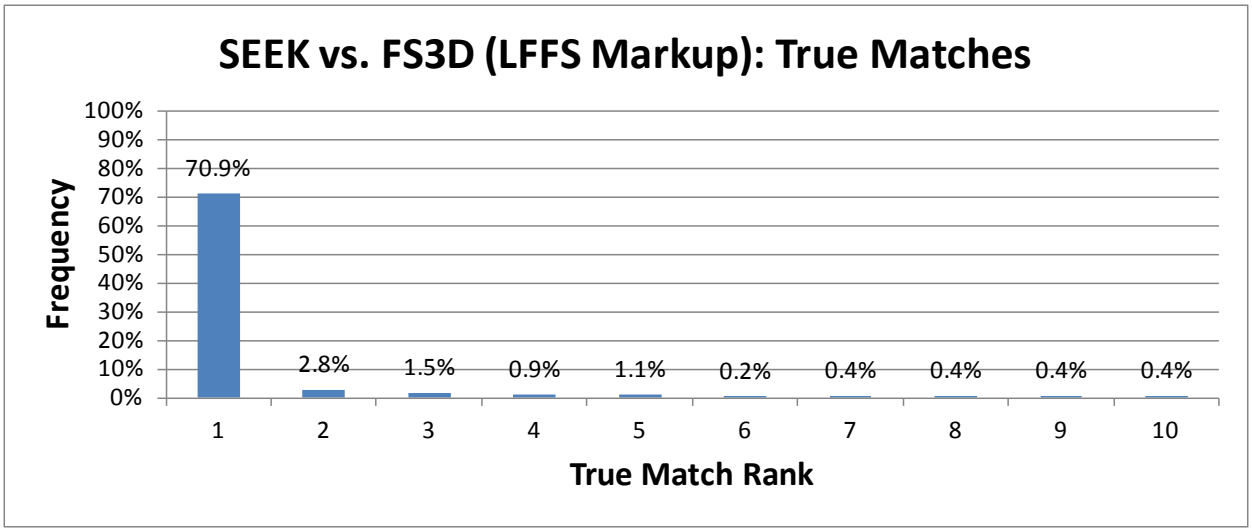
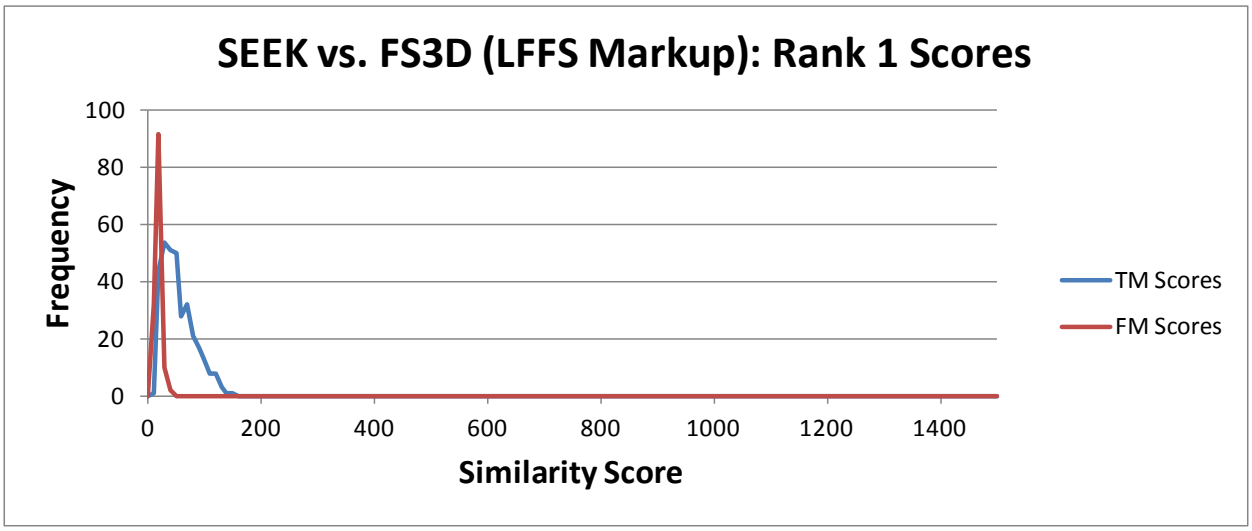
A.4.3.2 SEEK Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
FS3D LFFS Markup	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
SEEK LFFS Markup	**Unique Subjects**	468			
Matches	**True Matches**	332	71%	54	28
	False Matches	136	29%	18	5
	Total Matches	219024			





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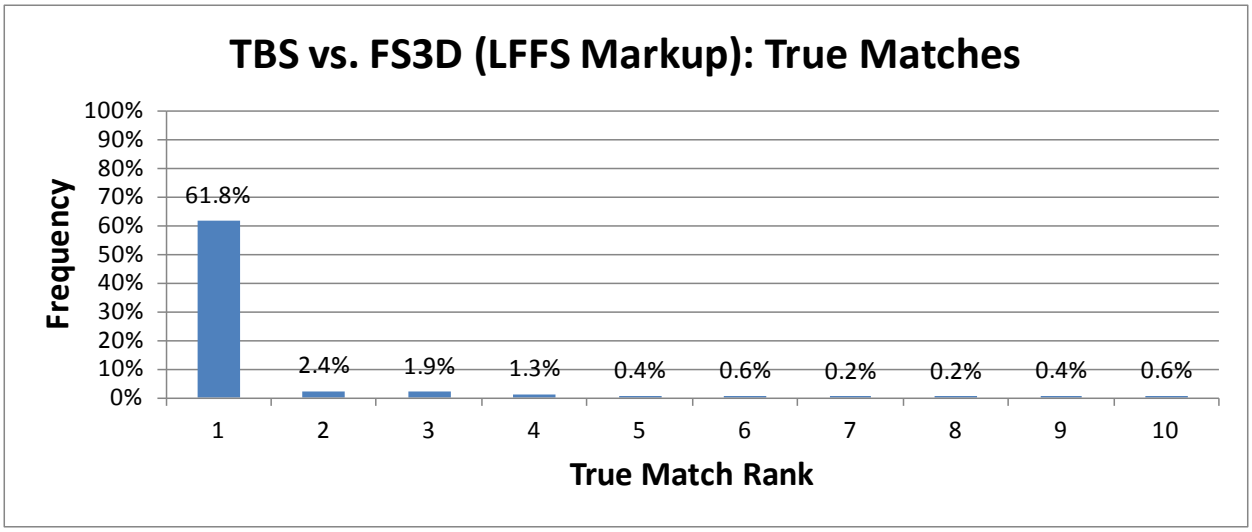
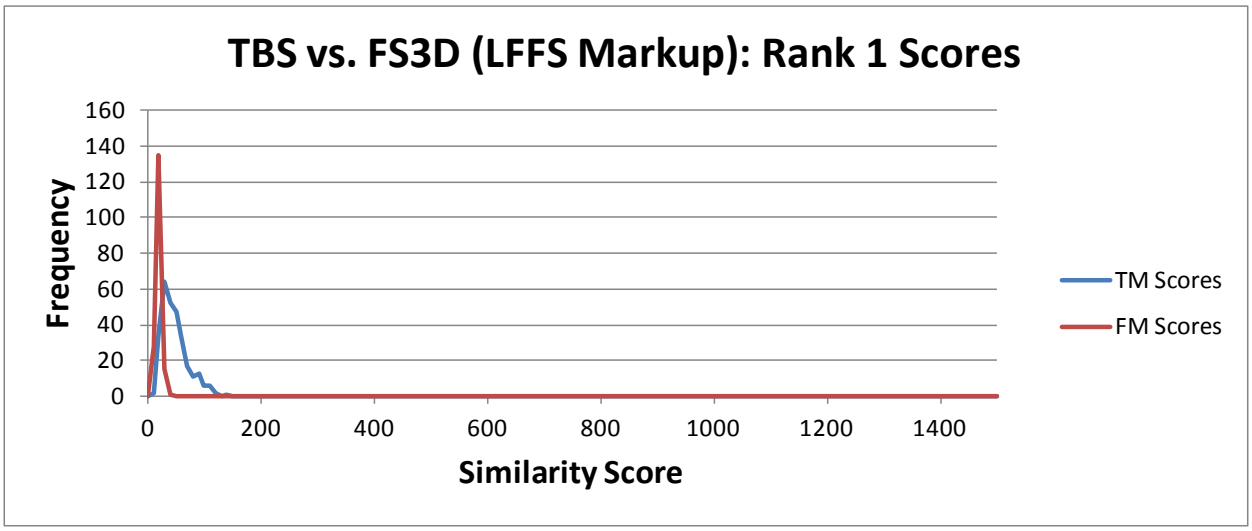
A.4.3.3 TBS Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
FS3D LFFS Markup	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
TBS LFFS Markup	**Unique Subjects**	468			
Matches	**True Matches**	289	62%	48	24
	False Matches	179	38%	18	4
	Total Matches	219024			





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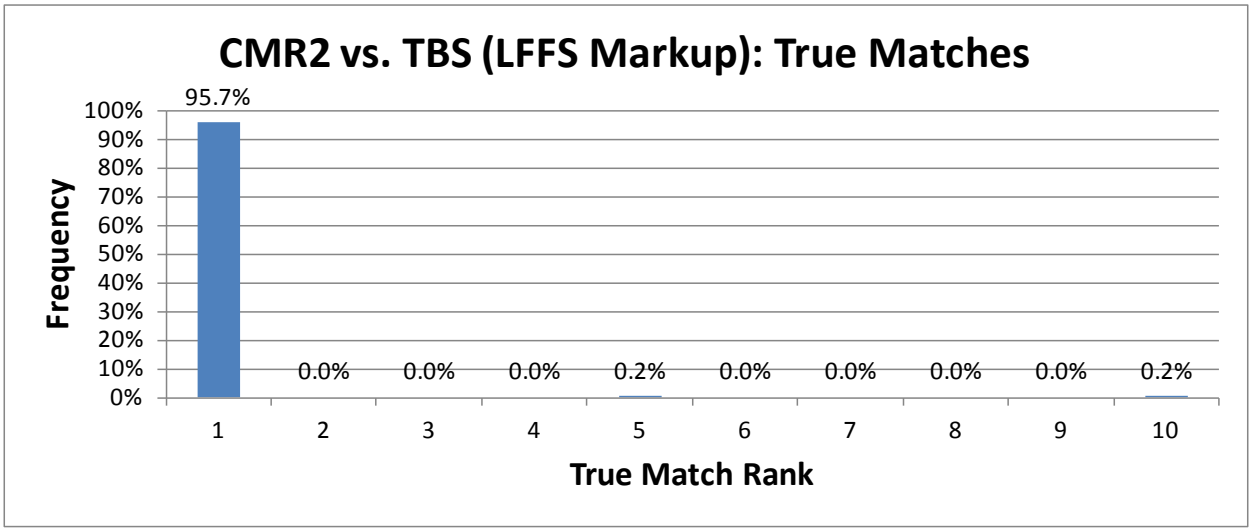
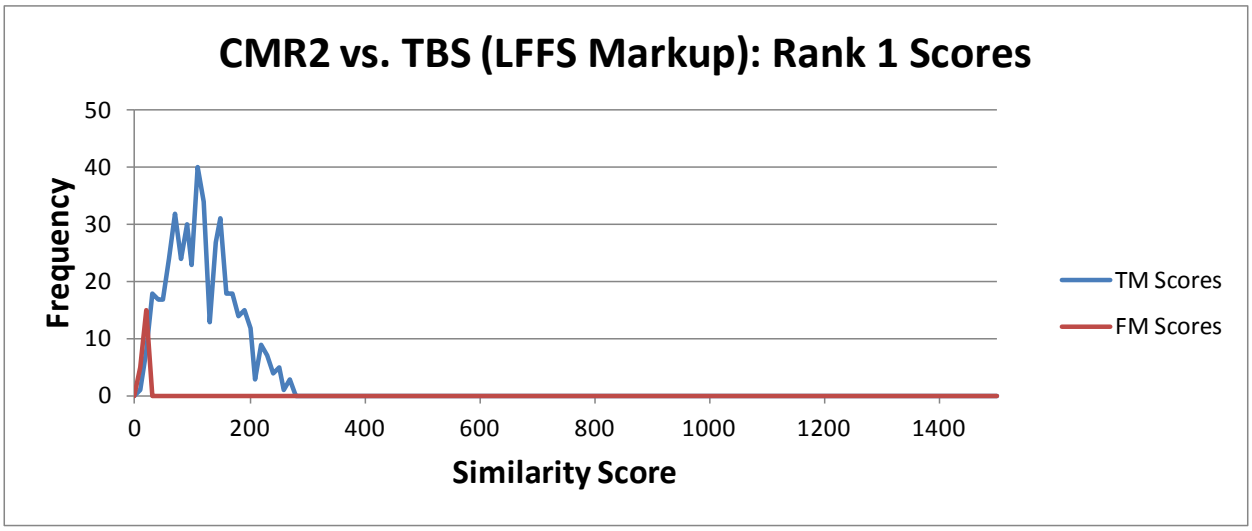
A.4.4 TBS Gallery

A.4.4.1 CMR2 Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
TBS LFFS Markup	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
CMR2 LFFS Markup	**Unique Subjects**	468			
Matches	**True Matches**	448	96%	117	56
	False Matches	20	4%	16	3
	Total Matches	219024			





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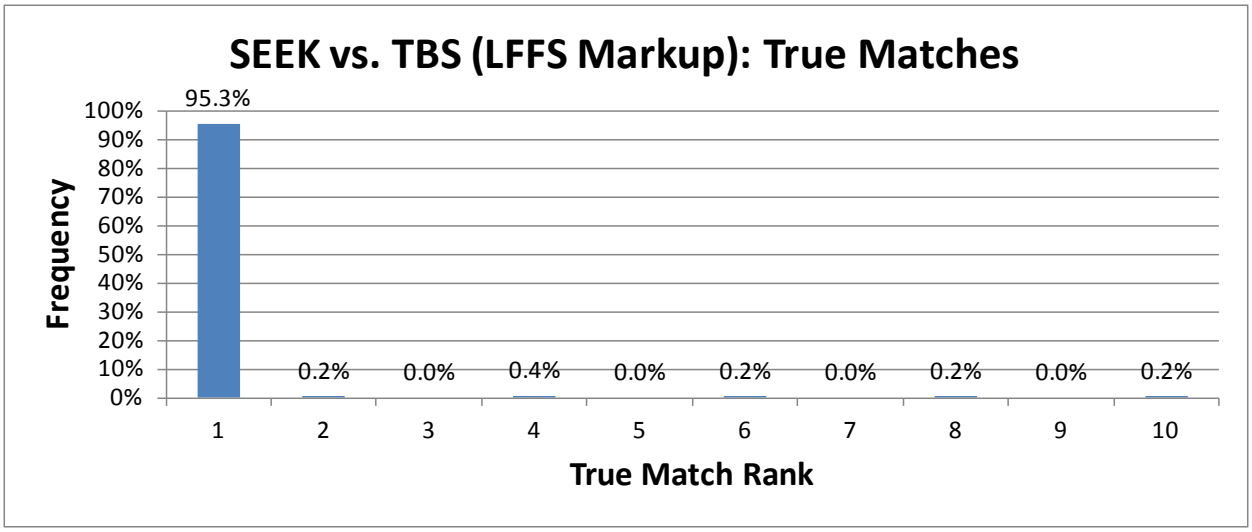
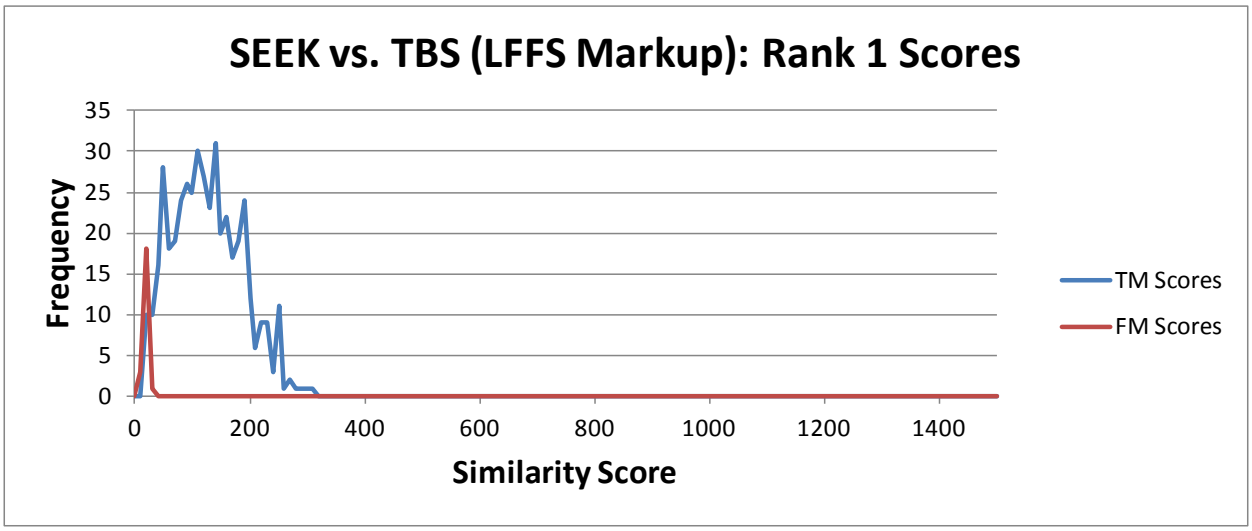
A.4.4.2 SEEK Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
TSB LFFS Markup	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
SEEK LFFS Markup	**Unique Subjects**	468			
Matches	**True Matches**	446	95%	125	60
	False Matches	22	5%	18	4
	Total Matches	219024			





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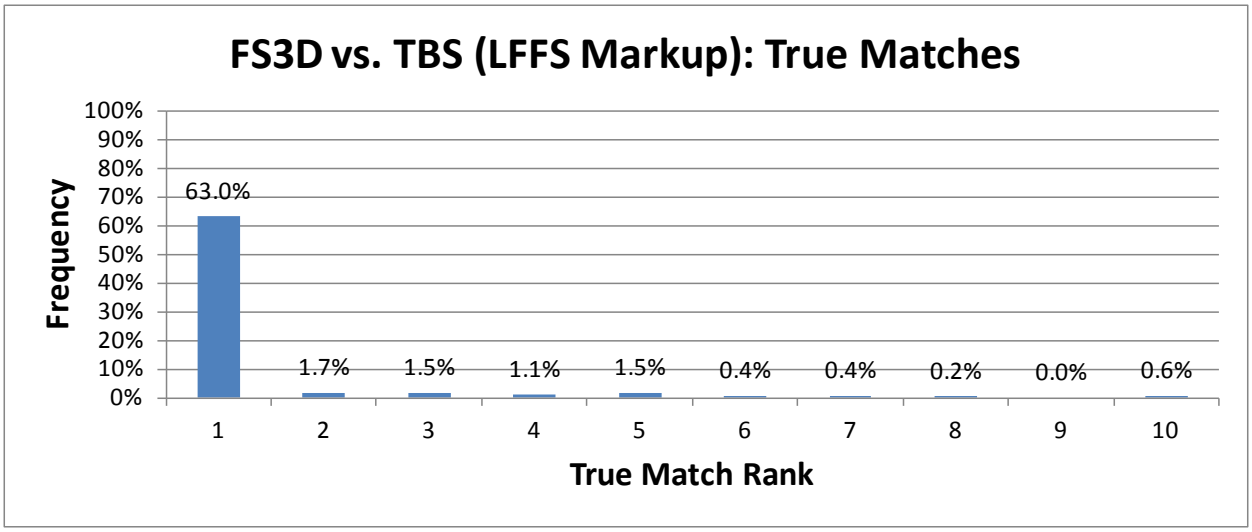
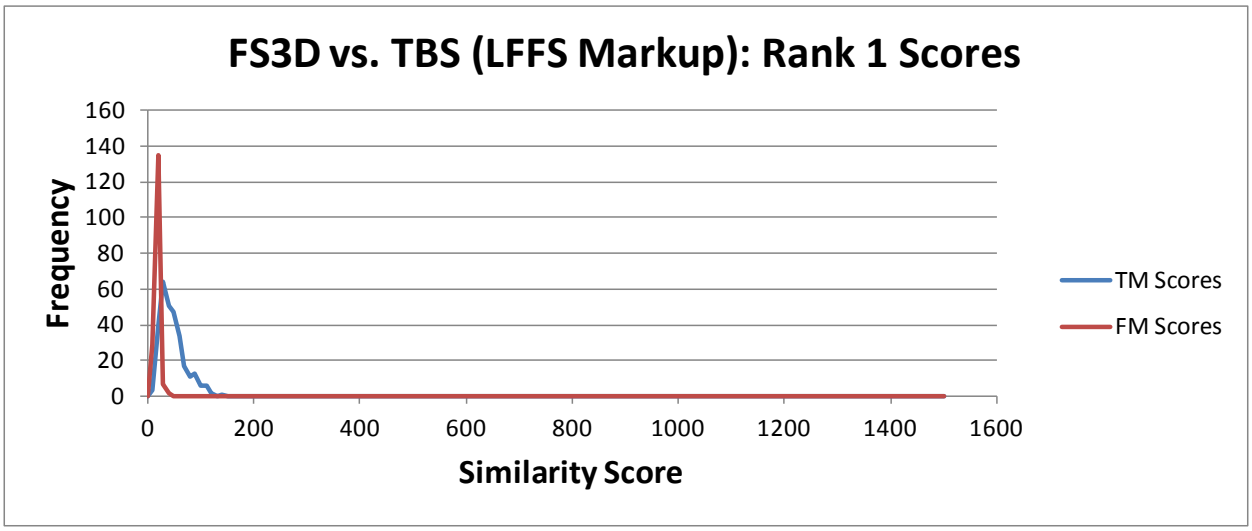
A.4.4.3 FS3D Probe Set

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
TBS LFFS Markup	**Unique Subjects**	468			
Probe	**Total Qualified**	468	100%		
FS3D LFFS Markup	**Unique Subjects**	468			
Matches	**True Matches**	295	63%	47	24
	False Matches	173	37%	18	4
	Total Matches	219024			





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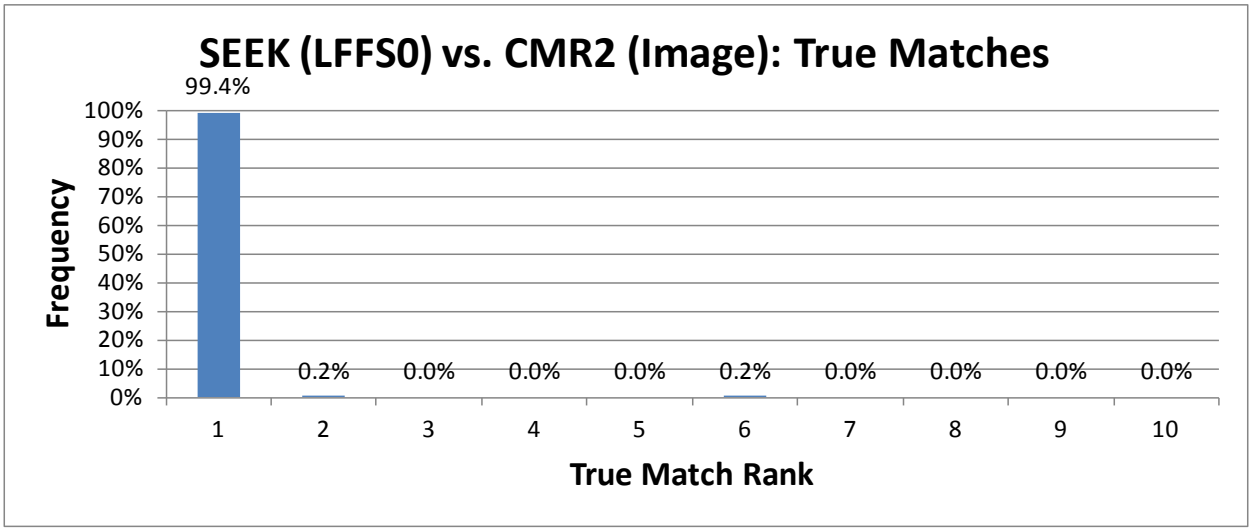
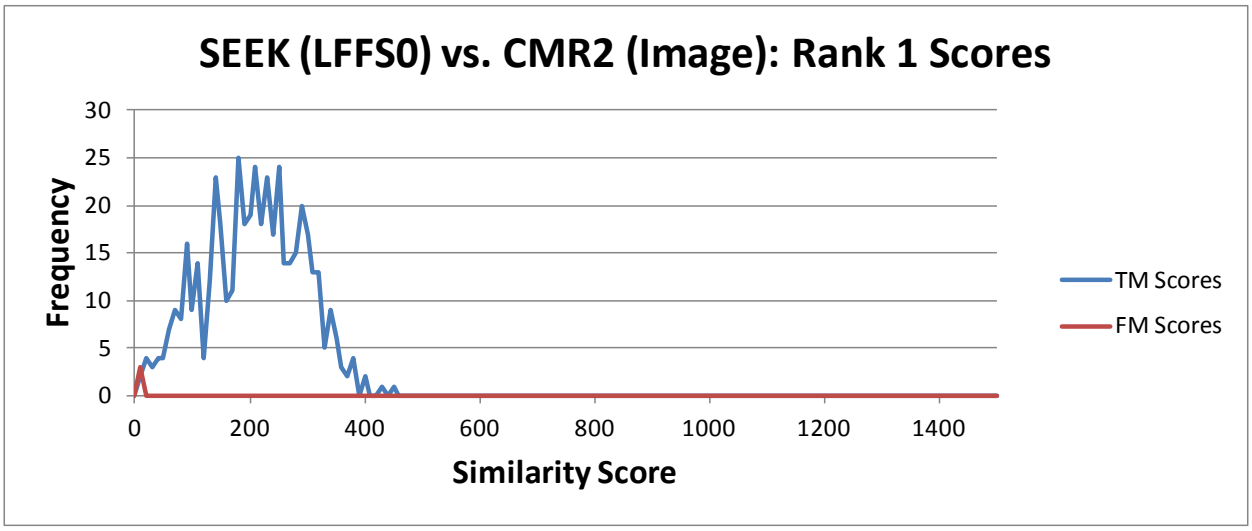
A.5 Matching Runs: Miscellaneous

A.5.1 Different Probes vs. Image Gallery

A.5.1.1 SEEK Probe (LFFS Original) vs. CMR2 Gallery (Image)

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 Image Original	**Unique Galleries**	468			
Probe	**Total Qualified**	468	100%		
SEEK LFFS Original	**UniqueProbes**	468			
Matches	**True Matches**	465	99%	207	85
	False Matches	3	1%	8	3
	Total Matches	219024			





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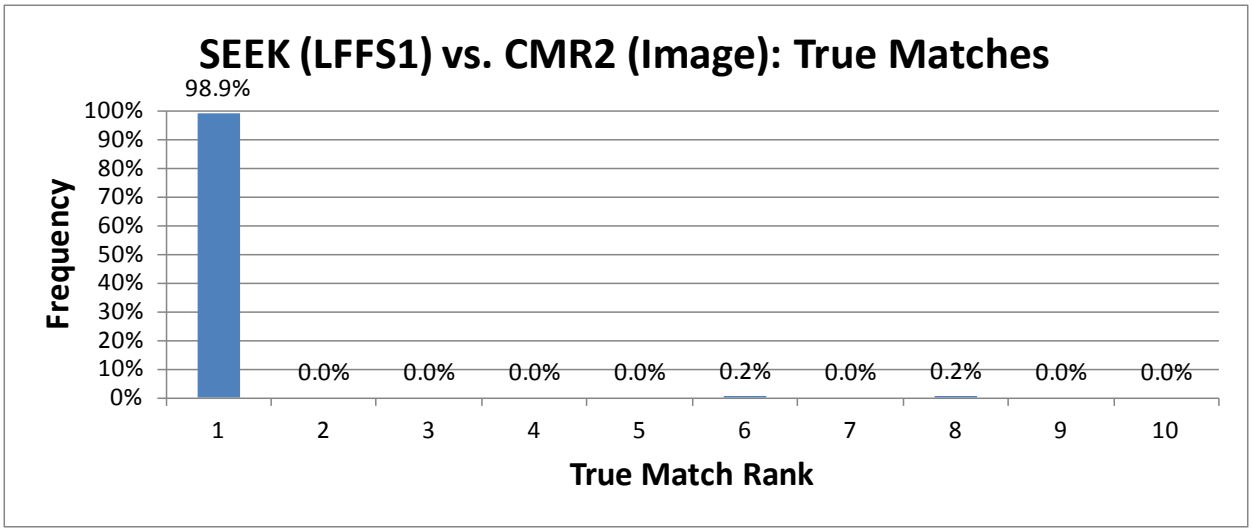
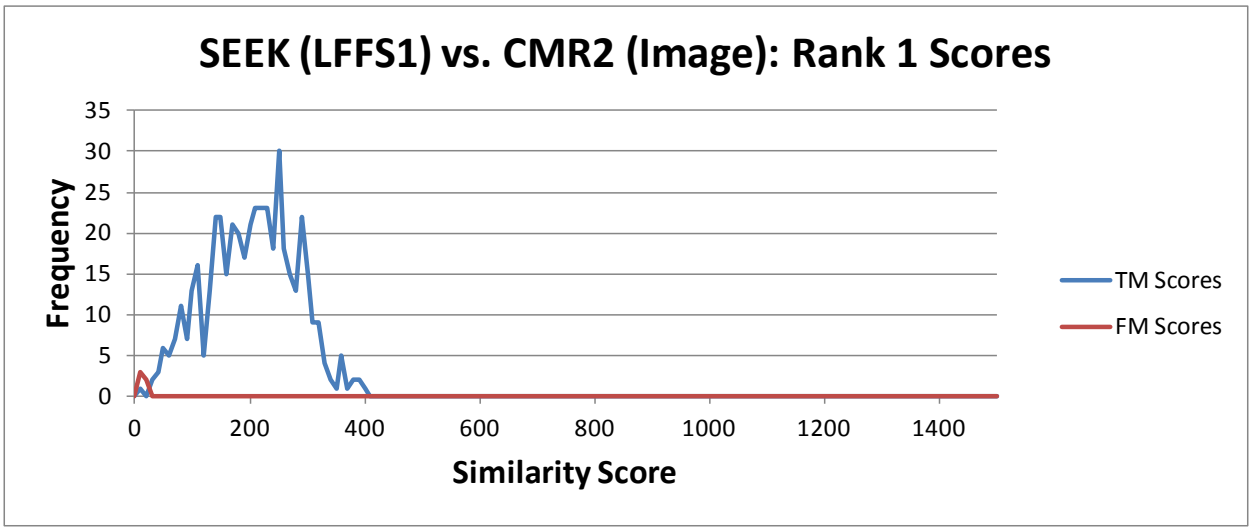
A.5.1.2 SEEK Probe (LFFS Markup) vs. CMR2 Gallery (Image)

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 Image Original	**Unique Galleries**	468			
Probe	**Total Qualified**	468	100.00%		
SEEK LFFS Markup	**UniqueProbes**	468			
Matches	**True Matches**	463	99%	202	76
	False Matches	5	1%	14	1
	Total Matches	219024			





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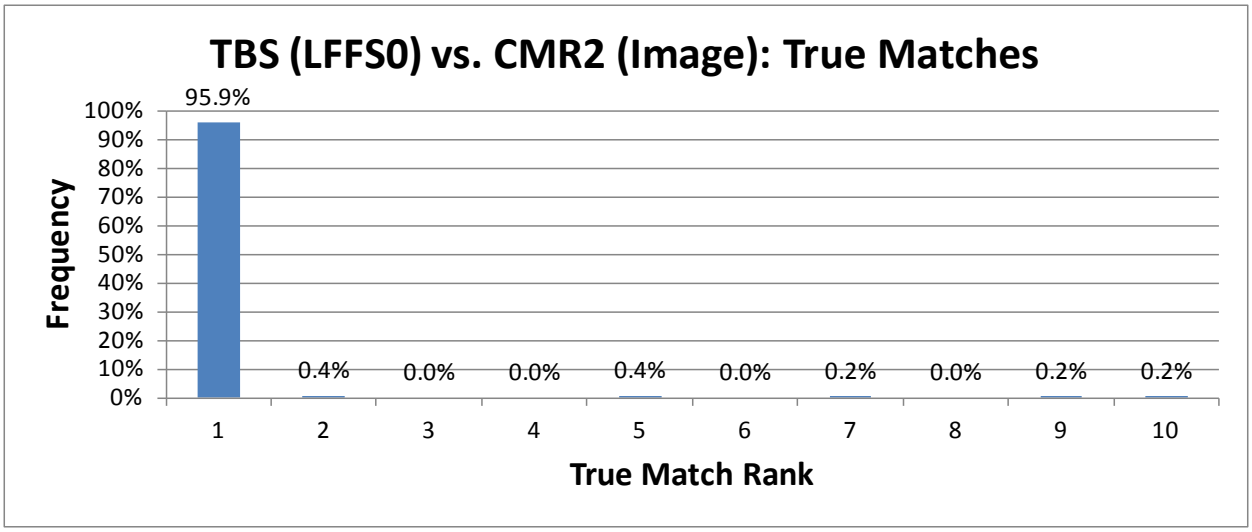
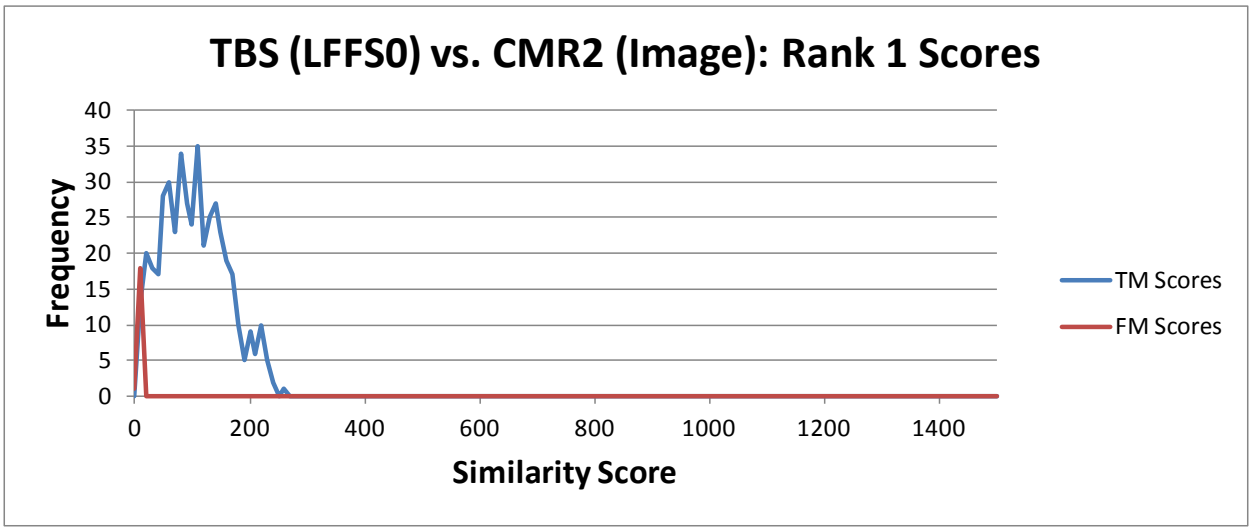
A.5.1.3 TBS Probe (LFFS Original) vs. CMR2 Gallery (Image)

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 Image Original	**Unique Galleries**	468			
Probe	**Total Qualified**	468	100.00%		
TBS LFFS Original	**UniqueProbes**	468			
Matches	**True Matches**	449	96%	104	55
	False Matches	19	4%	8	3
	Total Matches	219024			





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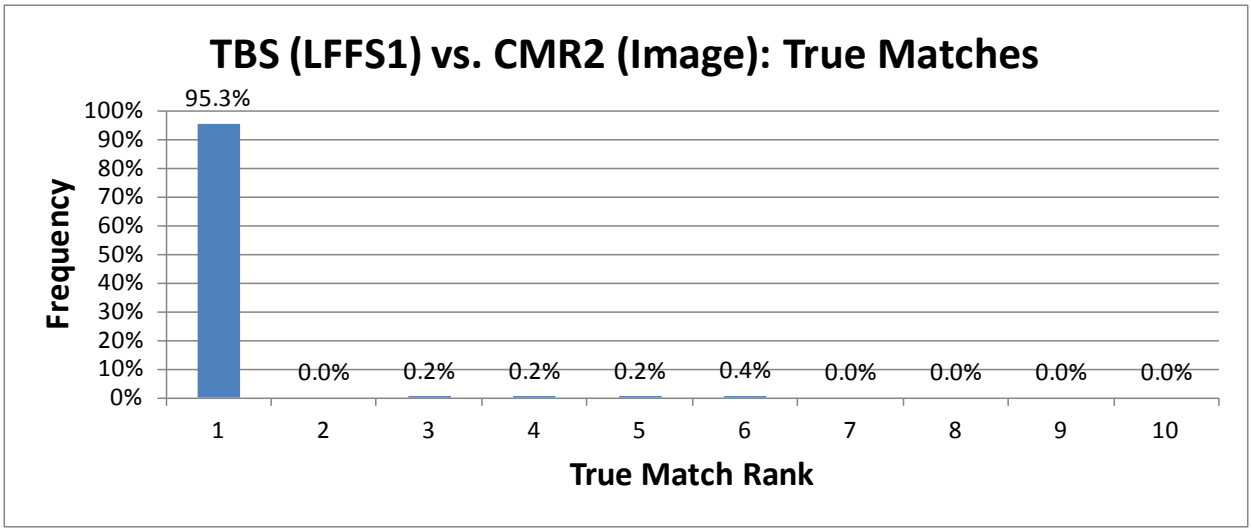
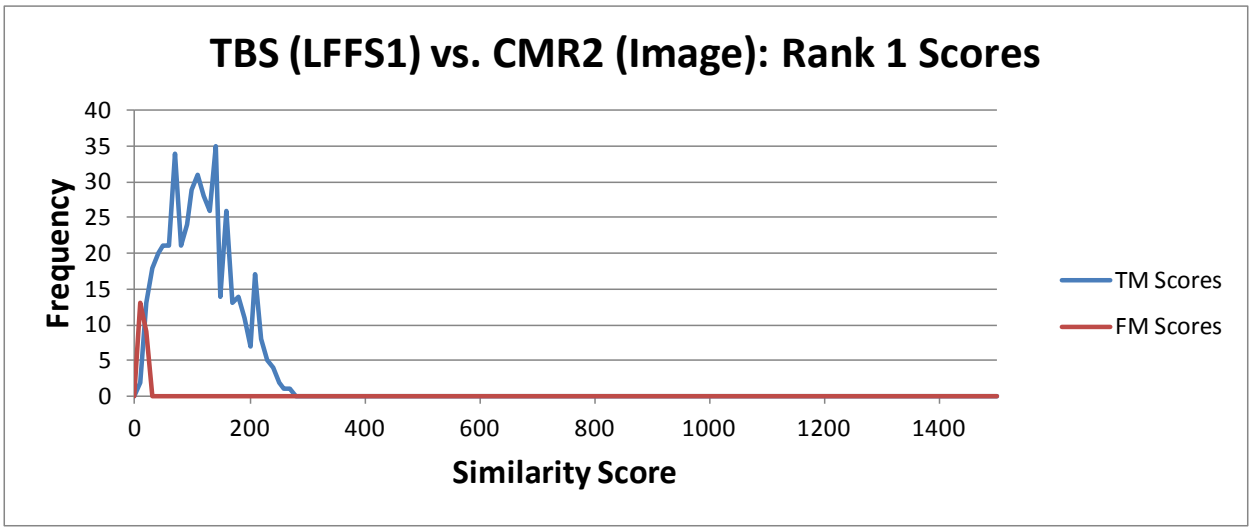
A.5.1.4 TBS Probe (LFFS Markup) vs. CMR2 Gallery (Image)

MegaMatcher		Results	Percent	Score, Mean	Score, Std Dev
Gallery	**Total**	468			
CMR2 Image Original	**Unique Galleries**	468			
Probe	**Total Qualified**	468	100.00%		
TBS LFFS Markup	**UniqueProbes**	468			
Matches	**True Matches**	446	95%	114	56
	False Matches	22	5%	15	3
	Total Matches	219024			





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APPENDIX B: ACRONYMS, ABBREVIATIONS, AND REFERENCES

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B.1 Acronyms and Abbreviations

ACRONYM	DESCRIPTION
2D	Two Dimensional
ACE-V	Analyze, Compare, Evaluate, and Verify
ANSI	American National Standards Institute
ASD(R&E)	Assistant Secretary of Defense for Research and Engineering
AT&L	Acquisition, Technology, and Logistics
CFP	Contactless Fingerprint
CFPv1	Contactless Fingerprint Collection, Round 1
CLPE	Certified Latent Print Examiner
CMR2	Cross Match Guardian R2
CoE	Center of Excellence
DET	Detection Error Trade-off
DOJ	Department of Justice
EBTS	Electronic Biometrics Transmission Specification
EFS	Extended Feature Set
FAR	False Acceptance Rate
FMR	False Match Rate
FRR	False Rejection Rate
FS3D	FlashScan 3D D1 Scanner or FlashScan3D LLC
GB	Gigabytes
ID	Identification
IRB	Institutional Review Board
LFFS	Latent Friction Ridge Features Search
LFFS0	Original LFFS File
LFFS1	Markup LFFS File
LFP	Legacy Fingerprint
MDT	Minutia Deviation Tool
MM	MegaMatcher
NFIQ	NIST Fingerprint Image Quality
NIJ	National Institute of Justice
NIST	National Institute of Standards and Technology
NLECTC	National Law Enforcement and Corrections Technology Center
NMR	Non-Match Rate

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ACRONYM	DESCRIPTION
OSD	Office of the Secretary of Defense
Ppi	Pixels per inch
QSP2	Quick Search Profile 2
R&D	Research and Development
RDT&E	Research, Development, Test & Evaluation
ROC	Receiver-Operator Characteristic
SDD	Software Design Description
SDK	Software Development Kit
SEEK	Cross Match SEEK II
SSBT	Sensor, Surveillance, and Biometric Technologies
StdDev	Standard Deviation
TAR	True Accept Rate
TB	Terabyte
TBS	Touchless Biometric Systems or Touchless Biometric Systems 3D Enroll
TM	True Match
TMR	True Match Rate
ULW	Universal Latent Workstation
WVU	West Virginia University

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