

Beyond Non-Unique Artifacts: SVD-Based PRNU Recovery for Samsung Device Identification

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Recap: PRNU-based Source Camera Verification

Sensor I/O model

[Lukáš et al., 2005] Single channel:

$$\text{Output } \mathbf{Y} = (1 + \text{PRNU } \mathbf{K}) \circ \text{Input } \mathbf{X} + \Theta$$

Noise Residue Extraction

Using [Mihcak et al., 1999]:

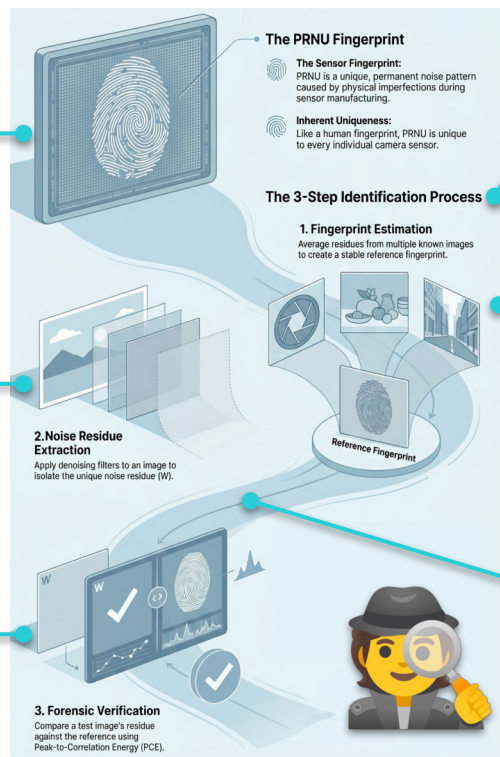
$$\mathbf{W} = \mathbf{Y} - F(\mathbf{Y})$$

Forensic Verification

Final Decision:

$$\text{PCE}(\mathbf{W}, \hat{\mathbf{K}} \circ \mathbf{Y}) \underset{\mathcal{H}_0}{\overset{\mathcal{H}_1}{\geq}} \tau$$

In practice: $\tau = 60$



AI-generated illustration (Google NotebookLM)

Binary Hypothesis Test

$\mathcal{H}_0$: $\mathbf{W}$ does not contain the PRNU $\mathbf{K}$

$\mathcal{H}_1$: $\mathbf{W}$ contains the PRNU $\mathbf{K}$

Fingerprint Estimation

[Chen et al., 2008] From L images:

$$\hat{\mathbf{K}} = \left(\sum_{l=1}^L \mathbf{W}_l \circ \mathbf{Y}_l \right) \circ \left(\sum_{l=1}^L \mathbf{Y}_l \circ \mathbf{Y}_l \right)^{o-1}$$

Test Statistic

[Goljan et al., 2009] Peak-to-Correlation Energy (PCE):

$$\text{PCE}(\mathbf{W}, \hat{\mathbf{K}} \circ \mathbf{Y}) \triangleq \frac{(H \cdot W - |\mathcal{N}|) \cdot (\rho_{(0,0)}(\mathbf{W}, \hat{\mathbf{K}} \circ \mathbf{Y}))^2}{\sum_{(s_1, s_2) \in \mathcal{S} \setminus \mathcal{N}} (\rho_{(s_1, s_2)}(\mathbf{W}, \hat{\mathbf{K}} \circ \mathbf{Y}))^2}$$

where:

$$\rho_{(s_1, s_2)}(\mathbf{A}, \mathbf{B}) \triangleq \frac{\sum_{i,j} (A_{i,j} - \bar{\mathbf{A}}) \cdot (B_{i+s_1, j+s_2} - \bar{\mathbf{B}})}{(\sum_{i,j} (A_{i,j} - \bar{\mathbf{A}})^2 \sum_{i,j} (B_{i+s_1, j+s_2} - \bar{\mathbf{B}})^2)^{\frac{1}{2}}}$$

Normalized Cross-Correlation: $\rho(\mathbf{A}, \mathbf{B}) \triangleq \rho_{(0,0)}(\mathbf{A}, \mathbf{B})$

Where it all started: 2021-2022

A Leak in PRNU Based Source Identification—Questioning Fingerprint Uniqueness

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¹Department of Information Engineering, University of Florence, 50139 Florence, Italy

²FORLAB—Multimedia Forensics Laboratory, 59100 Prato, Italy

³Amped Software, 34149 Trieste, Italy

2021

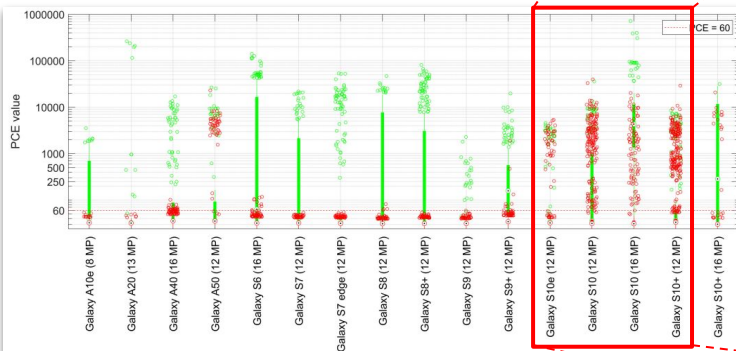
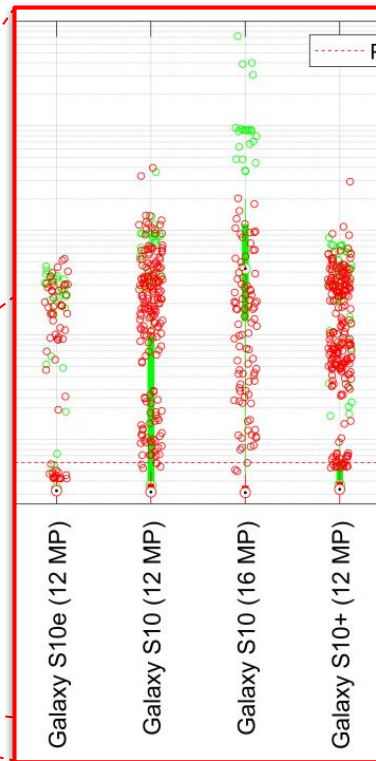


FIGURE 1. PCE statistics computed from Apple, Huawei, and Samsung devices (top, middle and bottom plot respectively). Matching and mismatching images are reported in green and red, respectively. The threshold of 60 is highlighted by the red dashed line.



CHECKING PRNU USABILITY ON MODERN DEVICES

C. Albisani, M. Iuliani, A. Piva

2021

Department of Information Engineering
University of Florence, Via di S. Marta, 3, 50139 Florence, Italy

C14 Samsung S9
C15 Samsung S9+



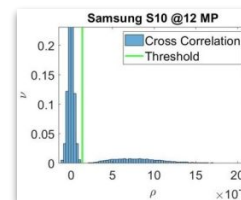
INVESTIGATING INCONSISTENCIES IN PRNU-BASED CAMERA IDENTIFICATION

Nabeel Nisar Bhat and Tiziano Bianchi

2022

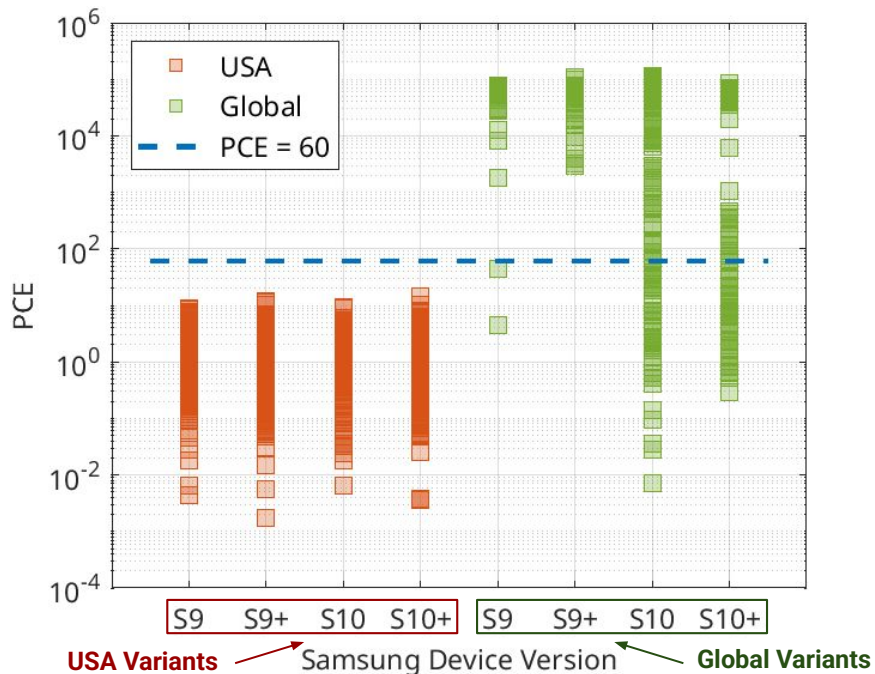
Politecnico di Torino

Model	Resolution	#Users	#Images
S10	12 MP	6	378



Fingerprint Collisions Analysis

1st Experiment: S10 (Global variant) vs. all



Dataset Details

Reference:

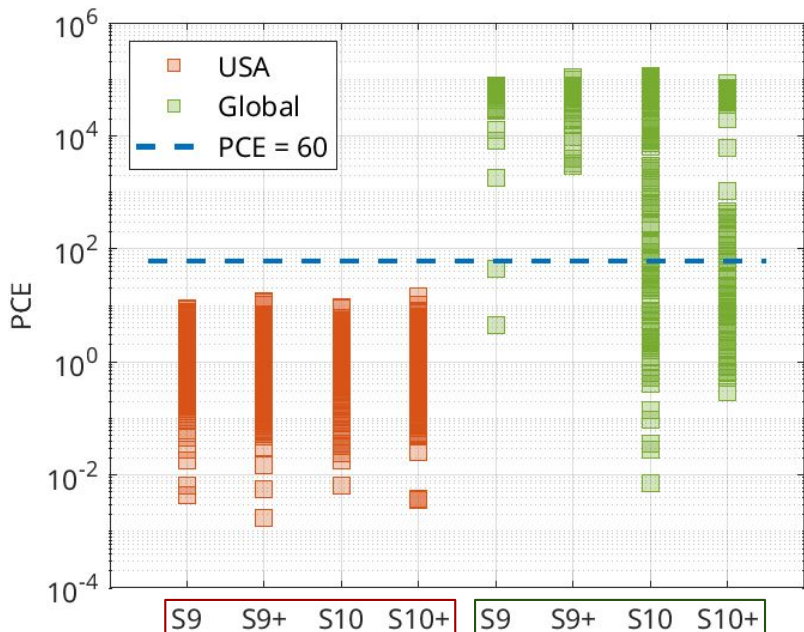
- Global Variant:
 - S10 (SM-G973F): $L = 20$ flatfield images

Test:

- USA Variants:
 - S9 (SM-G960U), S9+ (SM-G965U), S10 (SM-G973U), S10+ (SM-G975U)
[Iuliani et al., 2021], [Bhat and Bianchi, 2022]
- Global Variants:
 - S9 (SM-G960F), S9+ (SM-G965F), S10 (SM-G973F), S10+ (SM-G975F)
[Albisani et al., 2021], [Baracchi et al., 2023]

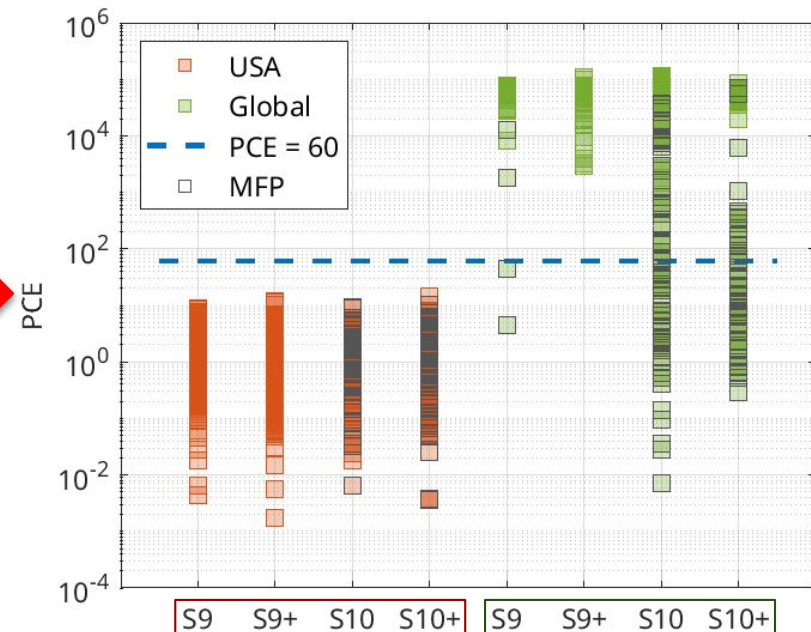
Fingerprint Collisions Analysis

1st Experiment: S10 (Global variant) vs. all



USA Variants → Samsung Device Version ← Global Variants

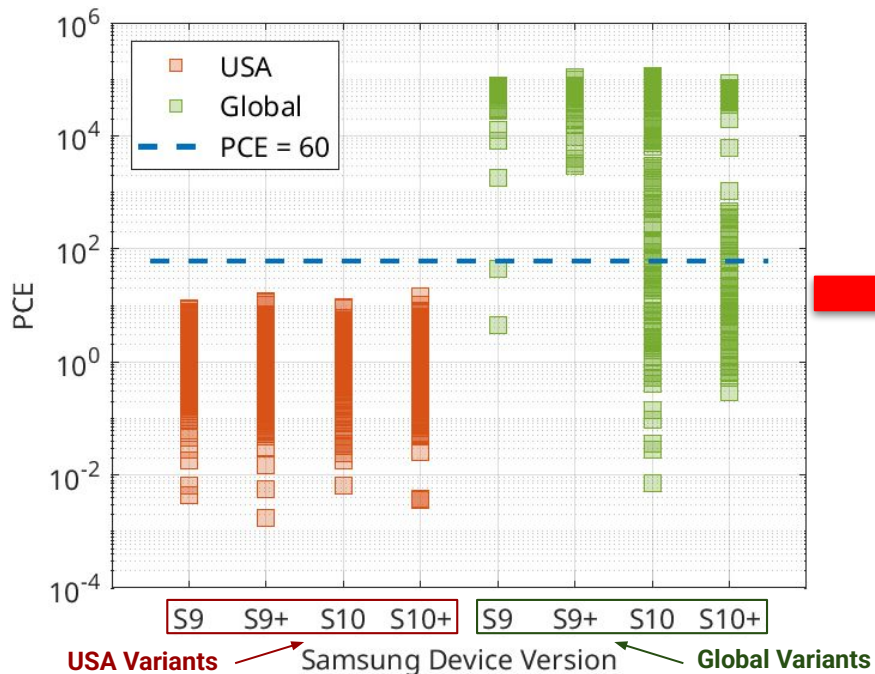
Metadata Analysis:



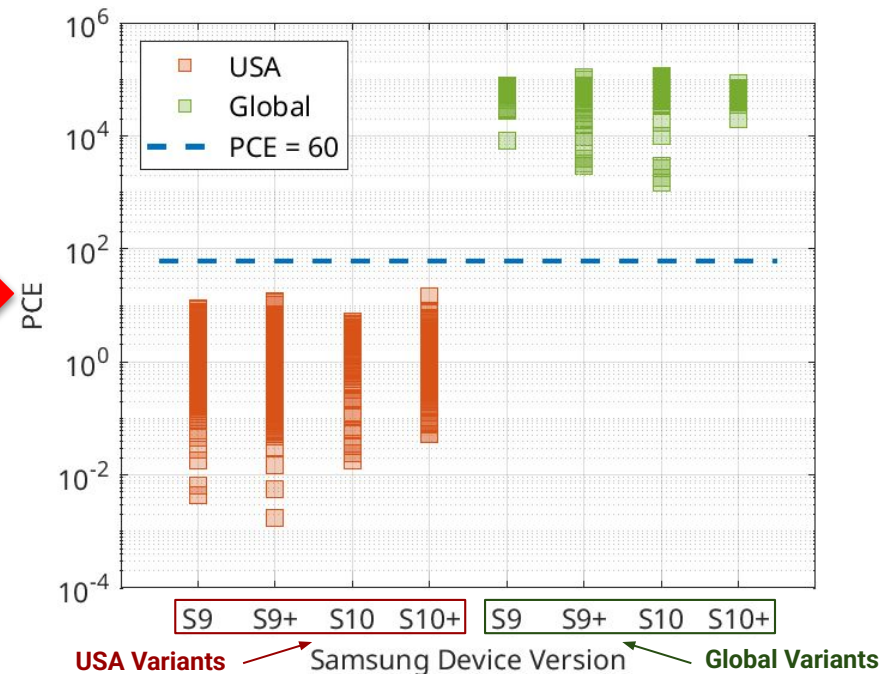
USA Variants → Samsung Device Version ← Global Variants

Fingerprint Collisions Analysis

1st Experiment: S10 (Global variant) vs. all

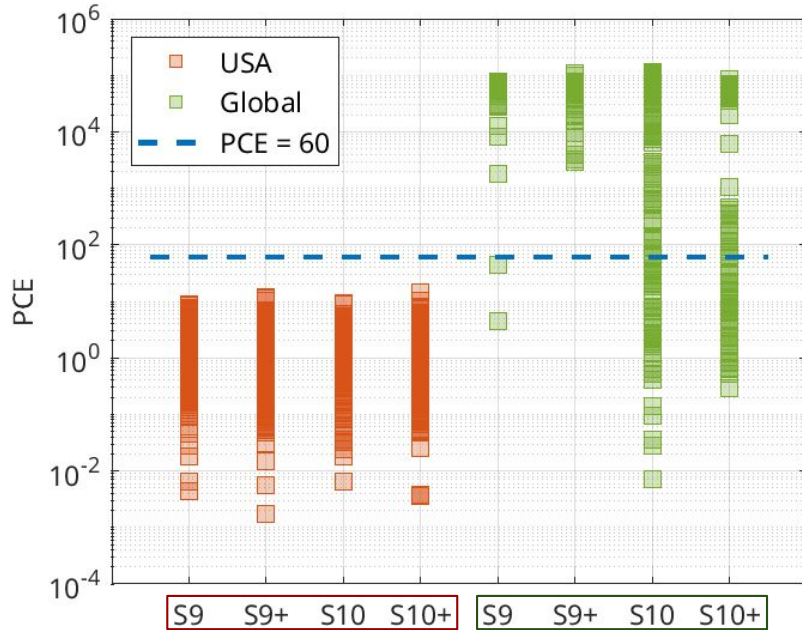


Metadata Analysis: discarding MFP images



Fingerprint Collisions Analysis

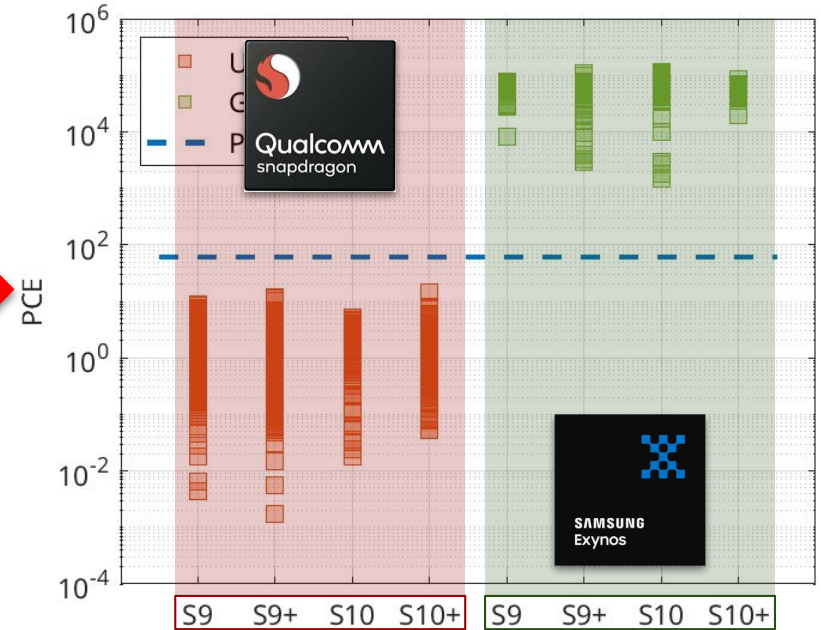
1st Experiment: S10 (Global variant) vs. all



USA Variants → Samsung Device Version ← Global Variants



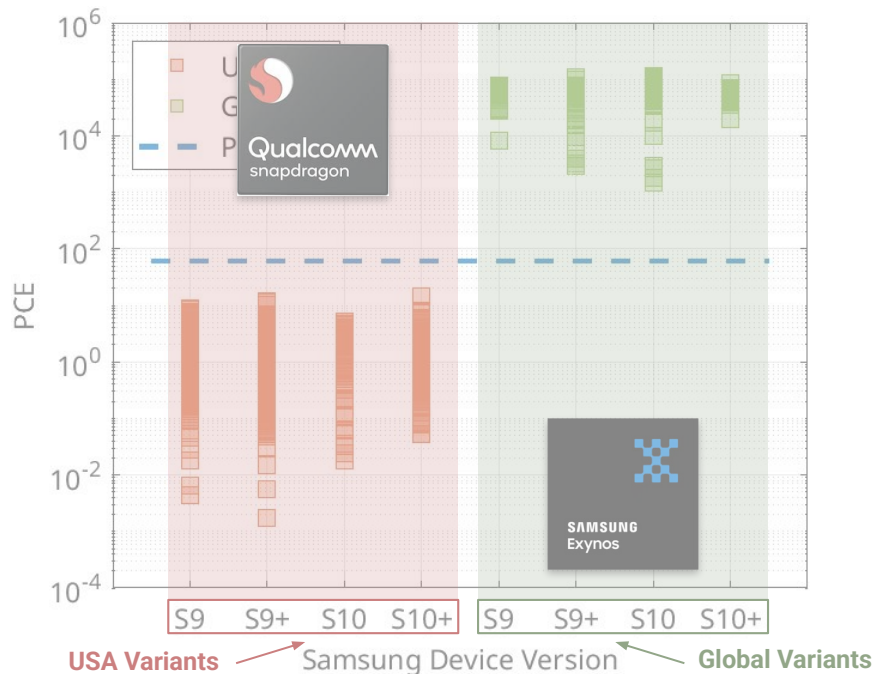
Exynos NUAs are uncorrelated with Snapdragon NUAs:



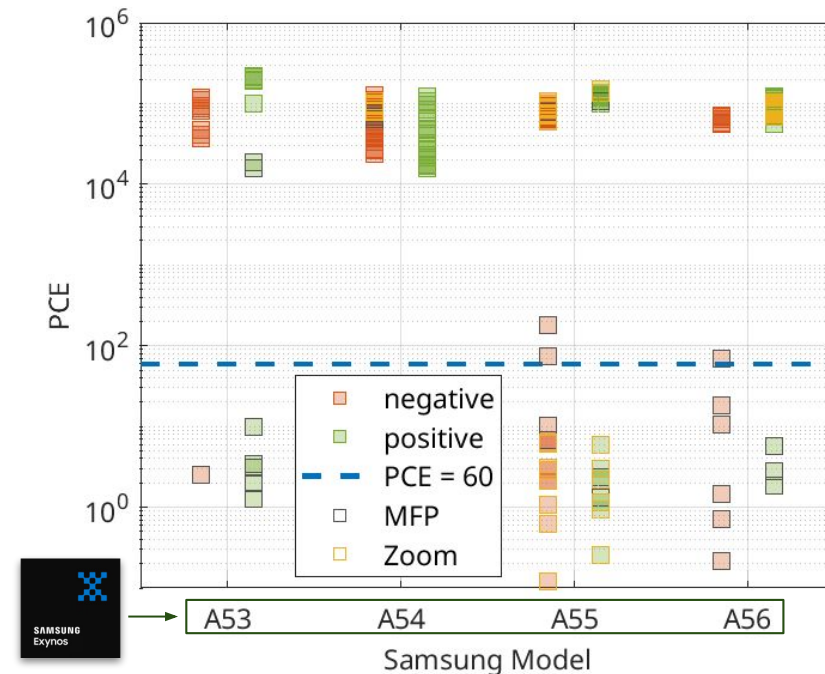
USA Variants → Samsung Device Version ← Global Variants

Fingerprint Collisions Analysis

1st Experiment: S10 (Global variant) vs. all

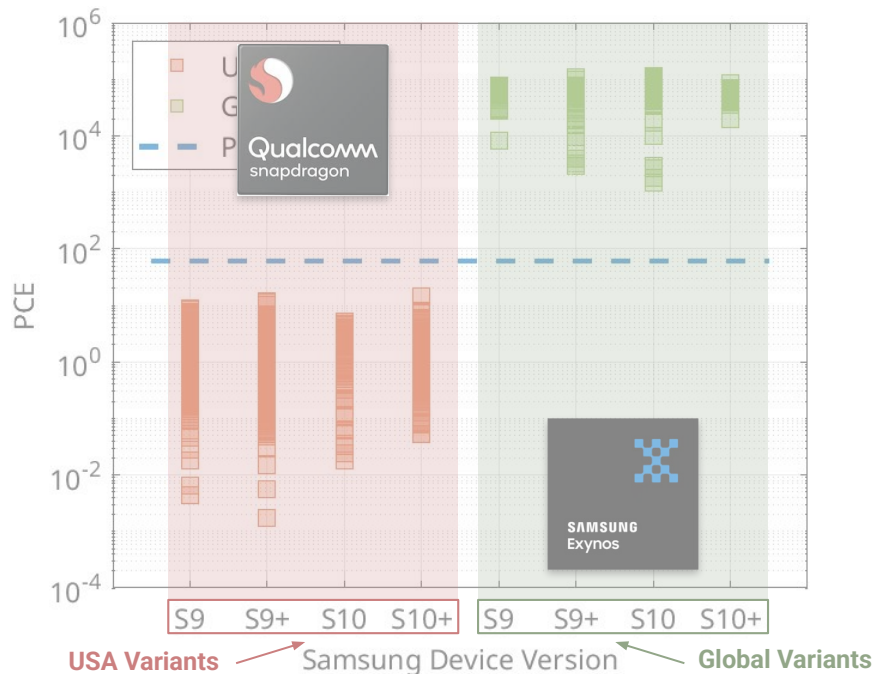


2nd Experiment: 2 units per A Series model

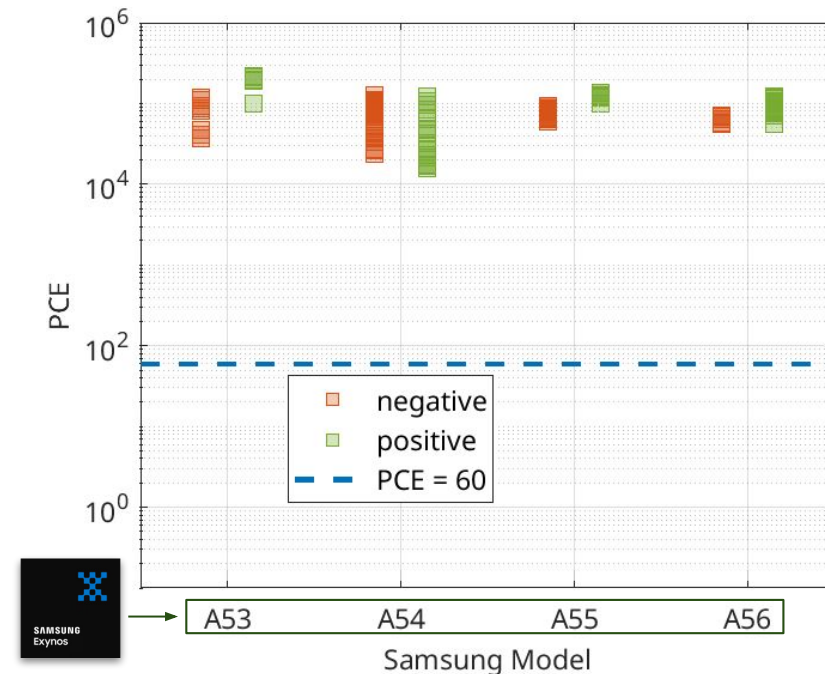


Fingerprint Collisions Analysis

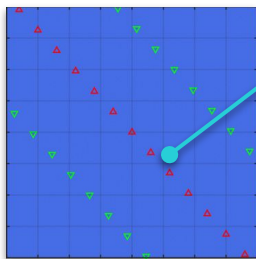
1st Experiment: S10 (Global variant) vs. all



2nd Experiment: 2 units per A Series model



Possible Origin of Exynos-based NUAs

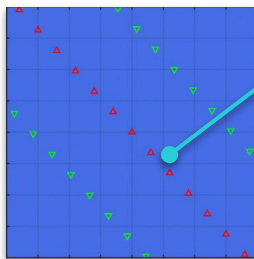


S10 (SM-G973F)

Periodicities in the autocorrelation of $\hat{\mathbf{F}}$ suggest block-based processing

1

Possible Origin of Exynos-based NUAs



S10 (SM-G973F)

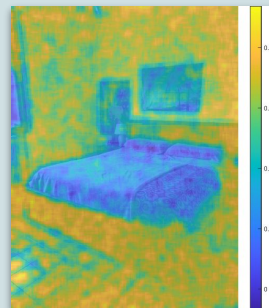
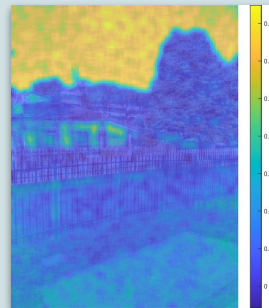
Periodicities in the autocorrelation of $\hat{F}$ suggest block-based processing

1

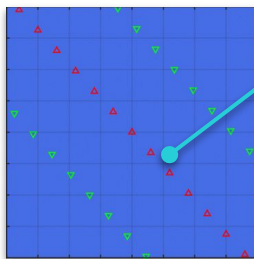
Spatially uniform regions exhibit higher correlation with $\hat{F}$

2

Block-wise NCC map ($W, \hat{F}$)



Possible Origin of Exynos-based NUAs



S10 (SM-G973F)

Periodicities in the autocorrelation of $\hat{F}$ suggest block-based processing

1

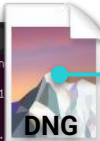
Spatially uniform regions exhibit higher correlation with $\hat{F}$

2

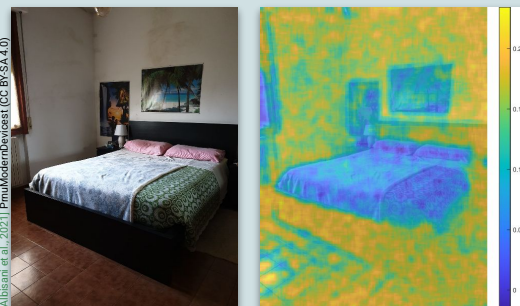
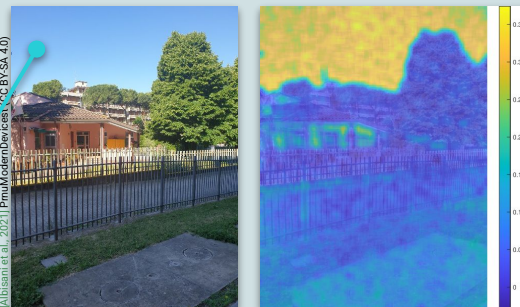
PRO mode generates raw **DNG** images whose residues do not exhibit NUAs.

3

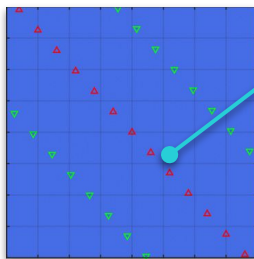
```
david@aolosl: ~  
$ exiftool /tmp/20250623_122911.dng  
ExifTool Version Number      : 12.76  
File Name                    : 20250623_122911.dng  
Directory                    : /tmp  
File Size                    : 25 MB  
File Modification Date/Time   : 2025:06:23 14:00:00  
File Access Date/Time        : 2026:06:02 17:58:58+02:00  
File Inode Change Date/Time   : 2026:06:02 17:58:58+02:00  
File Permissions              : -rw-r--r--  
File Type                    : DNG  
File Type Extension          : dng  
MIME Type                    : image/x-adobe-dng  
Exif Byte Order               : Little-endian (Intel, II)  
Image Width                  : 4032  
Image Height                 : 3024  
Bits Per Sample              : 16  
Compression                  : Uncompressed  
Photometric Interpretation    : Color Filter Array  
Image Description             :  
Make                         : samsung  
Camera Model Name             : SM-G973F  
Orientation                   : Horizontal (normal)  
Samples Per Pixel             : 1
```



Block-wise NCC map ($W, \hat{F}$)



Possible Origin of Exynos-based NUAs



S10 (SM-G973F)

Periodicities in the autocorrelation of $\hat{F}$ suggest block-based processing

1

Spatially uniform regions exhibit higher correlation with $\hat{F}$

2

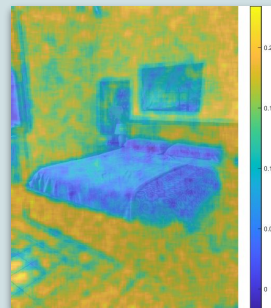
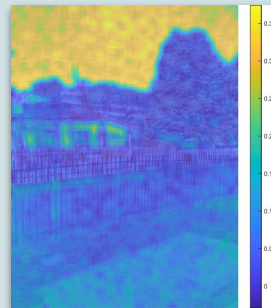
PRO mode generates raw **DNG** images whose residues do not exhibit NUAs.

Exynos
ISP?

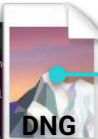
3

Ordered dithering during bit-depth reduction (16 bit RAW to 8 bit JPEG) to suppress color banding artifacts.

Block-wise NCC map ($W, \hat{F}$)

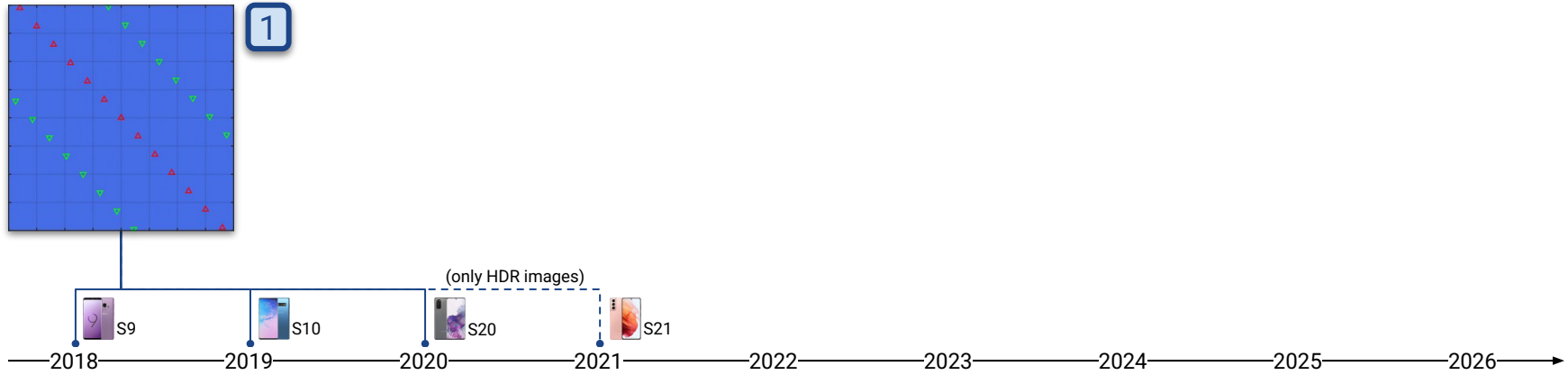


```
david@aolios: ~  
$ exiftool /tmp/20250623_122911.dng  
ExifTool Version Number : 12.76  
File Name : 20250623_122911.dng  
Directory : /tmp  
File Size : 25 MB  
File Modification Date/Time : 2025:06:23 14:14:14  
File Access Date/Time : 2026:06:02 17:58:58+02:00  
File Inode Change Date/Time : 2026:06:02 17:58:58+02:00  
File Permissions : -rw-r--r--  
File Type : DNG  
File Type Extension : dng  
MIME Type : image/x-adobe-dng  
Exif Byte Order : Little-endian (Intel, II)  
Image Width : 4032  
Image Height : 3024  
Bits Per Sample : 16  
Compression : Uncompressed  
Photometric Interpretation : Color Filter Array  
Image Description :  
Make : samsung  
Camera Model Name : SM-G973F  
Orientation : Horizontal (normal)  
Samples Per Pixel : 1
```

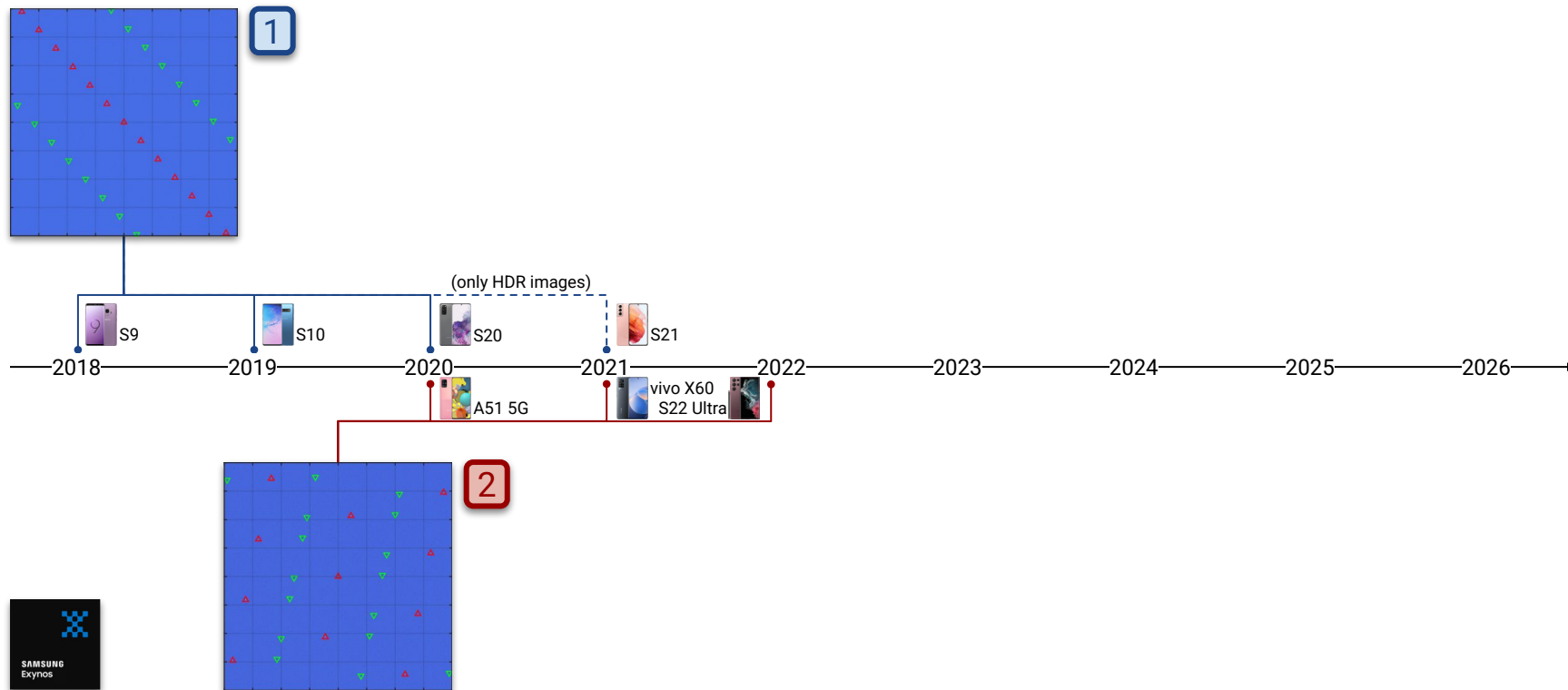


DNG

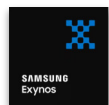
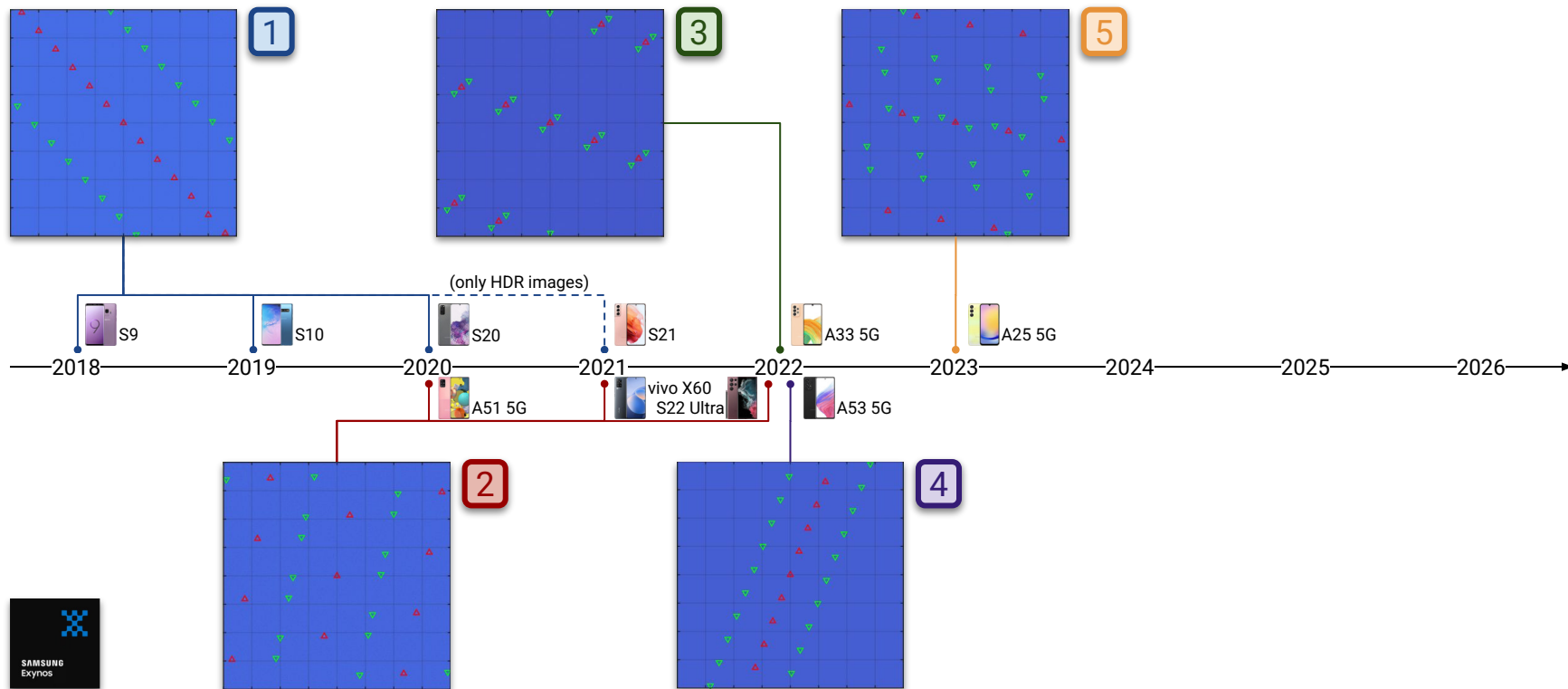
Samsung Image Artifacts: Exynos ISP NUAs



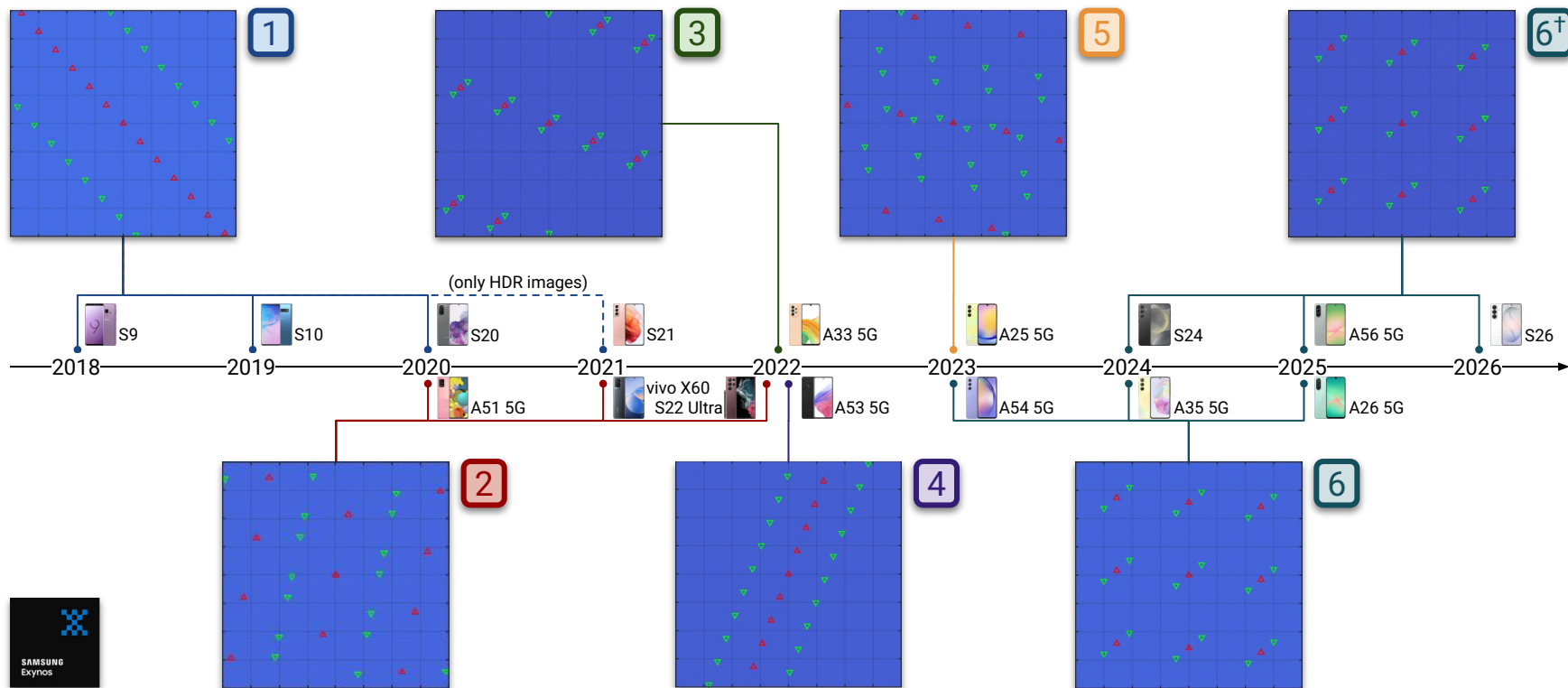
Samsung Image Artifacts: Exynos ISP NUAs



Samsung Image Artifacts: Exynos ISP NUAs



Samsung Image Artifacts: Exynos ISP NUAs



Does the Sensor Fingerprint Survive ISP Processing?

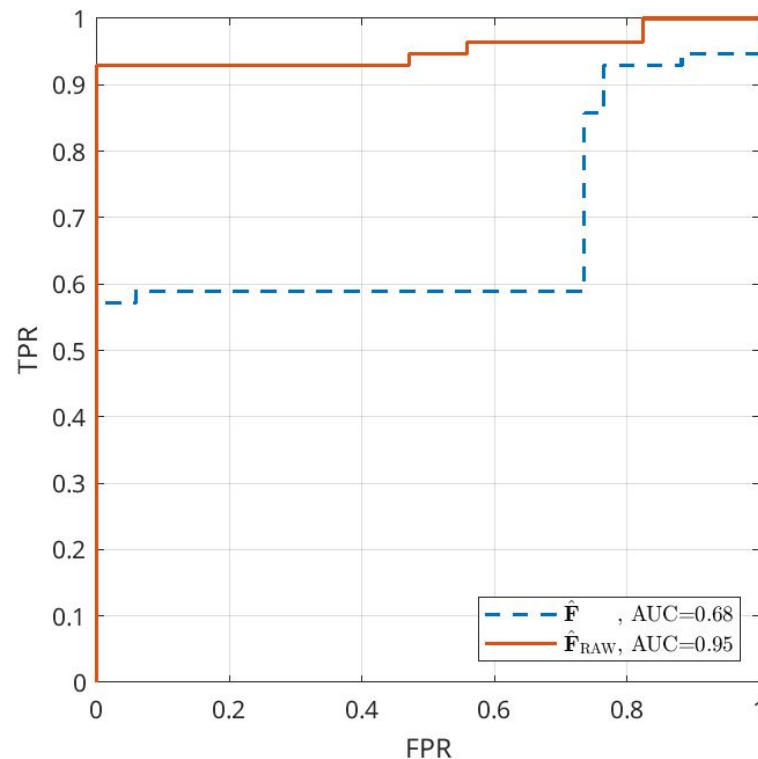
Single-Device Experiment: S10 (SM-G973F)

Reference:

- $\hat{\mathbf{F}}$: $L = 20$ flatfield JPEG images (Photo mode)
- $\hat{\mathbf{F}}_{\text{RAW}}$: $L = 20$ flatfield DNG images (PRO mode)

Test:

- **Wide sensor:** 71 JPEG images (Photo mode)
- **Telephoto sensor:** 41 JPEG images (Photo mode)



Does the Sensor Fingerprint Survive ISP Processing?

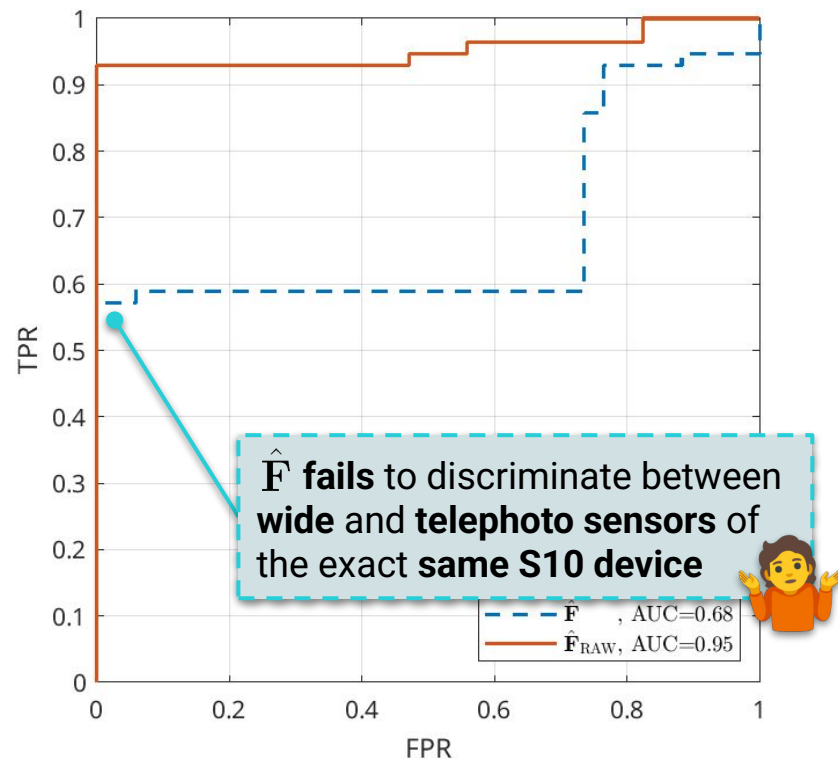
Single-Device Experiment: S10 (SM-G973F)

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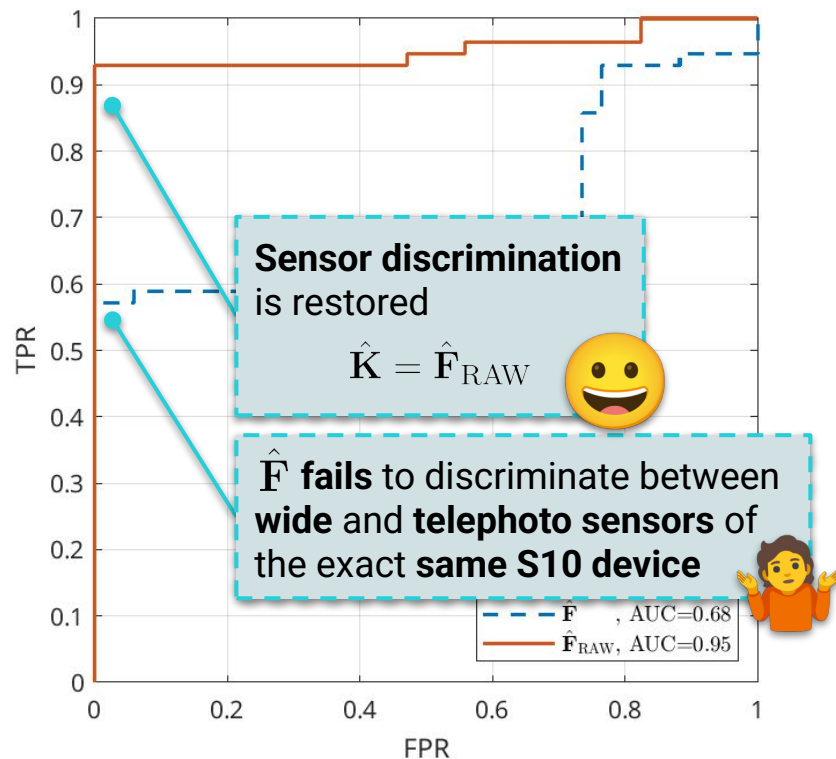
Single-Device Experiment: S10 (SM-G973F)

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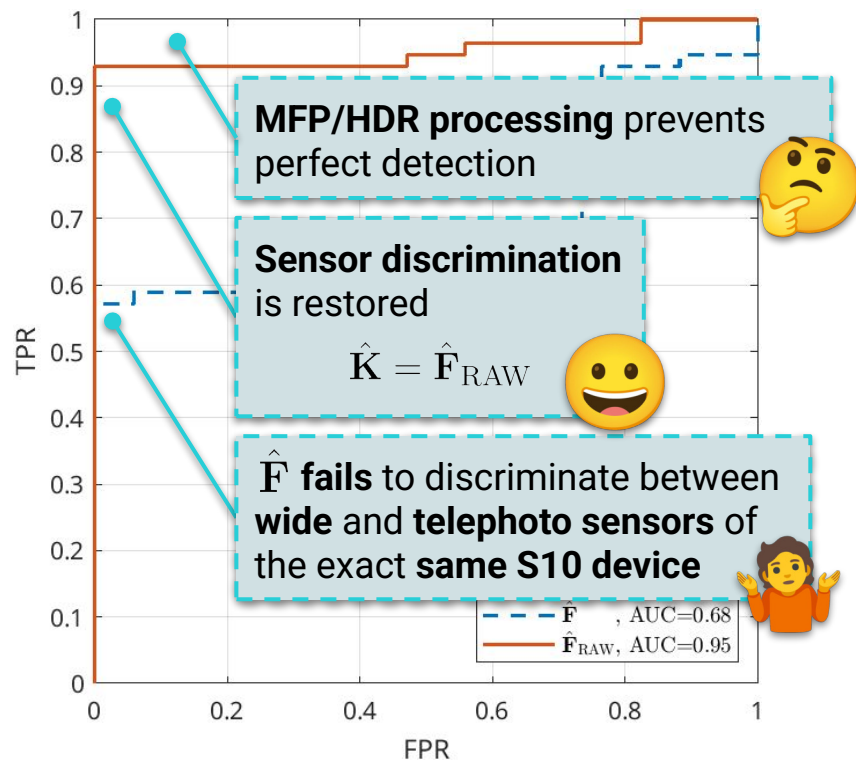
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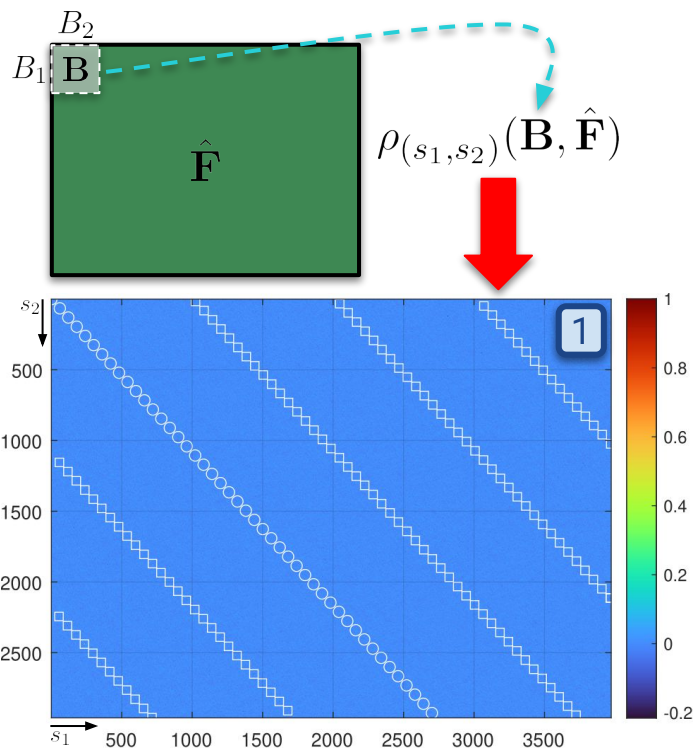
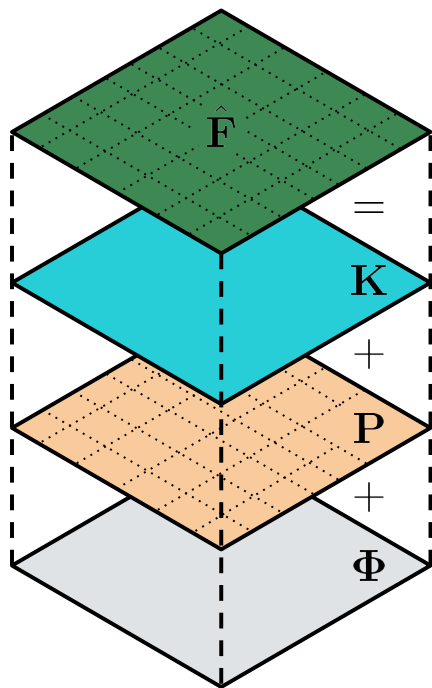
Test:

- **Wide sensor:** 71 JPEG images (Photo mode)
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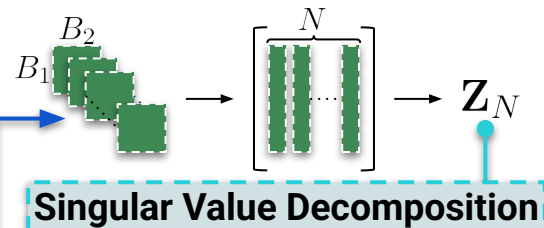
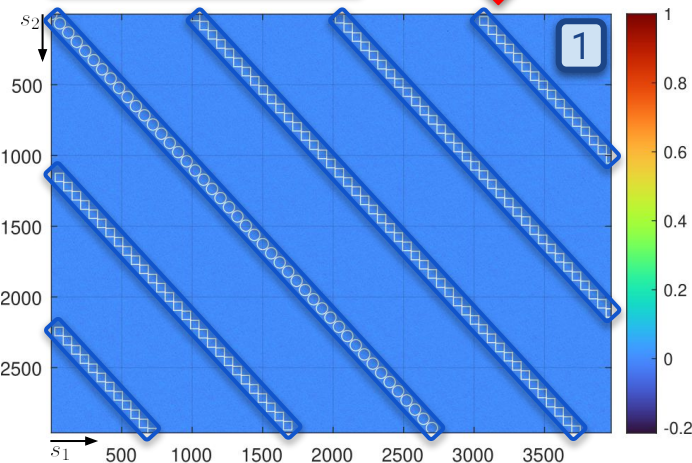
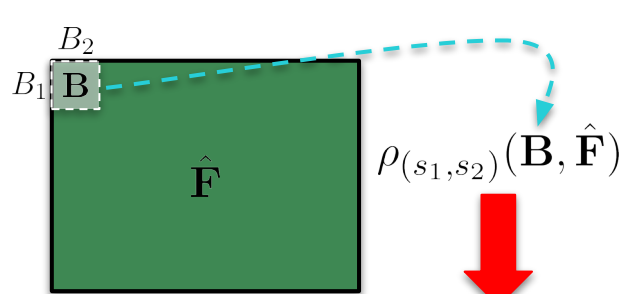
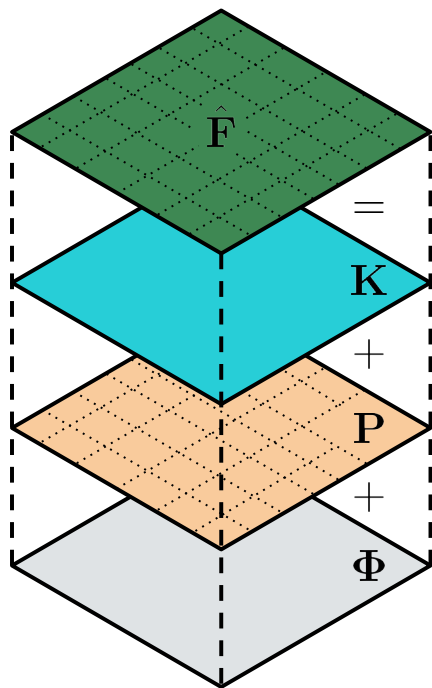
SVD-Based PRNU Recovery: Subspace Separation

Assumed Model



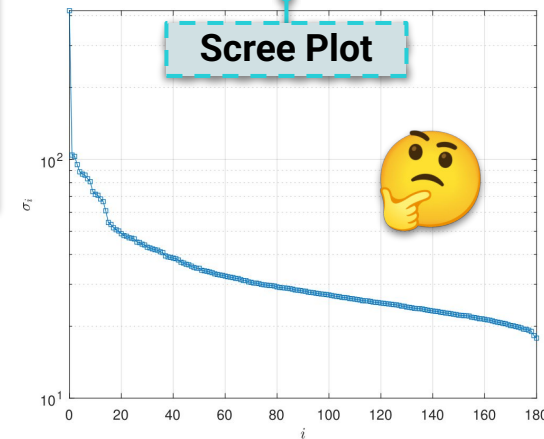
SVD-Based PRNU Recovery: Subspace Separation

Assumed Model



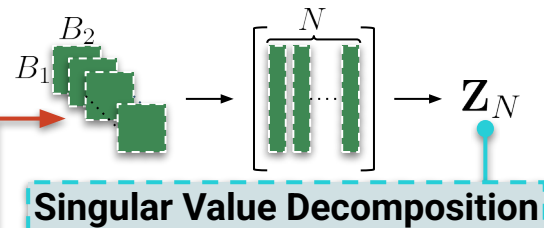
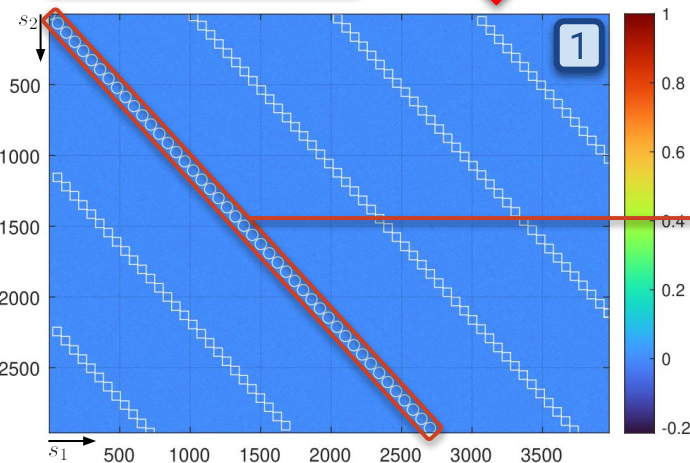
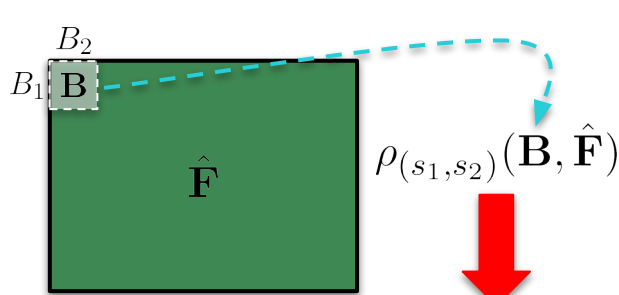
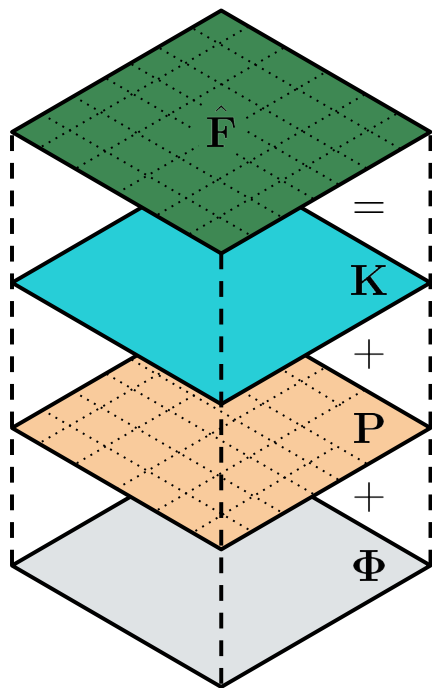
$$\mathbf{Z}_N = \mathbf{U}\Sigma\mathbf{V}^T$$

Scree Plot



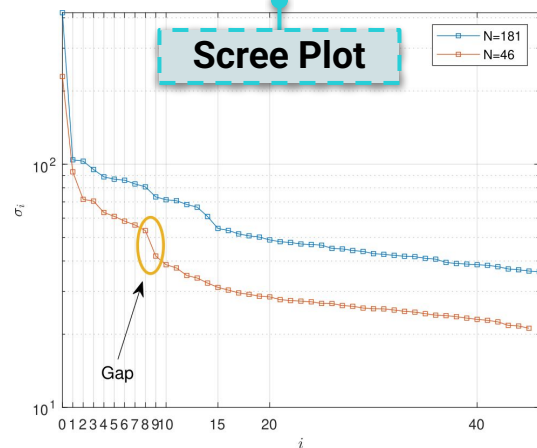
SVD-Based PRNU Recovery: Subspace Separation

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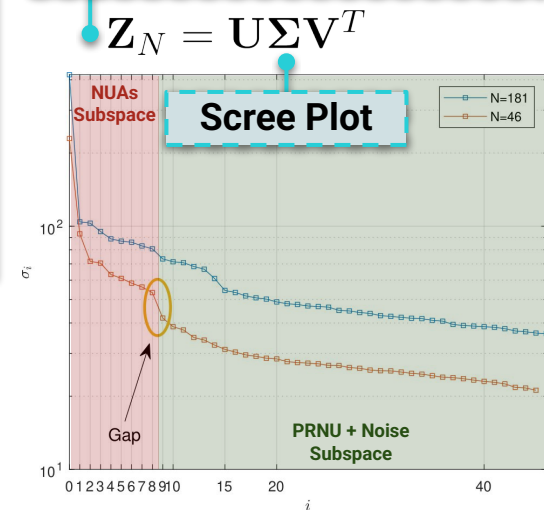
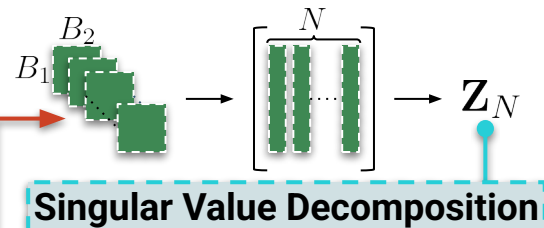
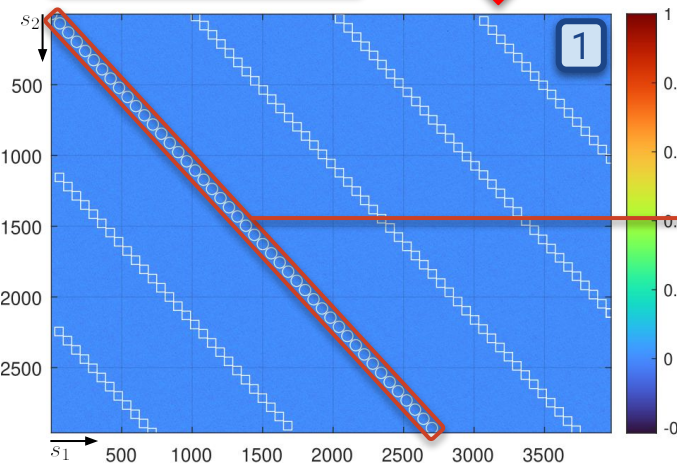
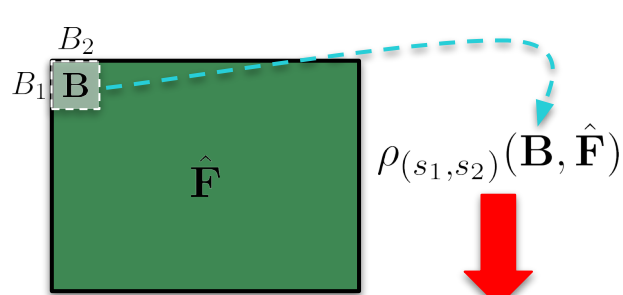
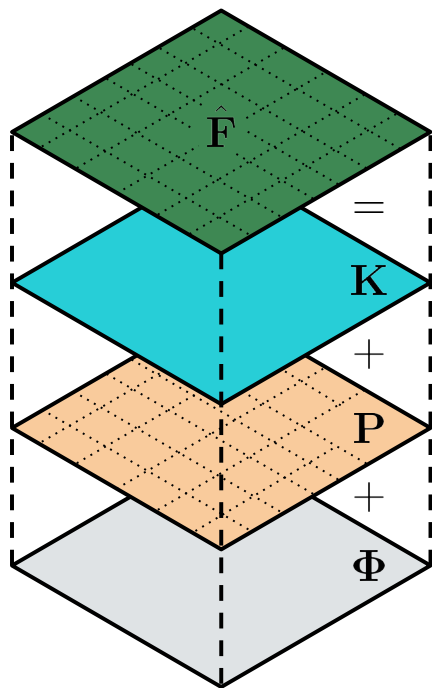
$$\mathbf{Z}_N = \mathbf{U}\Sigma\mathbf{V}^T$$

Scree Plot

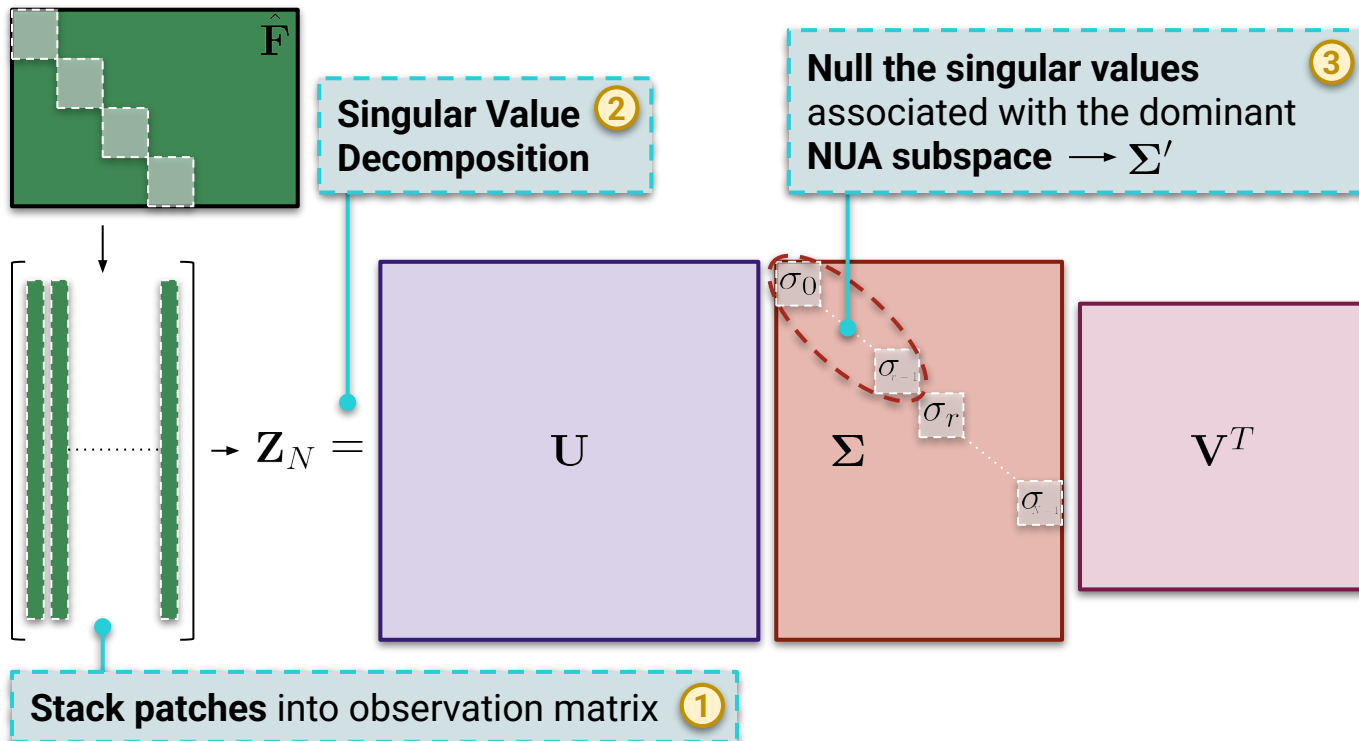


SVD-Based PRNU Recovery: Subspace Separation

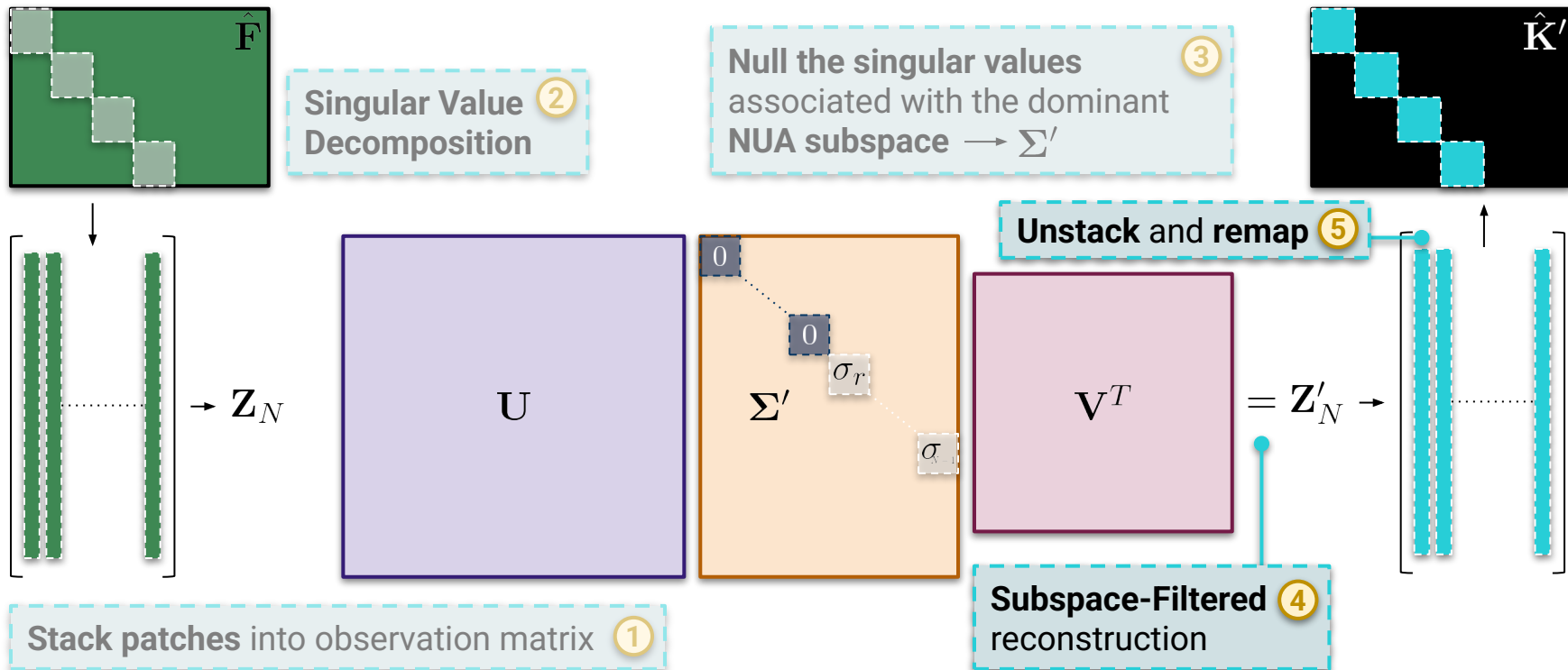
Assumed Model



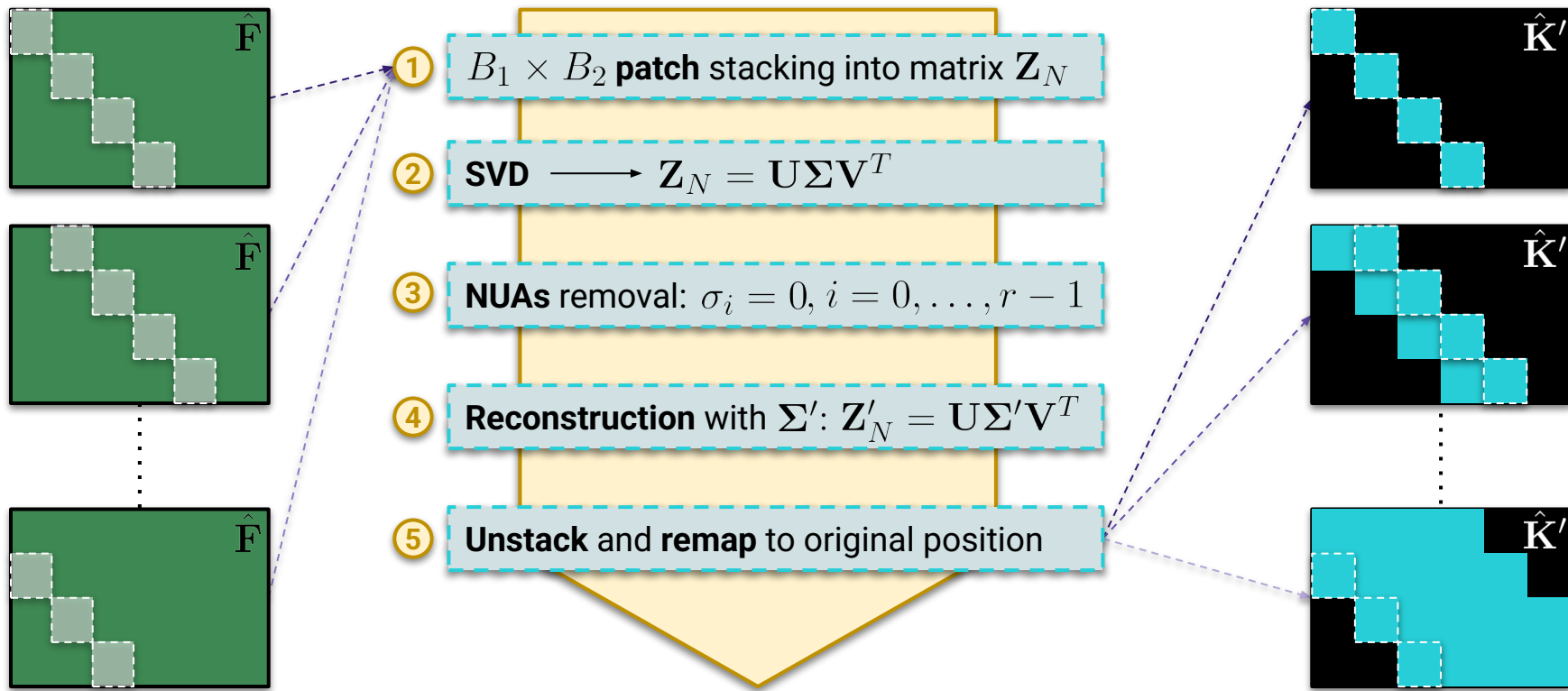
SVD-Based PRNU Recovery: Algorithm



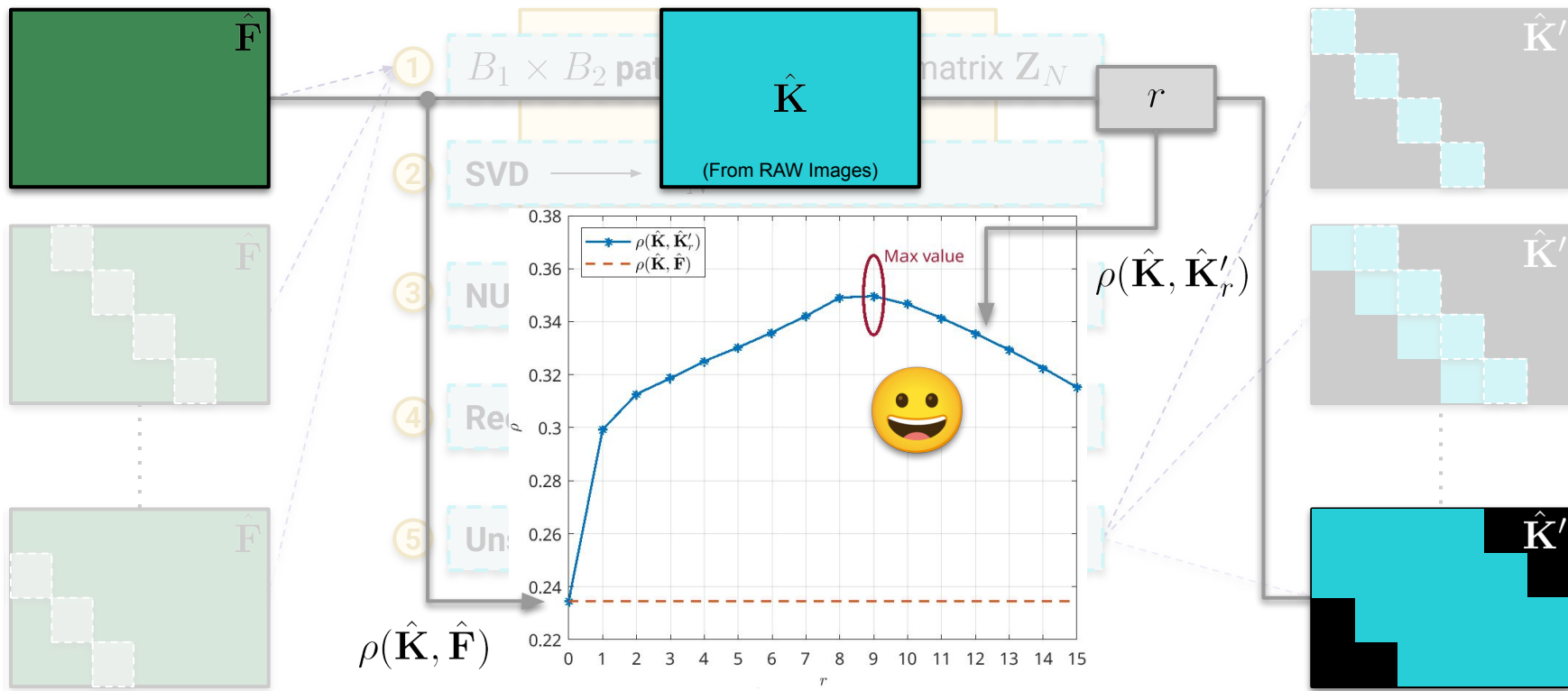
SVD-Based PRNU Recovery: Algorithm



SVD-Based PRNU Recovery: Algorithm



SVD-Based PRNU Recovery: Algorithm



Experimental Results: Pattern 1



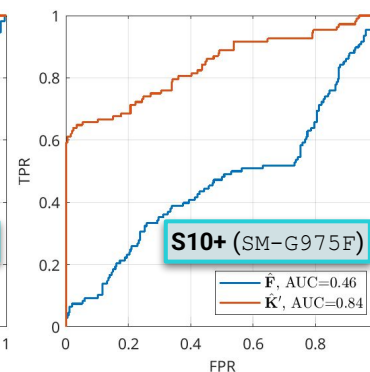
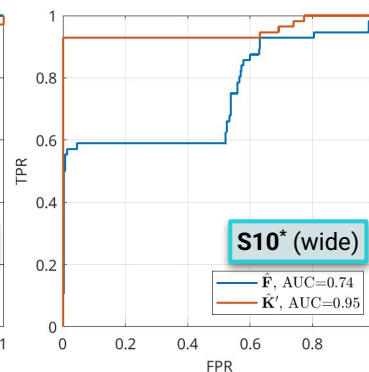
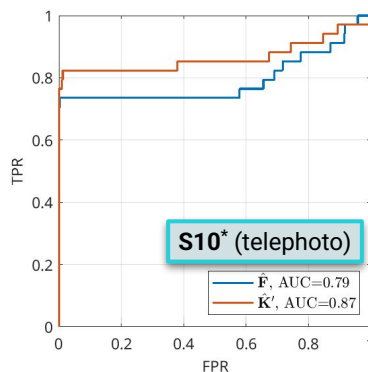
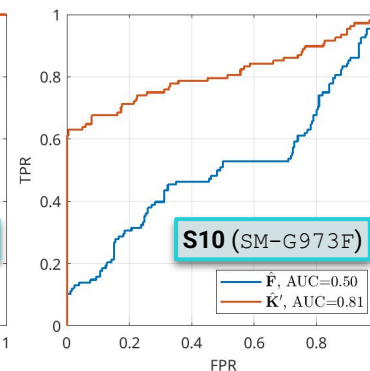
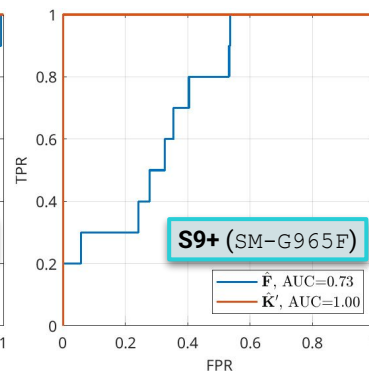
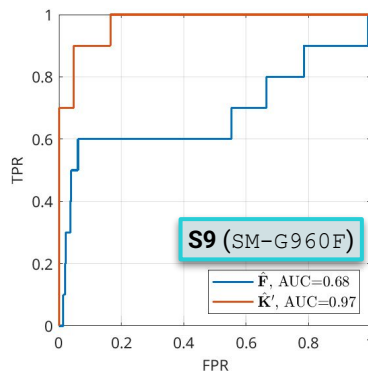
Multiple-Device Experiment

Reference:

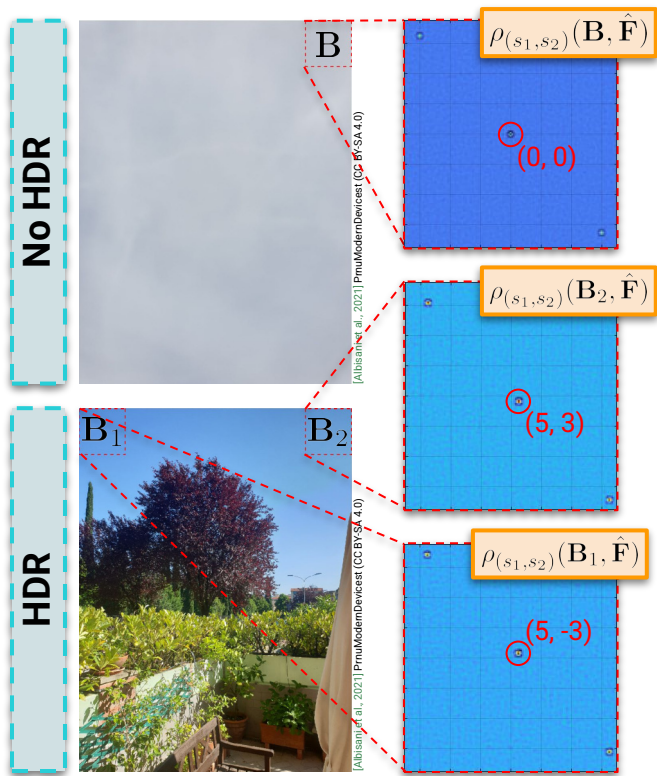
- S9
- S9+
- S10
- S10* (wide)
- S10* (telephoto)
- S10+

Test:

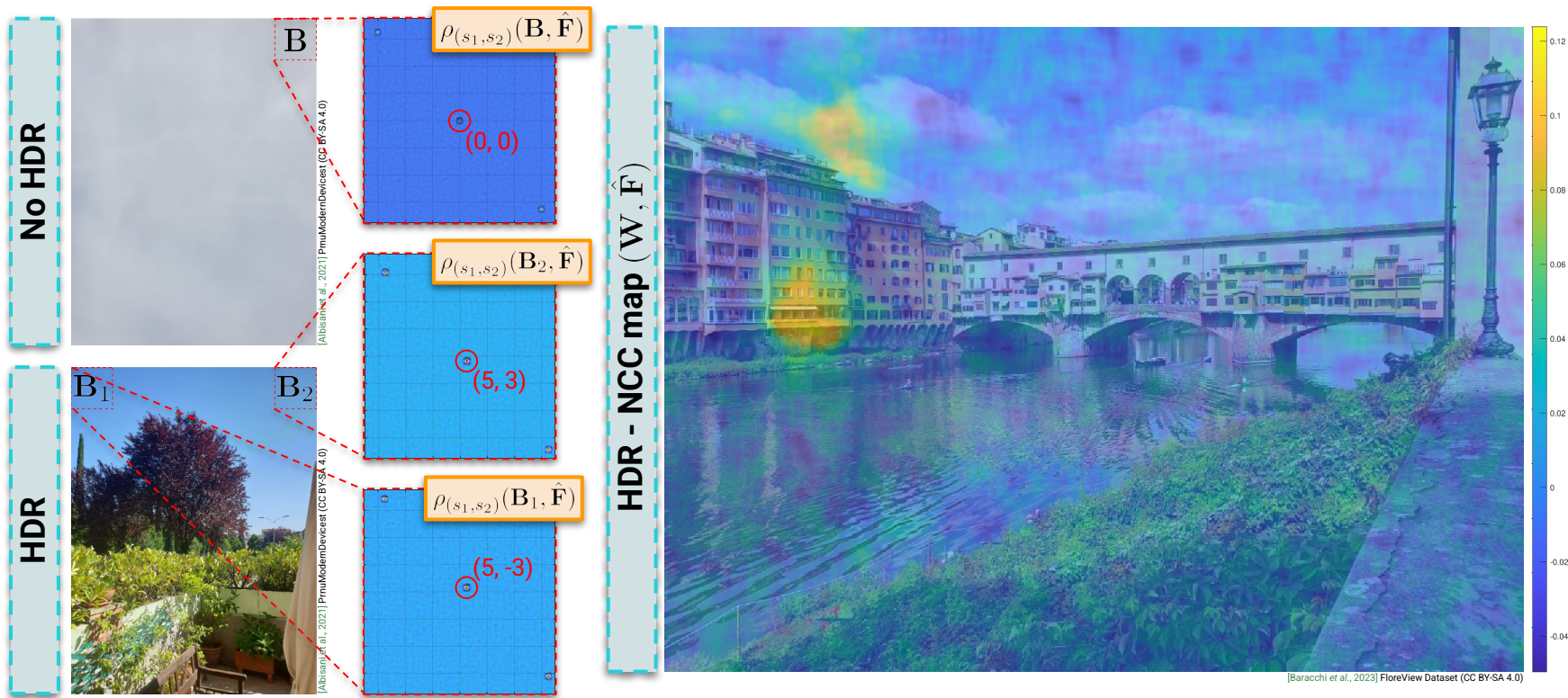
- 2x S9
- 2x S9+
- 3x S10
- 1x S10+
- 1x S20
- 1x S20+
- 1x Note9
- 1x Note10 Lite
- 1x Note10
- 1x Note10+



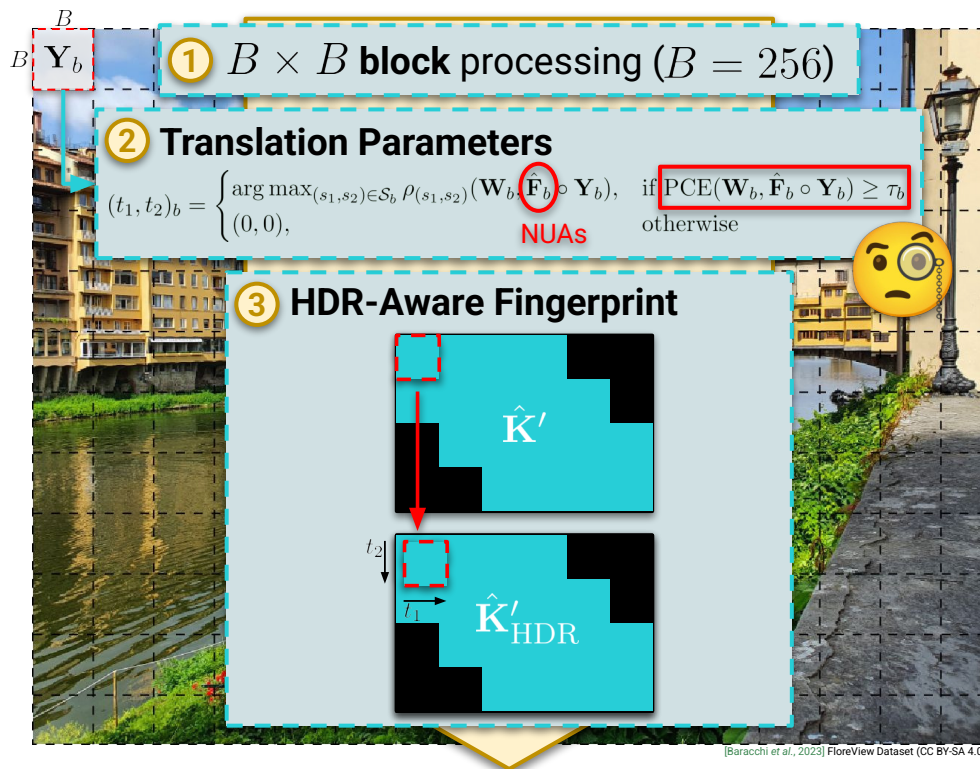
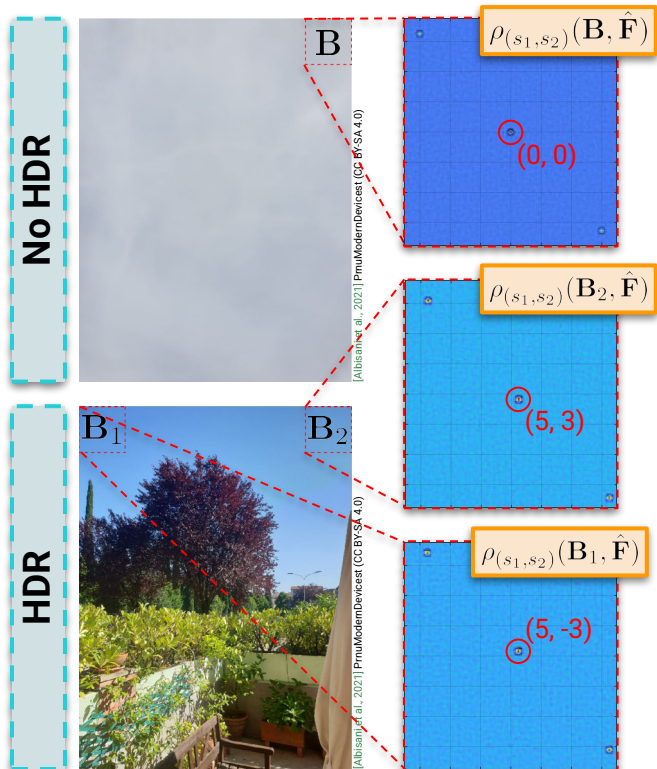
HDR Synchronization: Using NUAs as a Tracking Grid



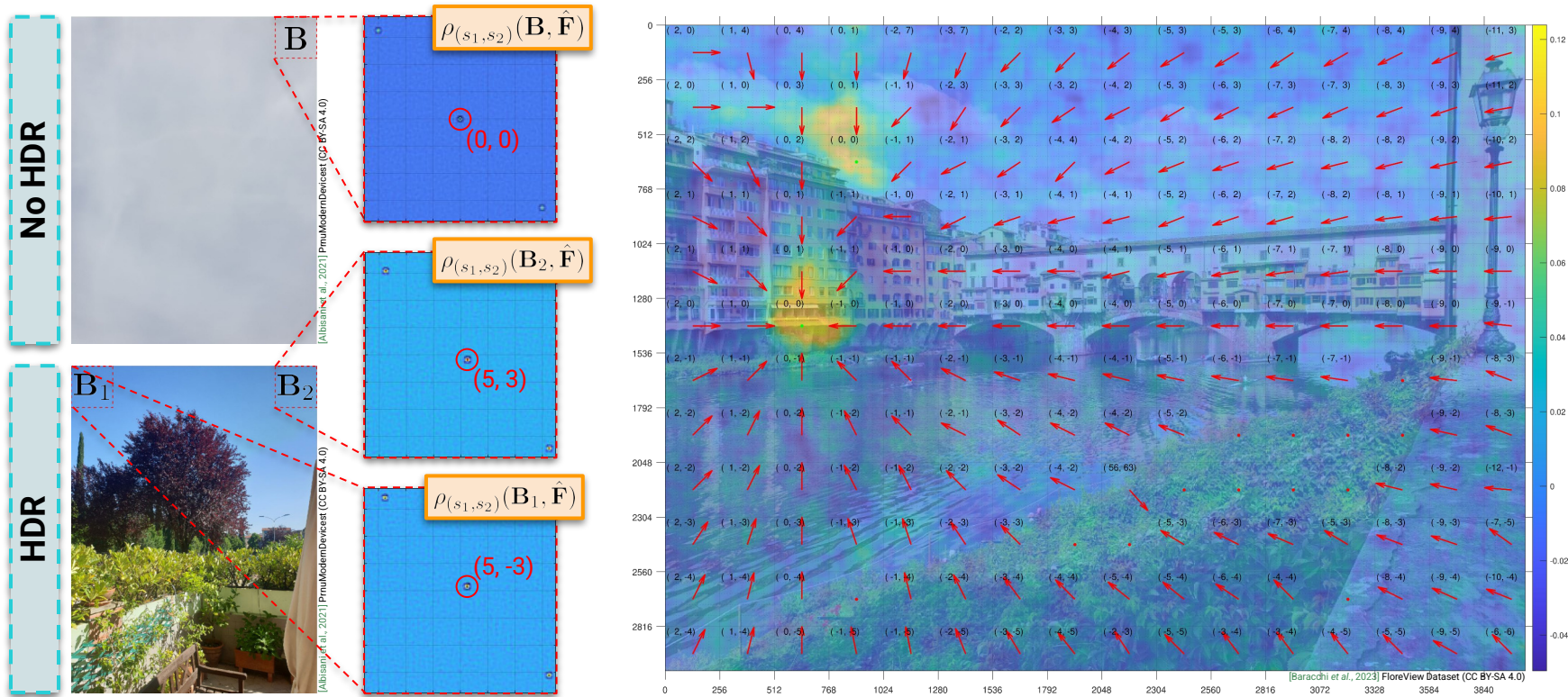
HDR Synchronization: Using NUAs as a Tracking Grid



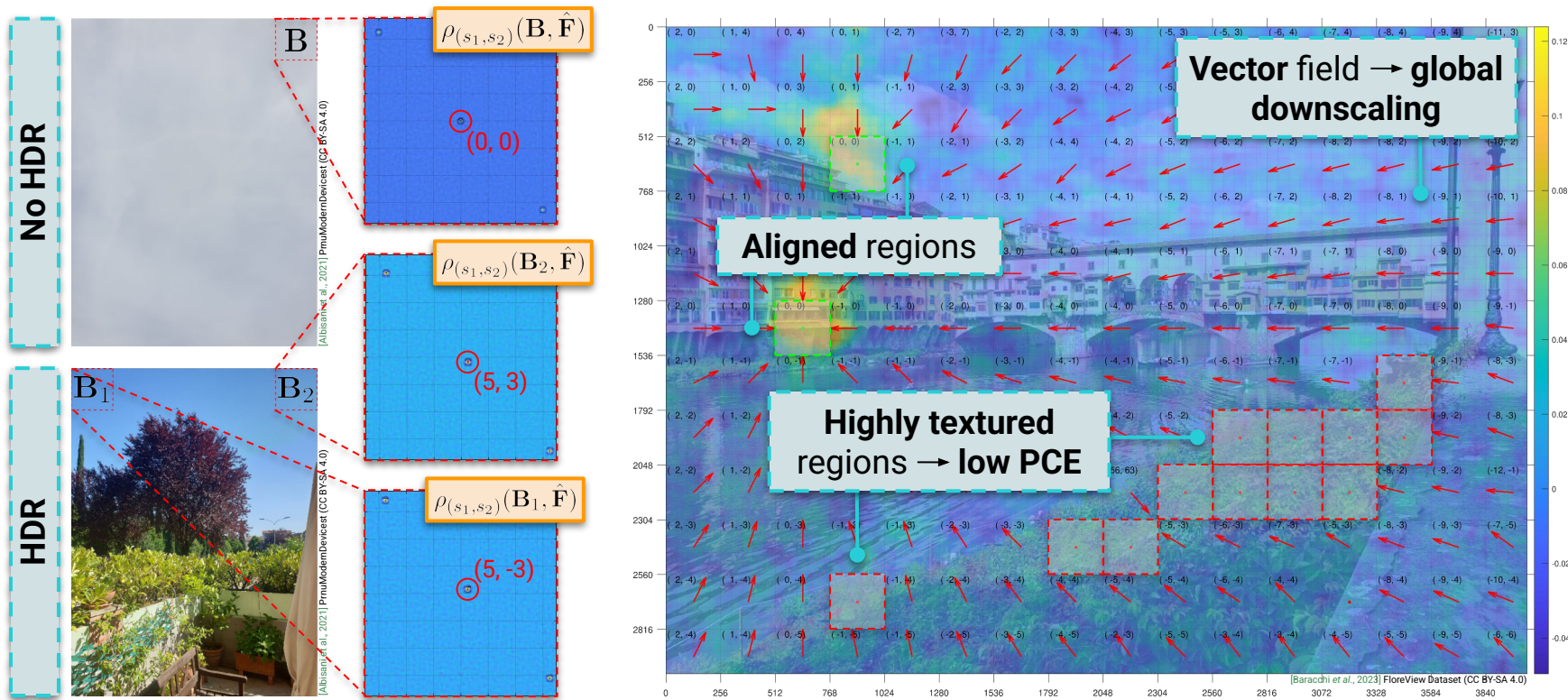
HDR Synchroization: Using NUAs as a Tracking Grid



HDR Synchroization: Using NUAs as a Tracking Grid



HDR Synchronization: Using NUAs as a Tracking Grid



Experimental Results: Pattern 1 (w/ HDR synchronization) 😊

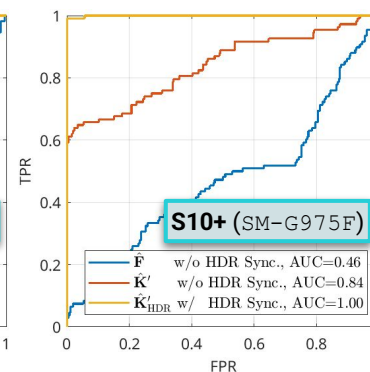
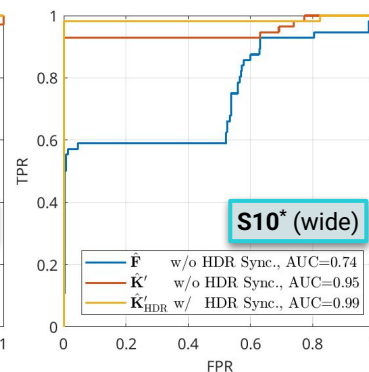
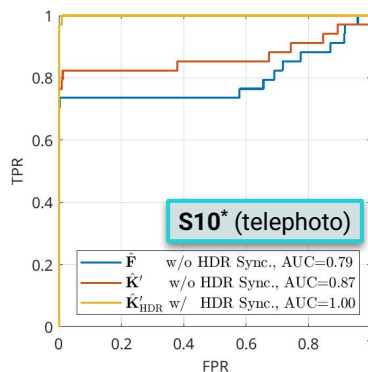
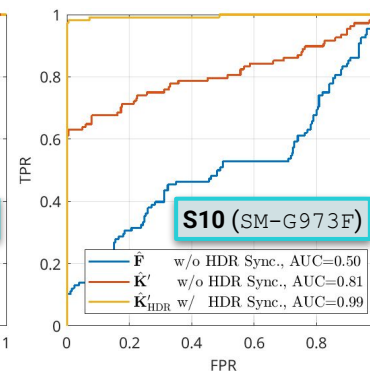
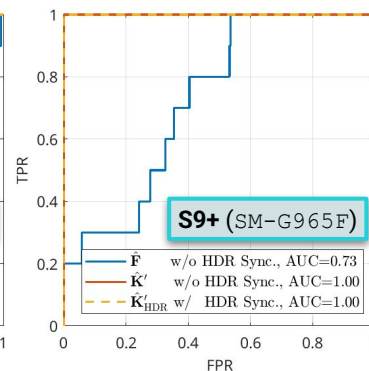
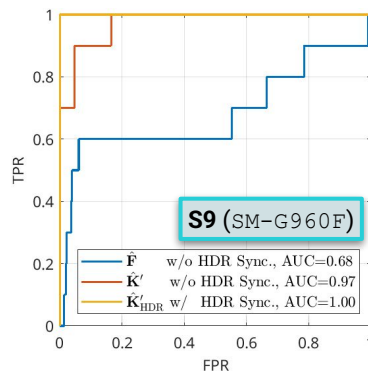
Multiple-Device Experiment

Reference:

- S9
- S9+
- S10
- S10* (wide)
- S10* (telephoto)
- S10+

Test:

- 2x S9
- 2x S9+
- 3x S10
- 1x S10+
- 1x S20
- 1x S20+
- 1x Note9
- 1x Note10 Lite
- 1x Note10
- 1x Note10+



Experimental Results: Pattern 1 (w/ HDR synchronization) 😊

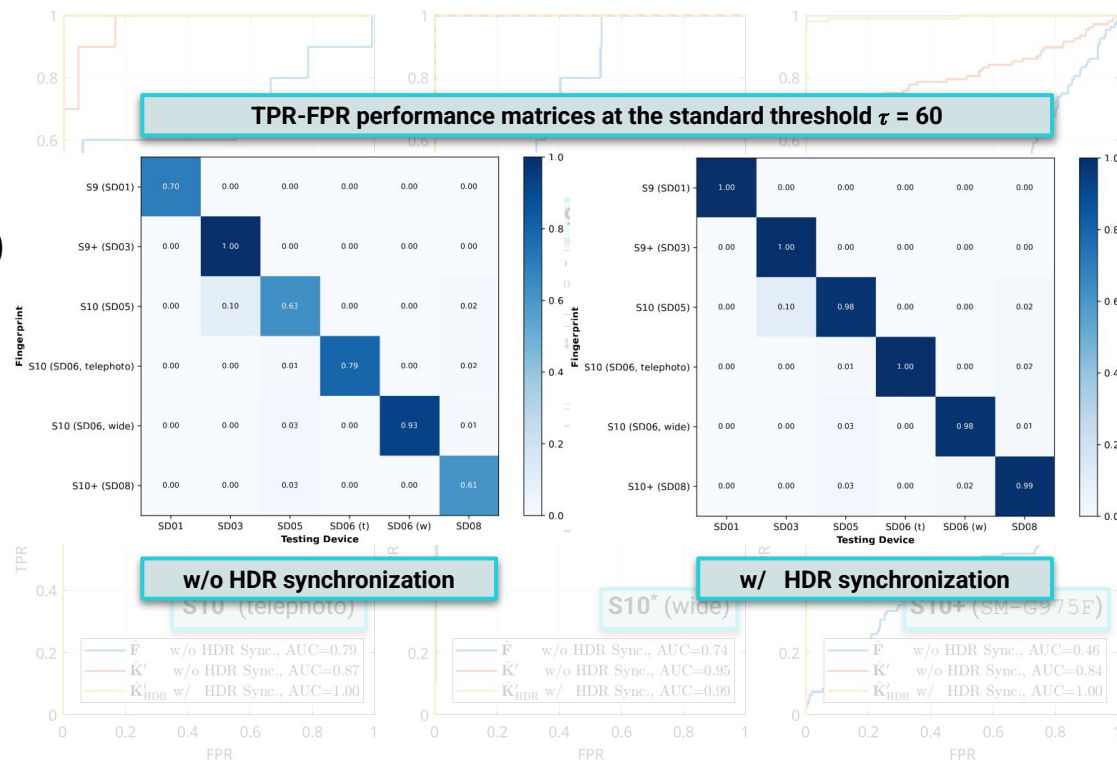
Multiple-Device Experiment

Reference:

- S9
- S9+
- S10
- S10* (wide)
- S10* (telephoto)
- S10+

Test:

- 2x S9
- 2x S9+
- 3x S10
- 1x S10+
- 1x S20
- 1x S20+
- 1x Note9
- 1x Note10 Lite
- 1x Note10
- 1x Note10+



Analysis of other NUA patterns: Pattern 6⁺

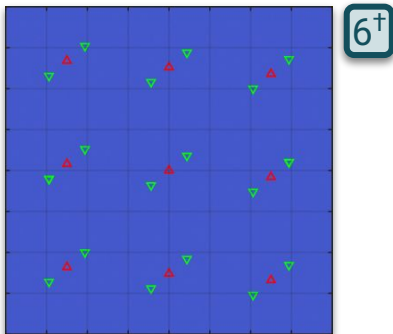
Multiple-Device Experiment

Reference:

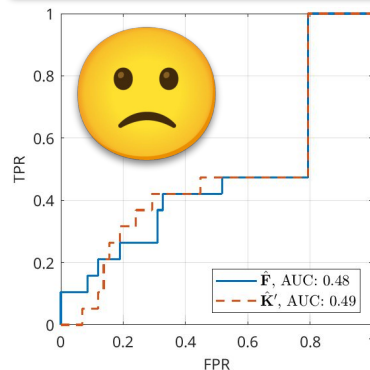
- $\hat{\mathbf{F}}$: $L = 20$
- $\hat{\mathbf{K}}'$: $B_1 = 1, B_2 = 250, N = 16$

Test:

- 3x S24



Similar Performance for 2 - 5



Analysis of other NUA patterns: Pattern 6⁺

Multiple-Device Experiment

Reference:

- $\hat{\mathbf{F}}$: $L = 20$
- $\hat{\mathbf{K}}$: $B_1 = 1, B_2 = 250, N = 16$

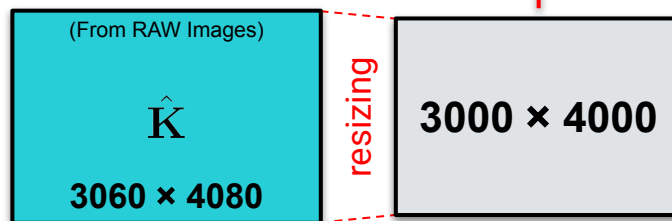
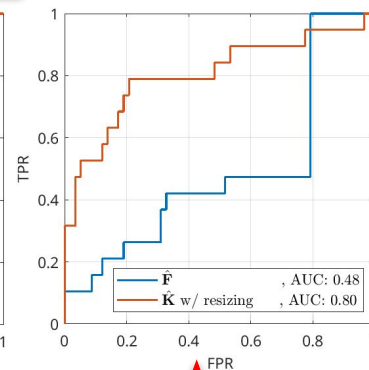
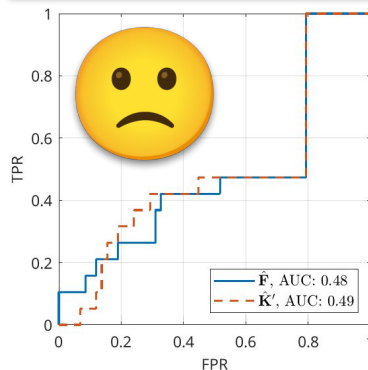
Test:

- 3x S24

Details:

- Default (JPEG) Resolution:
 - 3000×4000
- Raw (DNG) Resolution:
 - 3060×4080

Similar Performance for 2 - 5



Analysis of other NUA patterns: Pattern 6⁺

Multiple-Device Experiment

Reference:

- $\hat{\mathbf{F}}$: $L = 20$
- $\hat{\mathbf{K}}$: $B_1 = 1, B_2 = 250, N = 16$

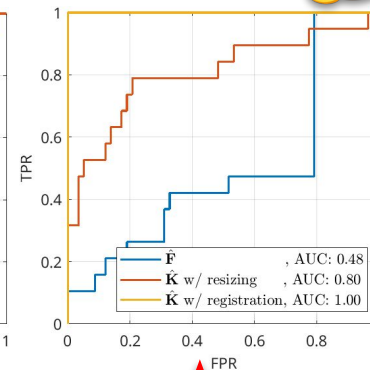
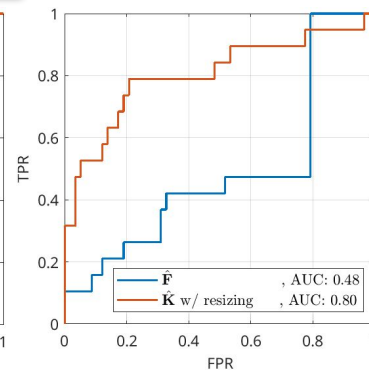
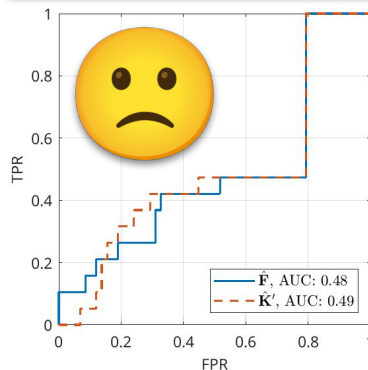
Test:

- 3x S24

Details:

- Default (JPEG) Resolution:
 - 3000×4000
- Raw (DNG) Resolution:
 - 3060×4080

Similar Performance for 2 - 5



(From RAW Images)

$\hat{\mathbf{K}}$

3060 × 4080

Raw + JPEG: affine transformation

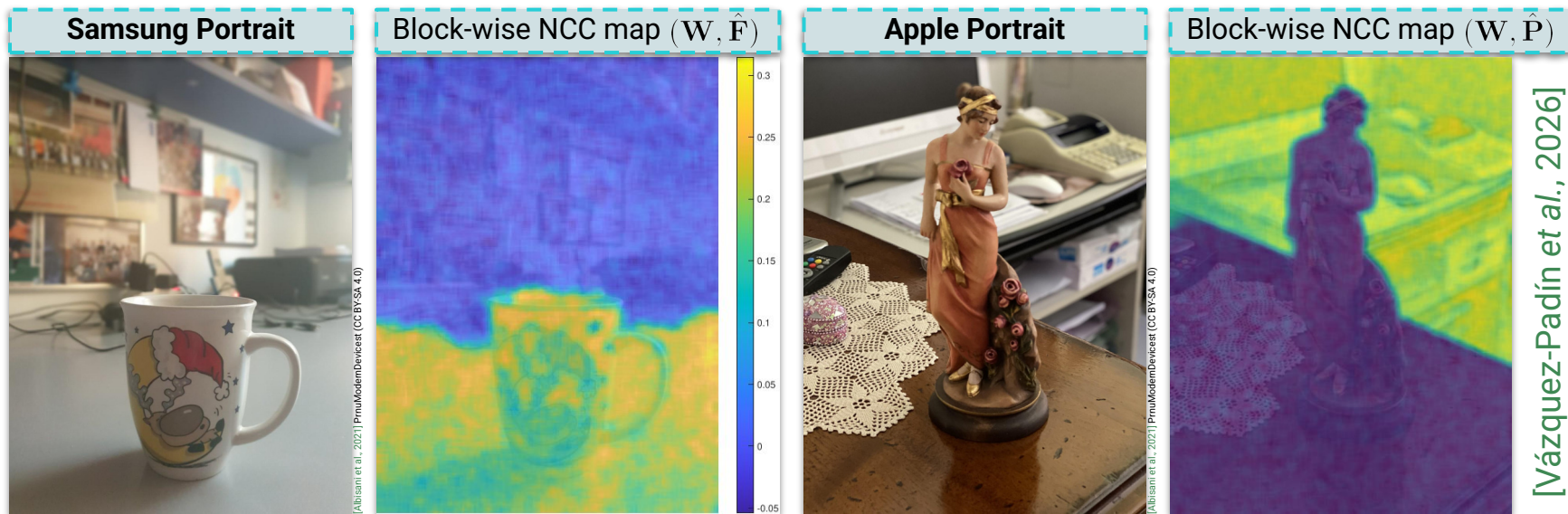
$$\begin{pmatrix} 0.9803 & 0.0000 & -0.9207 \\ 0.0001 & 0.9791 & 3.8936 \\ 0 & 0 & 1.0000 \end{pmatrix}$$

3000 × 4000

Portrait Mode Images: Bokeh Analysis

Unlike Apple, Samsung does not introduce correlated artifacts in bokeh regions:

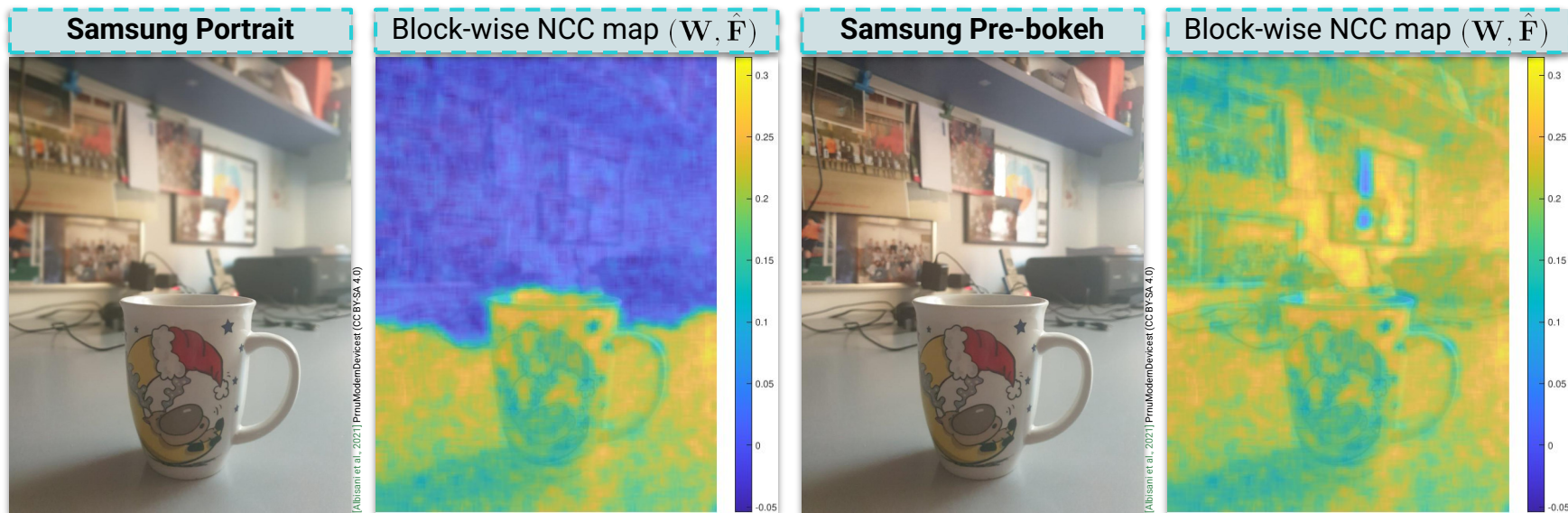
- Samsung bokeh $\neq$ source of false positives
- Bokeh weakens PRNU $\rightarrow$ mask bokeh areas when possible



Portrait Mode Images: Bokeh Analysis

Unlike Apple, Samsung does not introduce correlated artifacts in bokeh regions:

- Samsung bokeh $\neq$ source of false positives
- Bokeh weakens PRNU $\rightarrow$ mask bokeh areas when possible



Conclusions and Future Work

Solved Case: Pattern 1

✓ **SVD** subspace separation successfully decouples the **PRNU** from **ISP-based NUAs**

✓ **NUA suppression** restores PRNU verification

✓ **HDR-aware synchronization** boosts performance

Unsolved Cases:



! ? **Newer Exynos** generations with **NPU**s exhibit increasingly complex **NUAs**

! ? **SVD** subspace separation yields **limited effectiveness**

! ? **Resizing** is applied in **default photo mode**

Key Forensic Takeaways:

🔑 The **PRNU uniqueness assumption** must be **validated** against **modern ISP pipelines**

🔑 **PRNU persists** in **default photo mode**

🔑 **PRNU persistence** motivates **unified NUA mitigation** methods

Thanks for your attention!

GitHub Repository



<https://github.com/dvazquezpadin/samsung-NUAs>

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