EMSY Noise Filtering Methods

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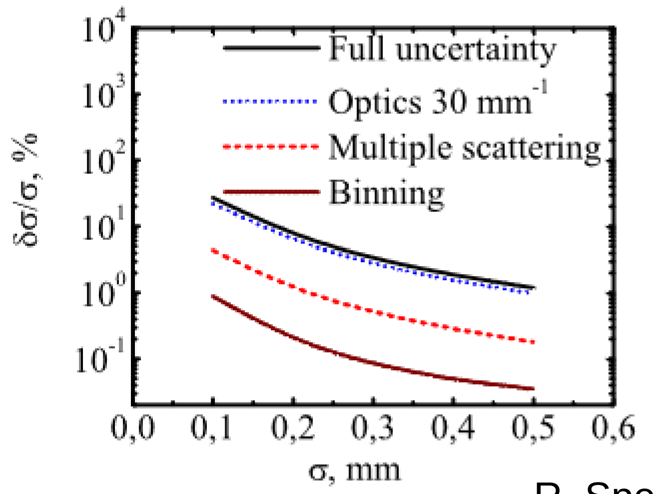
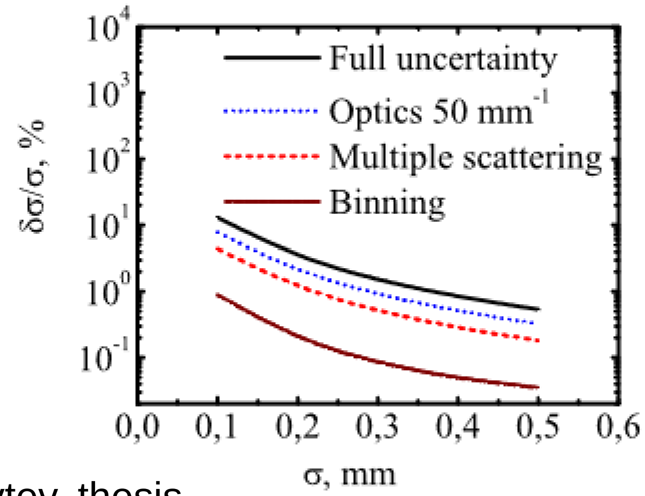
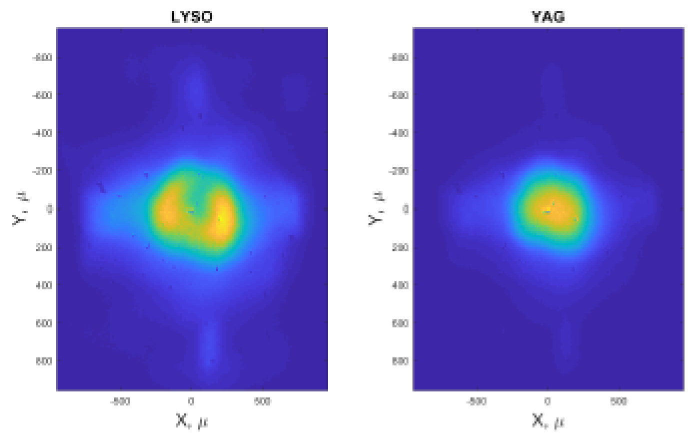
Understanding the noise removal methodology

- Need to ensure the noise processing accurately reconstructs the beamlet images.
  - Minimize and understand systematic distortions due to noise removal
- Need to be aware of limitations of noise removal process
  - E.g. at what SNR does noise start to seep into the processed images
- Need slice images to be cleaned before correcting for other systematic effects
  - Camera resolution. For an rms size of ~0.2 mm, the measured emittance can have errors up to ~100%
  - Slit size when comparable to the beam size
  - Scintillator saturation and/or quenching





R. Spesyvtev, thesis

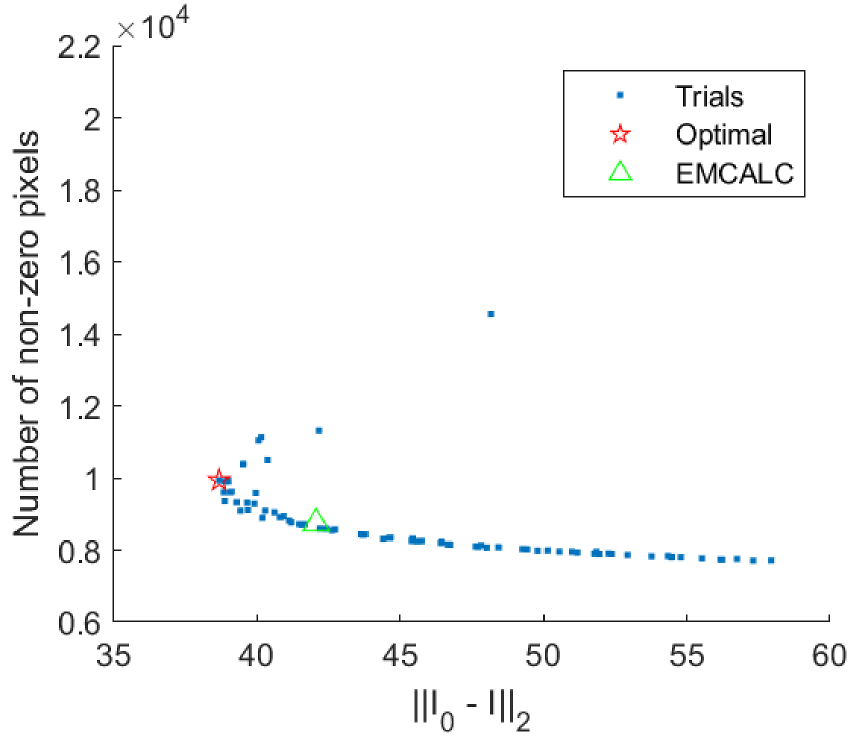


G. Kube et. al. IBIC'18

Characterizing noise filters

- Using two figures of merit. Goal is to minimize both
  - Number of non-zero pixels: Measure of cut size. Less pixels means larger cut. Want larger cut to ensure noise is removed
  - Euclidean norm between cleaned and true images: Measure of reconstructed image quality. Want to minimize error
- Determining optimal setting using Pareto analysis
  - Plot both quantities for a set of filter parameters. The lower bound of the points is the set of optimal
- Currently, chose minimum of Euclidean norm as best solution
- Use std(noise)/I_max to quantify noise and parameterize the optimal settings

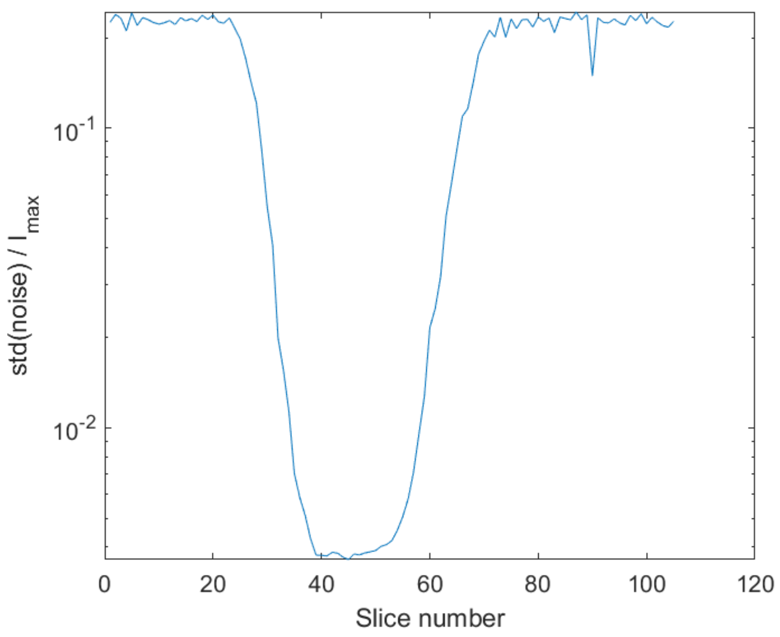
Median filter parameter scan



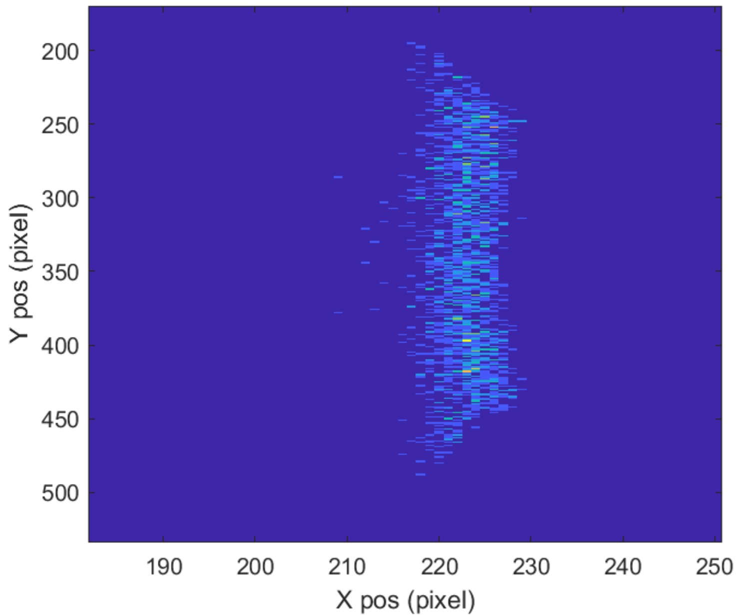
Creating a slice image to test

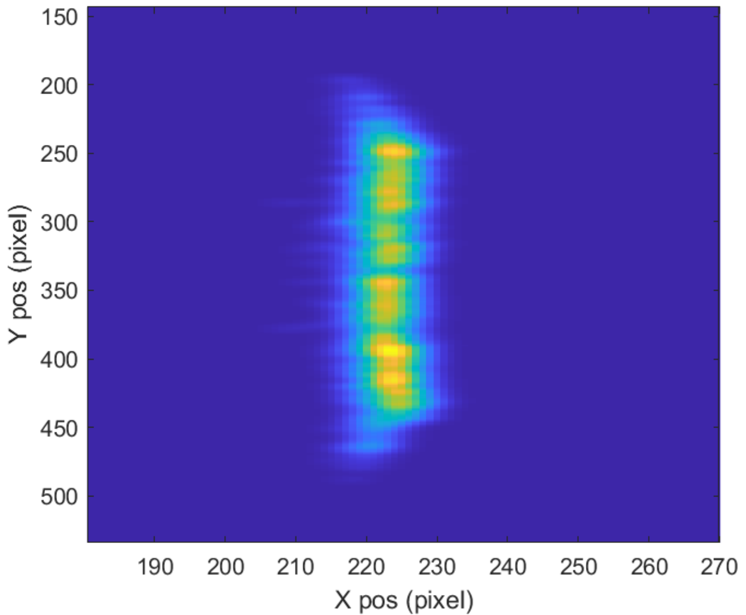
- Initial phase space is from ASTRA simulations with 200k particles at High1.screen1
- A 0.05 mm slice in x is taken and particles projected 3.1 m to view screen
- Issue: image is noisy due to limited number of particles after the slit
  - Convolve with Gaussian (sig_x,y = 0.12 mm) to smooth
- Add Gaussian random noise at desired level
  - Characterize noise as std(noise)/I_max
  - From EMSY images this varies from ~0.001-0.25 across a beam

Example EMSY slices noise levels



Slice example 1 nC beam

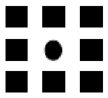




EMCALC-like filter

- EMCALC-like filter method
  - Make a cut at n*rms_noise
  - Create mask. 1 is I_ij > 0, 0 else
  - Product removal filter is applied m times to mask
  - Sum restoration filter is applied k times mask
  - Multiply mask by original image
- Parameters: cut level, removal filter iterations, restoration filter iterations
- Pros: fast, simple, independent of signal
- Cons: doesn't remove the noise on top of the signal. Issue for low SNR

Each filter applied N times, $N \in \mathbb{N}$.



Removing product filter:

$$
\begin{aligned}
M_{w,h,b} &= SmB_{w+1,h,b} \cdot SmB_{w+1,h-1,b} \cdot SmB_{w,h-1,b} \cdot \\
&\cdot SmB_{w-1,h-1,b} \cdot SmB_{w-1,h,b} \cdot SmB_{w-1,h+1,b} \cdot \\
&\cdot SmB_{w,h+1,b} \cdot SmB_{w+1,h+1,b}
\end{aligned}
$$

If $M_{w,h,b} == 0$ then $SmB_{w,h,b} = 0$

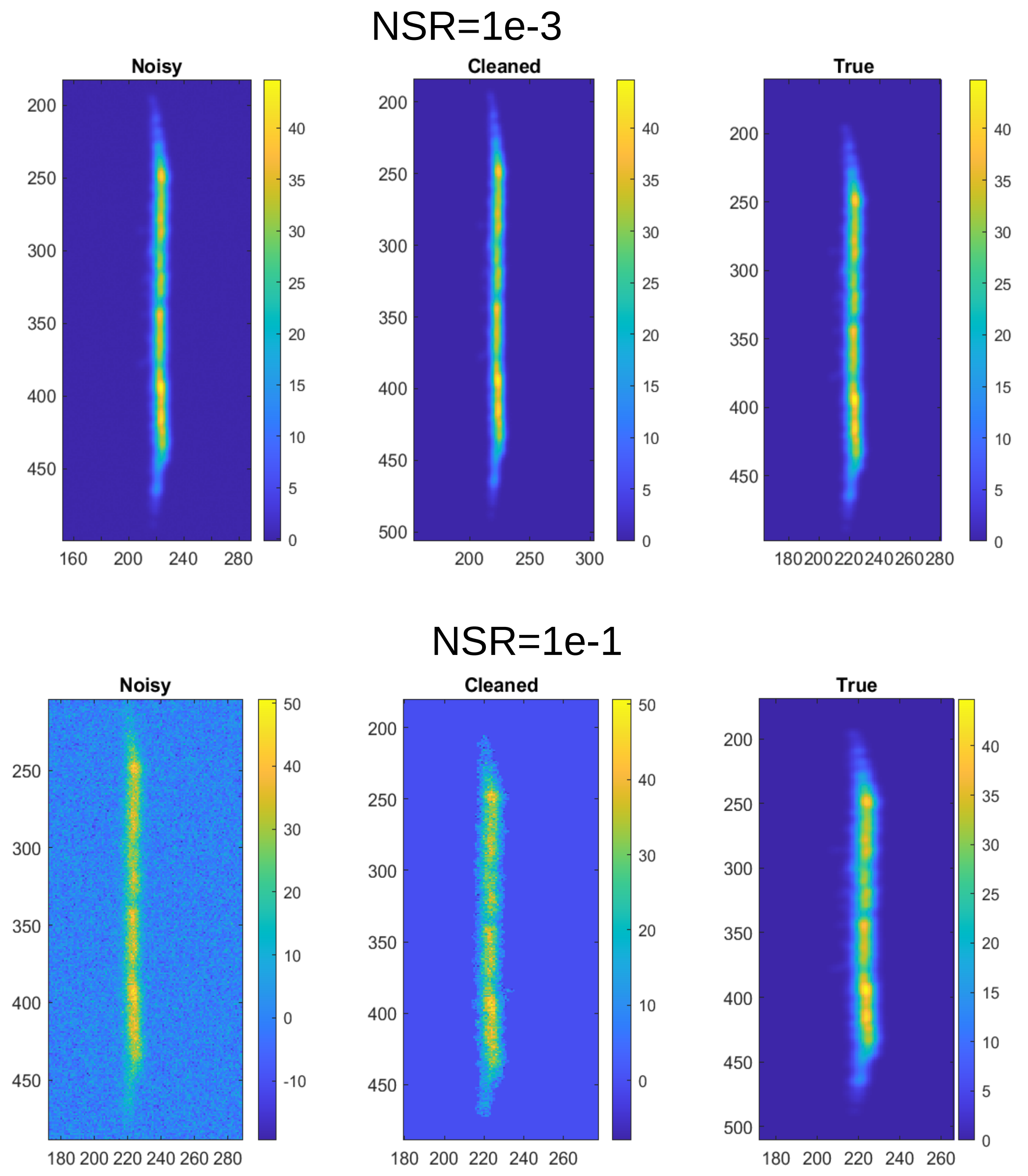
Strange filter:

$$
\begin{aligned}
M_{w,h,b} &= SmB_{w+1,h,b} + SmB_{w+1,h-1,b} + SmB_{w,h-1,b} + \\
&+ SmB_{w-1,h-1,b} + SmB_{w-1,h,b} + SmB_{w-1,h+1,b} + \\
&+ SmB_{w,h+1,b} + SmB_{w+1,h+1,b}
\end{aligned}
$$

If $M_{w,h,b} \leq 0$ then $SmB_{w,h,b} = 0$.

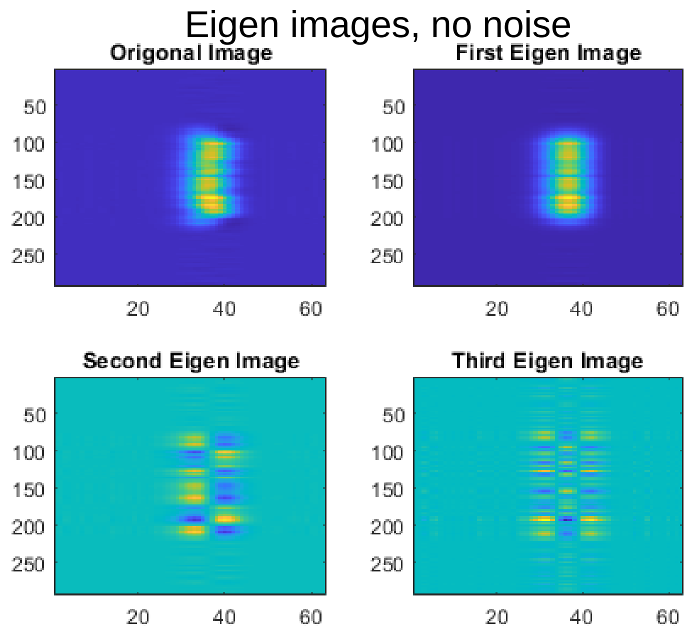
Median filter

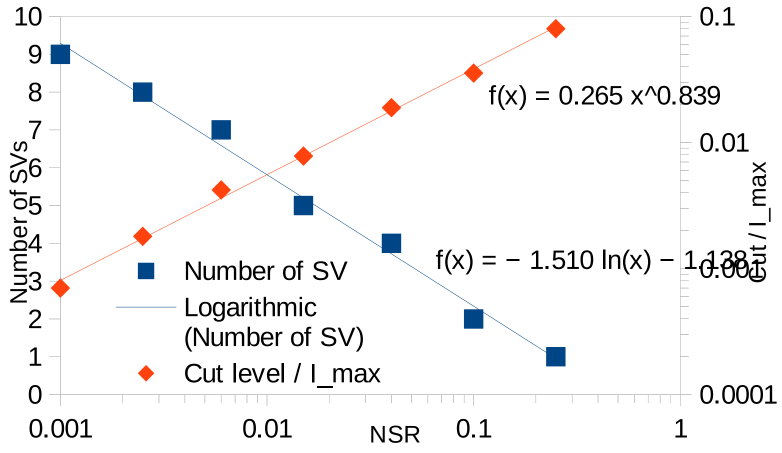
- Median filter method
  - Make a cut at n*rms_noise
  - Create mask. 1 is I_ij > 0, 0 else
  - Applied mxm median filter k times to mask
  - Multiply mask by original image
- Parameters
  - Cut level, median filter size, median filter iterations
- Behaves basically the same as the EMCALC filter, but less aggressive
- Pros: fast, simple, independent of signal
- Cons: doesn’t remove the noise on top of the signal. Issue for low SNR

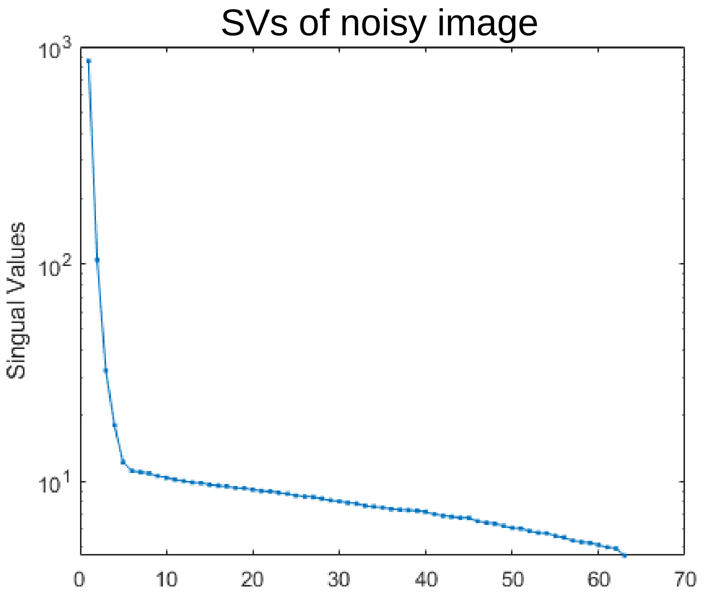


Singular value decomposition (SVD) filter [1]

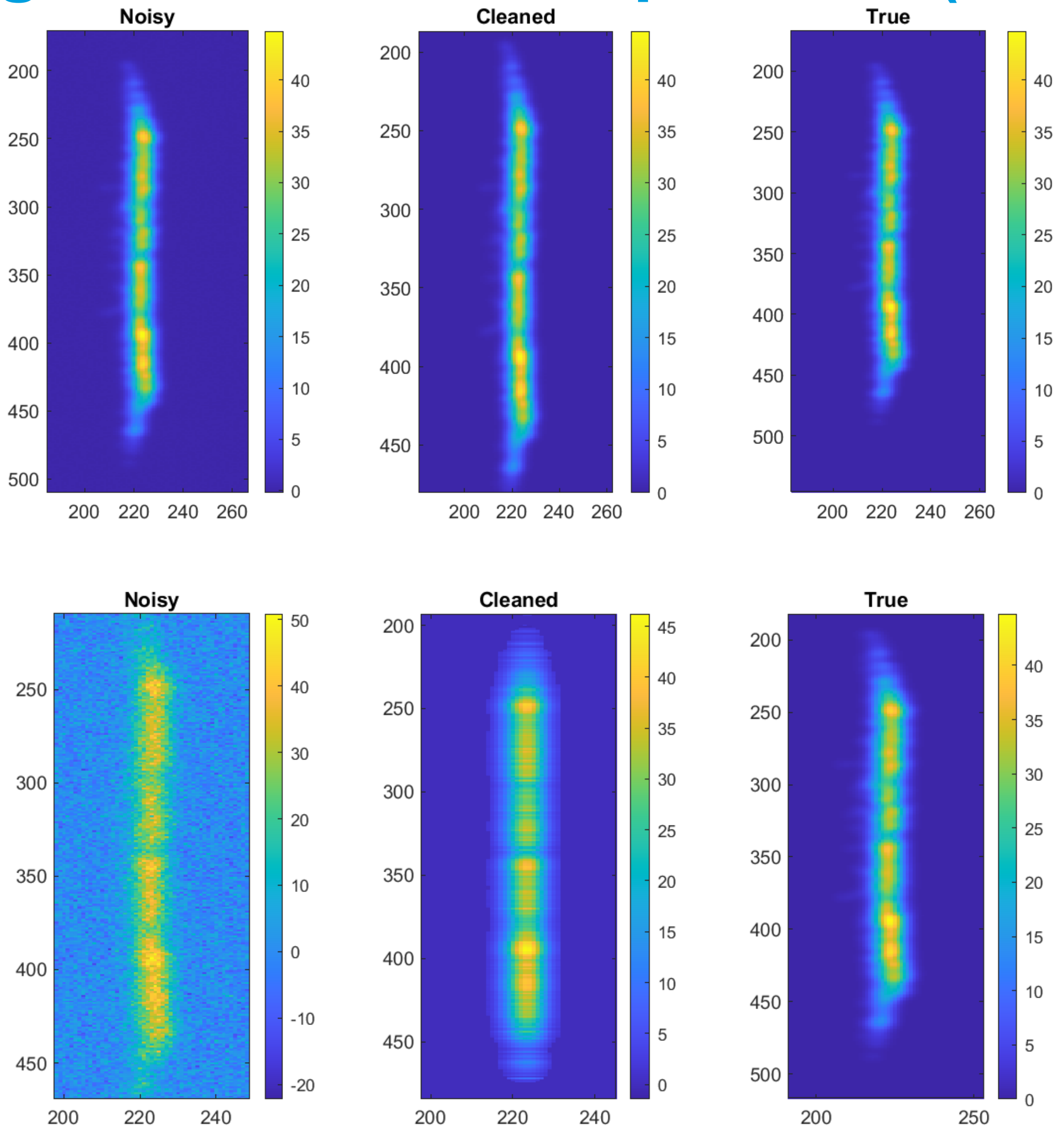
- SVD filter method
  - Isolate signal with aggressive erode and dilate filters
  - Perform SVD decomposition on image
    - M = USV* where S is diagonal containing the singular values (SVs)
  - Keep n largest SVs, the rest are set to zero. I.e. keep the most dominant eigen images
  - Reconstruct image with modified singular values
  - Apply median filter to remove artifacts
- Parameters: number of singular values and median filter parameters
- Pros: Separates noise and beamlet signals in real domain
- Cons: lose features at low SNR because only one SV is used







Singular value decomposition (SVD) filter [2]

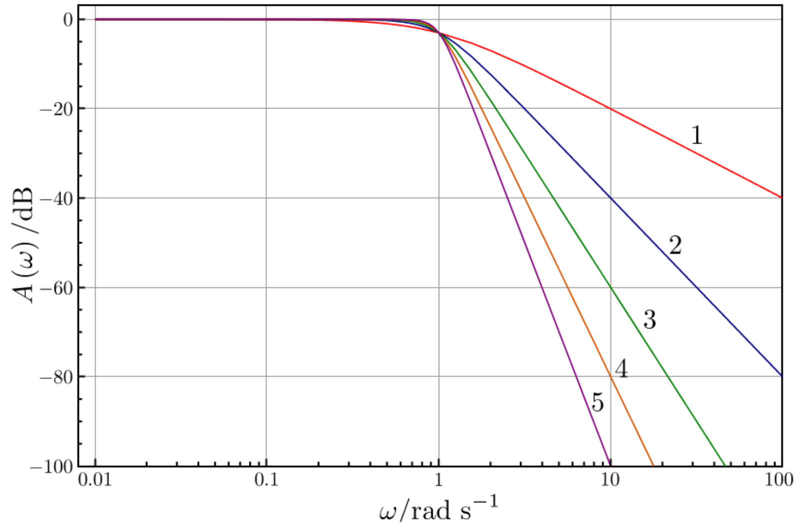


- NSR = 1e-3
  - Uses 7 singular values.
- NSR = 1e-2
  - Uses 1 singular value.
  - Noise on top of the signal is removed but the curve in the distribution cannot be reproduced

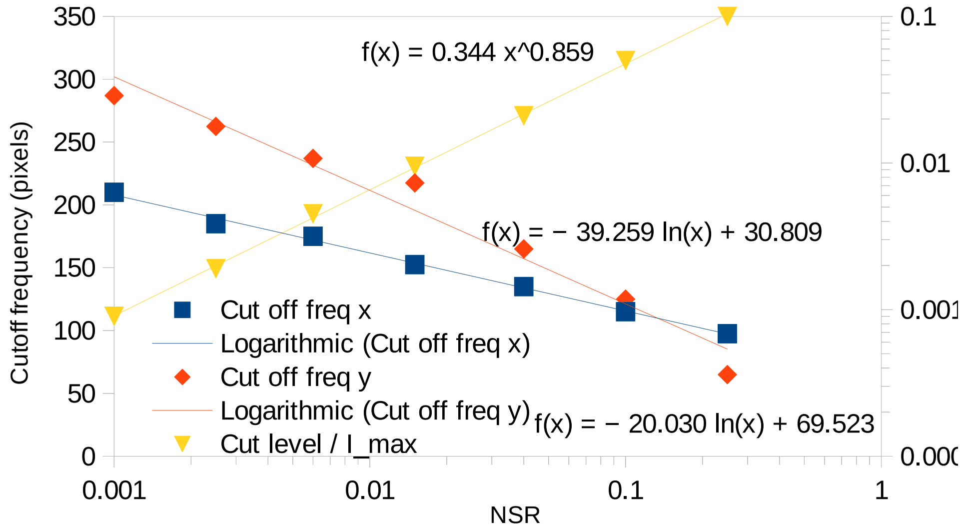
Fourier transform filter [1]

- Fourier transform filter method
  - Take 2D Fourier transform of image
  - Apply an order n Butterworth filter with cutoff frequencies f_x, f_y
  - Take inverse Fourier transform
  - Apply median filter to remove artifacts

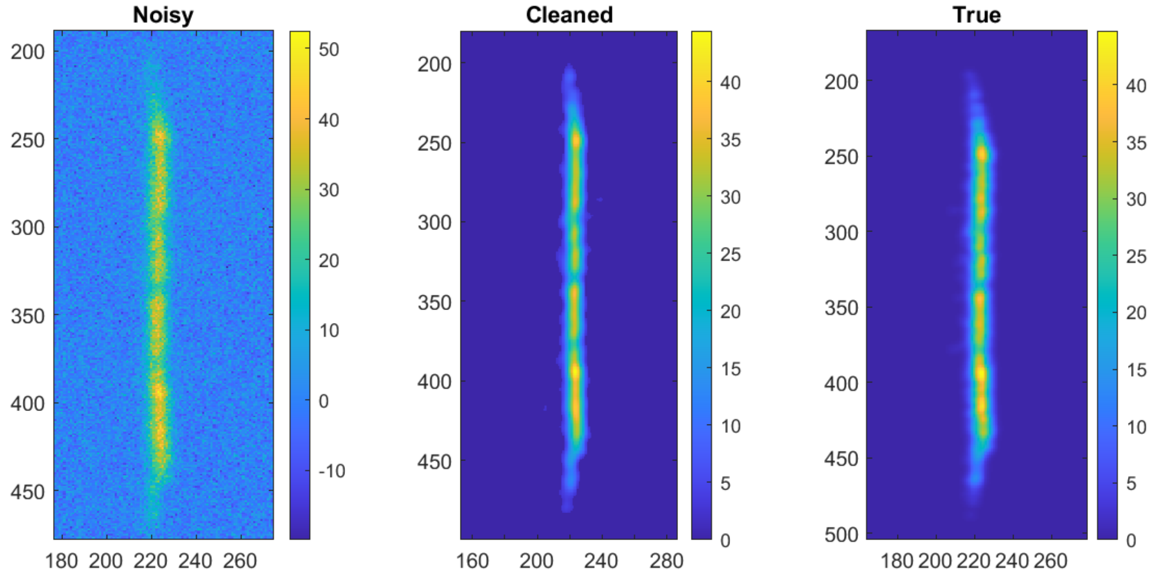
Butterworth filters of different orders



- Parameters: Butterworth filter order, cutoff frequencies in x and y, median filter parameters
- Pros: Globally removes high frequency noise
- Cons: Cause ringing in the real domain

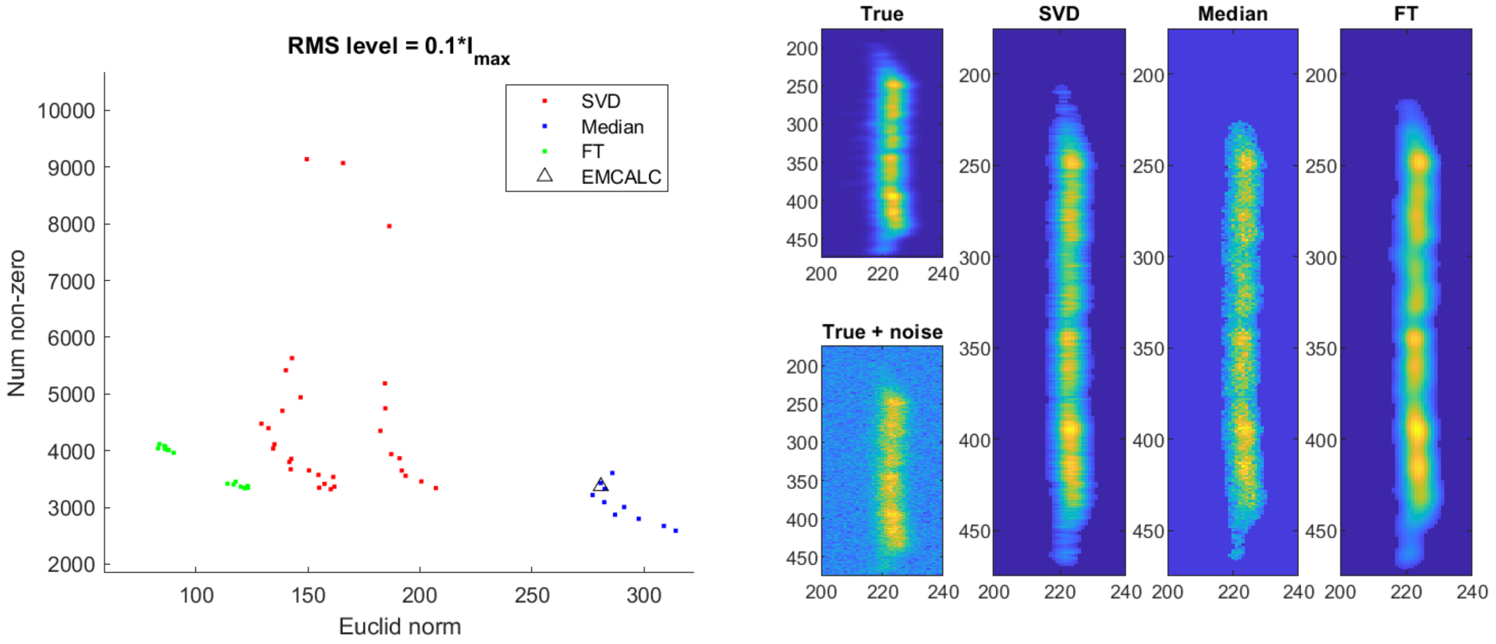


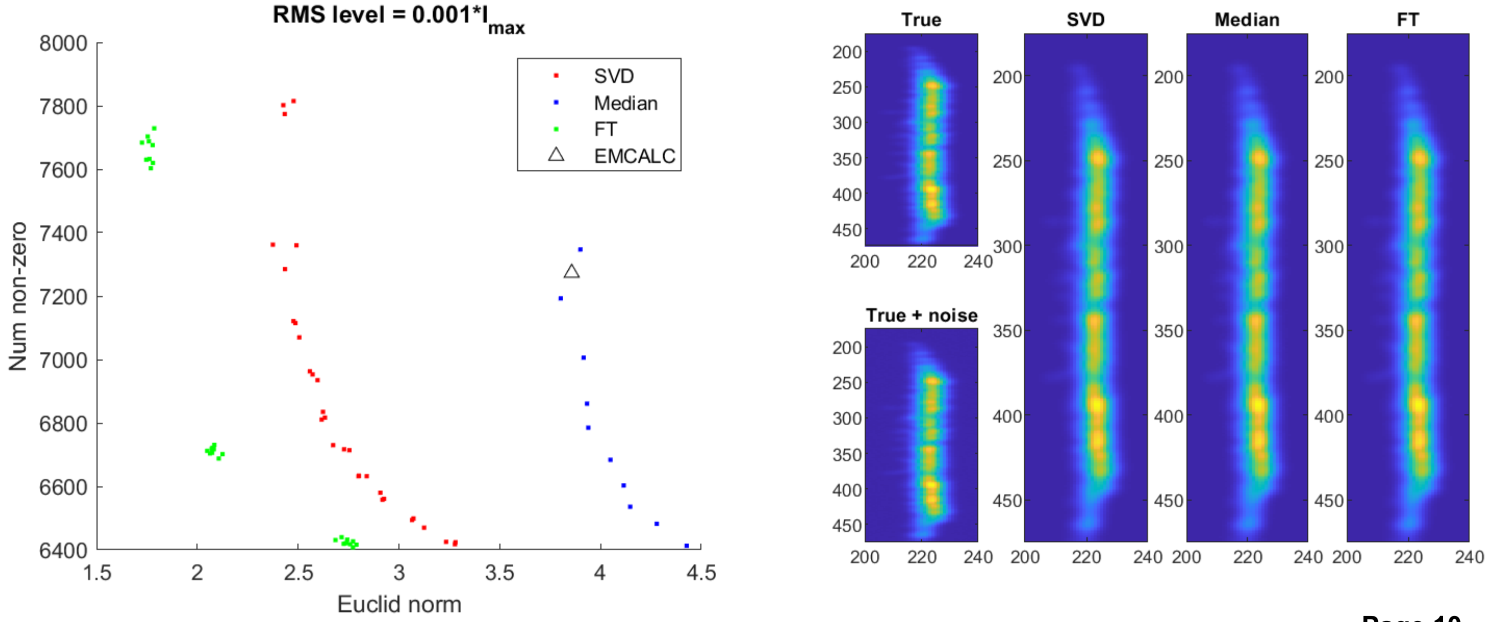
NSR = 1e-1



Filter comparison

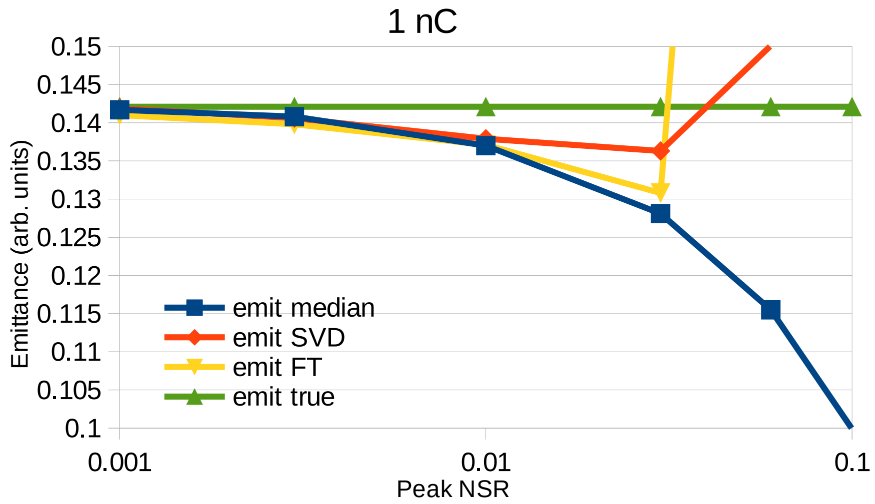
- Median and EMCALC filters are comparable and perform the worst
  - Expected because they both work by selecting the signal region
- SVD filter is second best
  - Therefore, at high NSR it is more important to remove the noise on top of the signal, even at the cost of distorting the signal
- Fourier performs best in all cases
- Differences in performance become less significant at low NSR

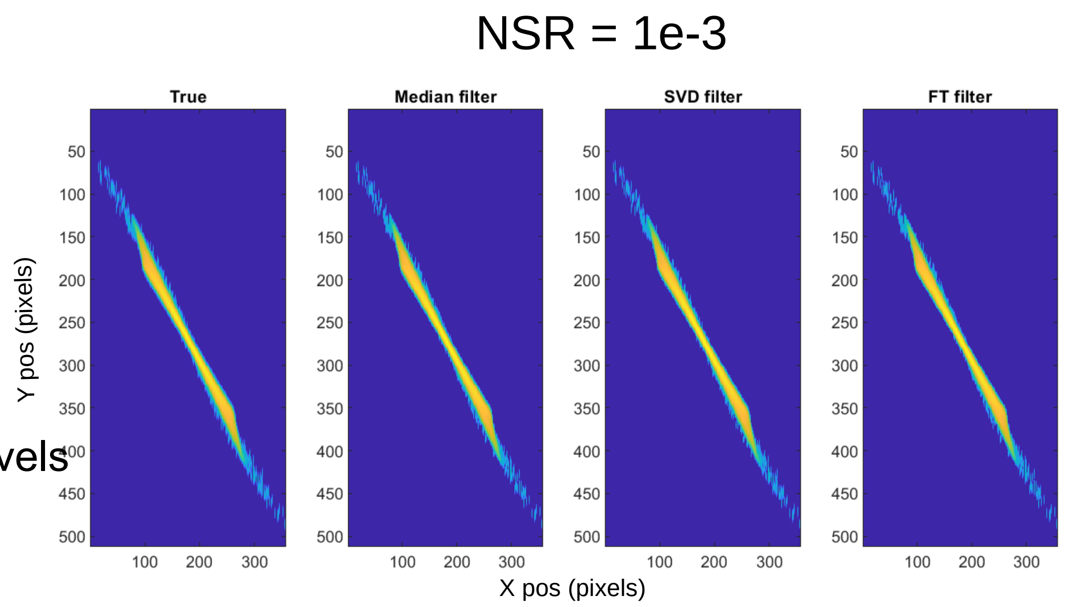


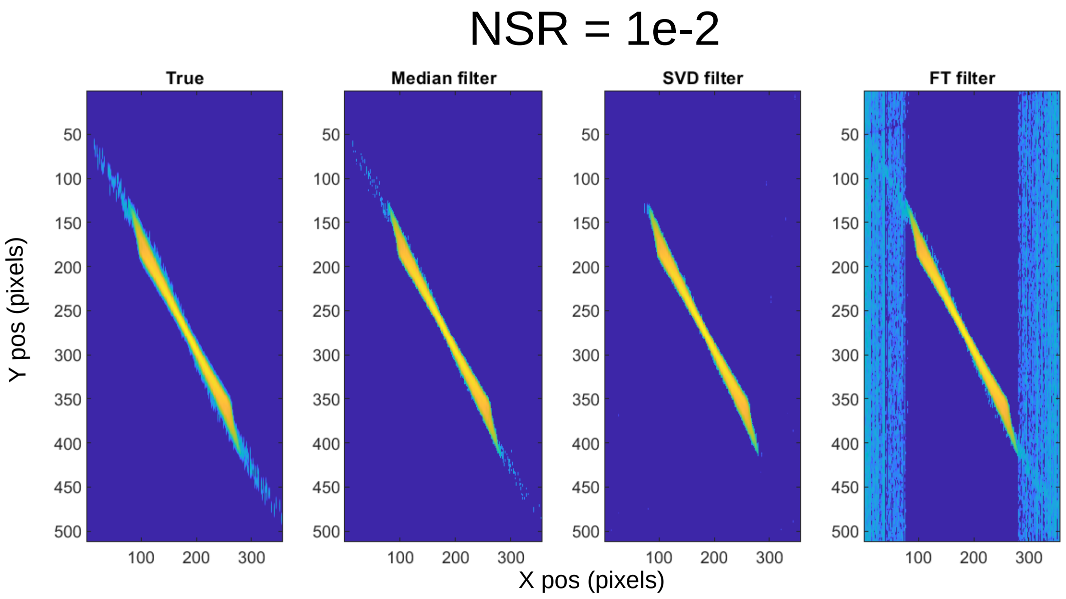


Reconstructed phase-spaces [1]

- Reconstructed the ASTRA phase spaces with added noise
- At low 'peak' NSR, all filters gives emittance close to 100% emittance
- At high NSR, the FT method performs very poorly
  - But, these noise levels doesn't represent typical EMSY noise levels
  - Noise is seeping into the cleaning images, particularly near tails
  - Have the same issue with SVD fitler, but not as significant
- Min(Euclid norm) may not be best choice
  - May be better to cut more pixels to ensure noise removal







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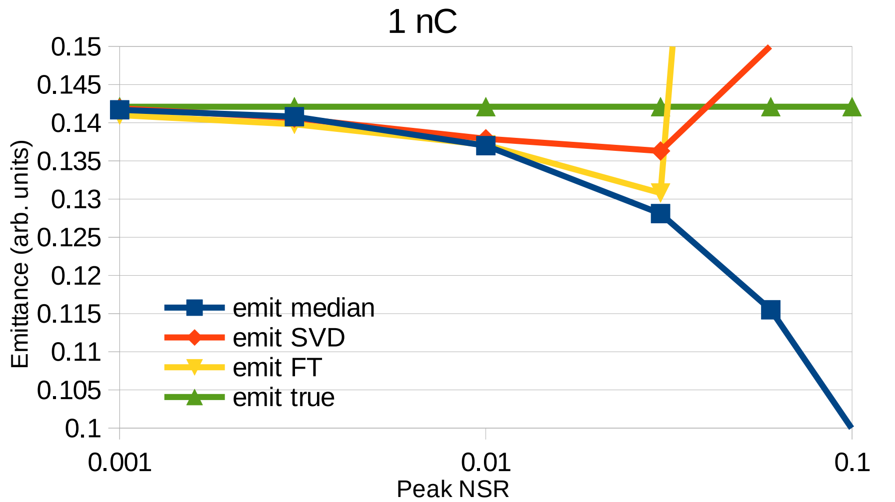
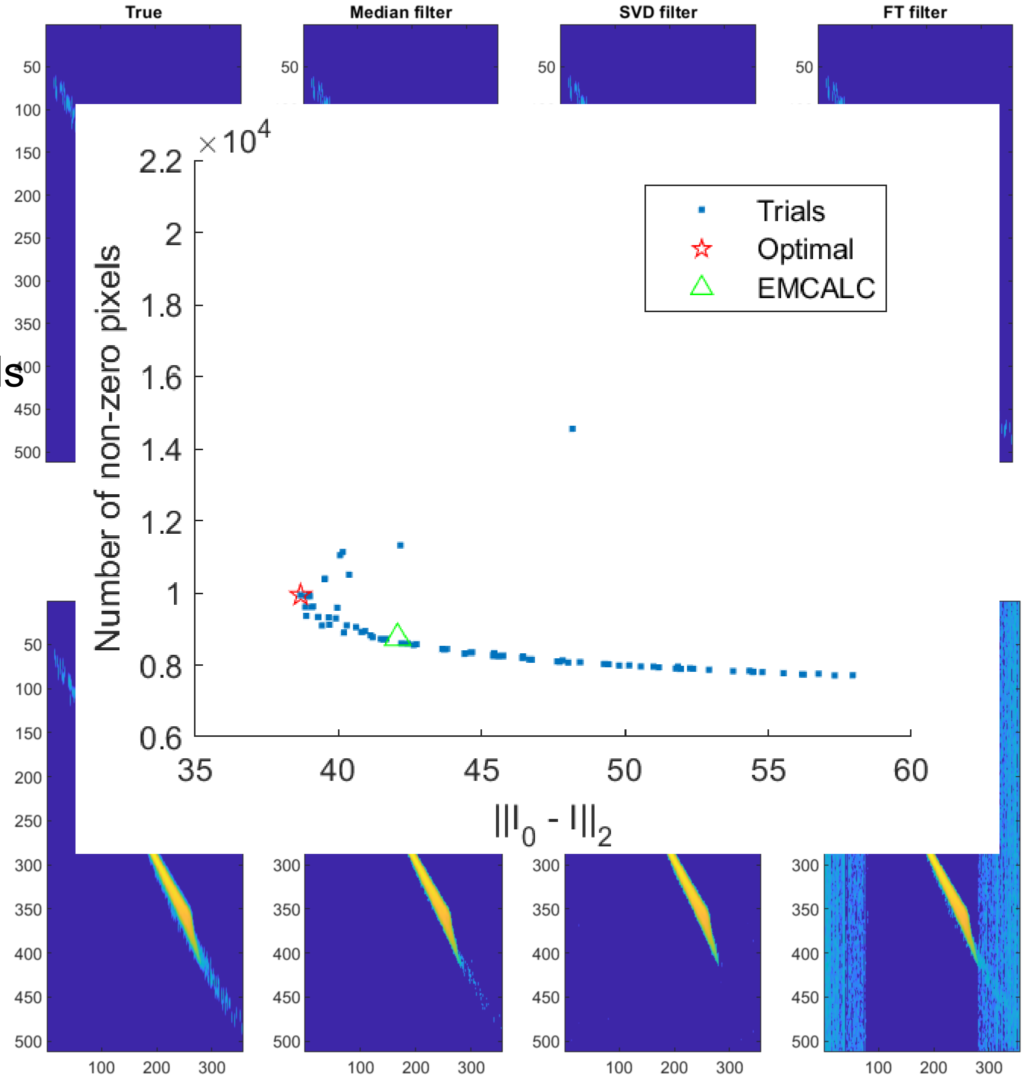


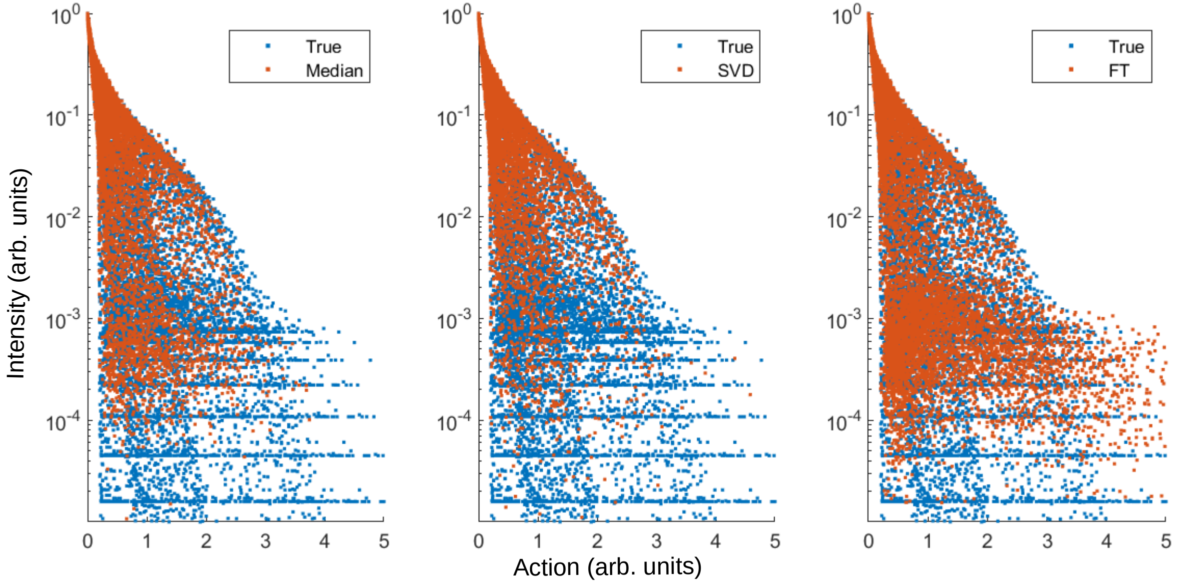
NSR = 1e-3



Reconstructed phase spaces [2]

- Convert all phase spaces into action-phase coordinates.
  - Define action for all images with core Twiss parameters of the true phase space
  - Core Twiss parameters determined from pixels comprising top 50% of the total intensity
  - Calculate mean and std of intensities as a function of action
- In all cases, the FT filter is closest to the true signal. Emittance issue is due to noise
  - Noise issue is only at large actions, need to improve cleaning

NSR = 1e-2



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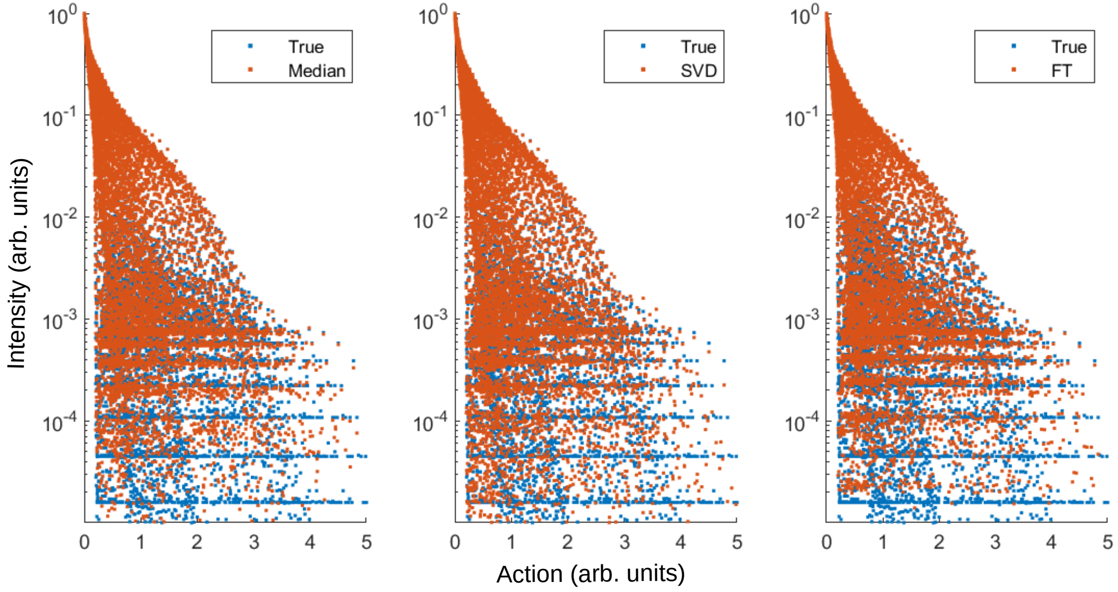

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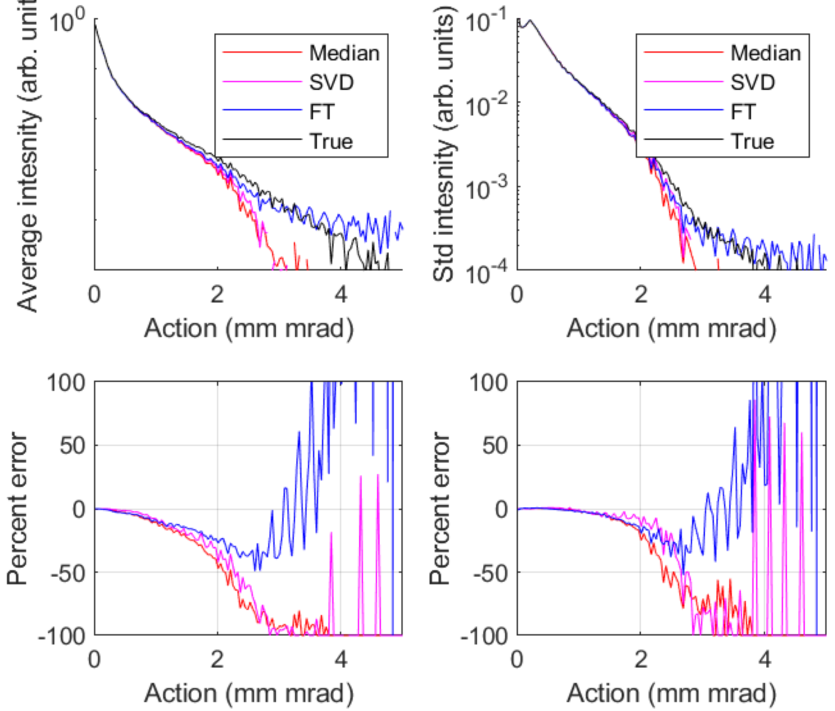
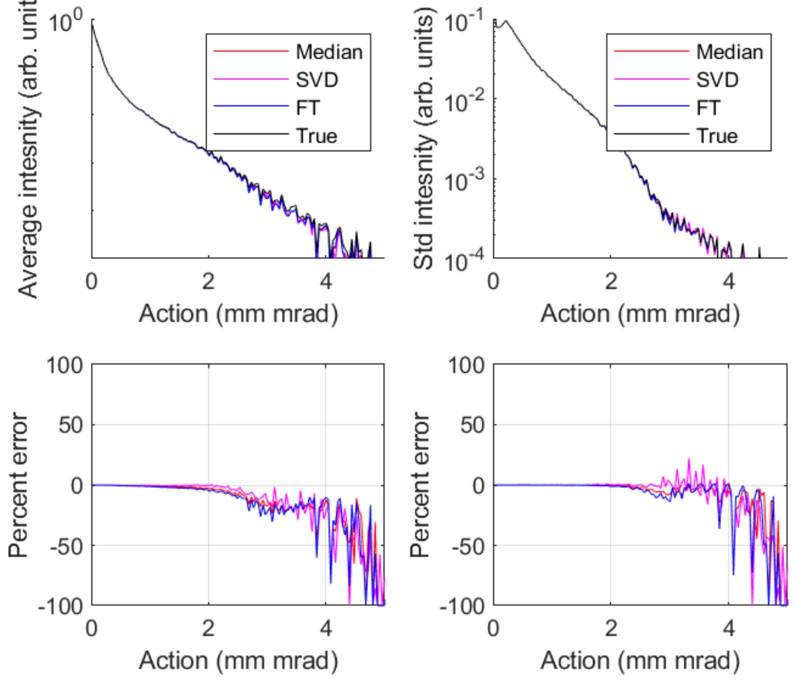


NSR = 1e-3



Summary

- The Fourier transform filter is the best option for noise filtering; the resulting images are the closest to the true images
- However, this filter currently has issues with noise at large actions
- Future studies to improve the noise reduction
  - Chose an optimal solution that has a larger cut
  - Currently, I'm only using one slice from the center of the phase space to determine the optimal filter parameters. It may be better to use slices in the appropriate regions
    - The cut off frequencies may change based on the beamlet shape
  - Develop a method of determining the cutoff frequencies that looks at the noise level and the beamlet signal
  - Use measured EMSY noise levels instead of synthetic noise