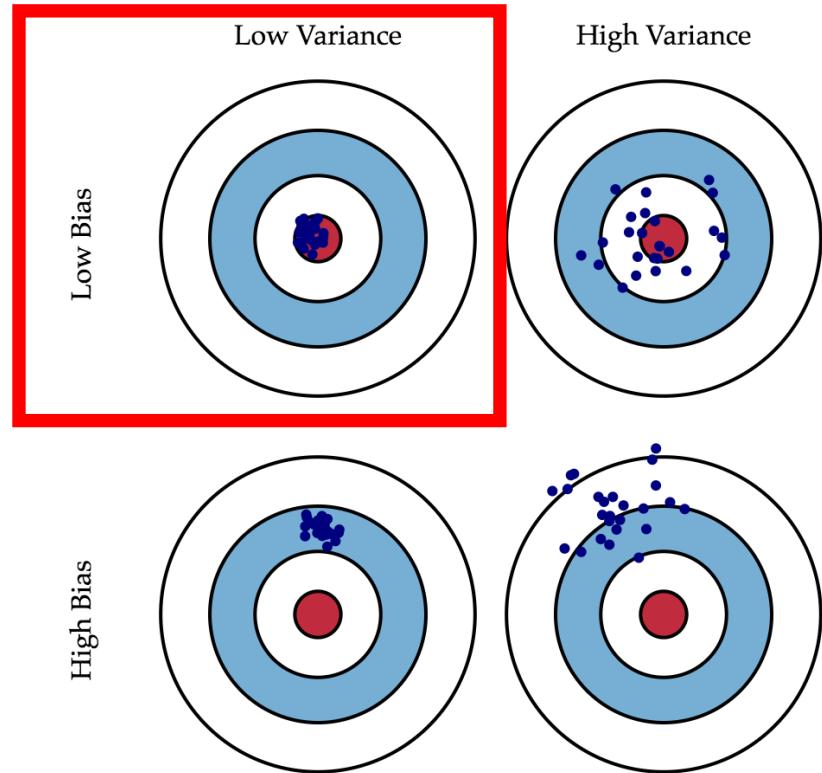


Localization and tracking of fish sounds with a 4-element underwater passive acoustic array

Camille Pagniello and Gerald D'Spain
Scripps Institution of Oceanography
University of California San Diego

Localization

- behavior of animals
- towards abundance estimation
- parameter estimation problem
- metrics of performance:
 - bias: mean of estimated positions minus true position
 - variance: variability in measured position



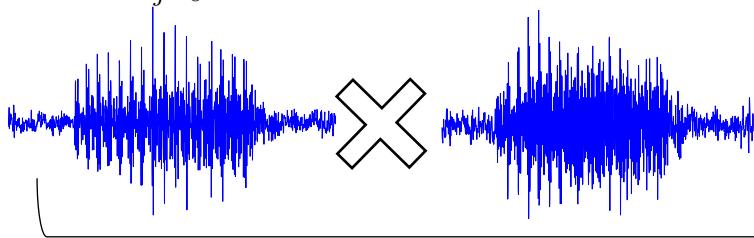
Methods

Time-Domain Beamforming

time difference of arrival (TDOA) of incoming signals

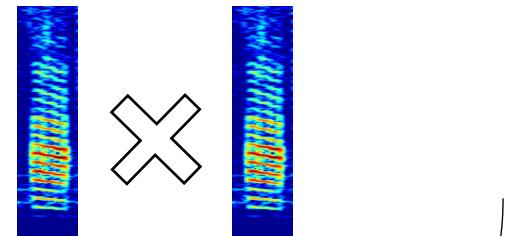
TDOAs from **waveform** cross-correlation

$$C(l) = \sum_{j=0}^{J-1} x(j)y(j-l), \text{ over range of } l$$



TDOAs from **spectrogram** cross-correlation

$$C(k, l) = \sum_{i=0}^{I-1} \sum_{j=0}^{J-1} S_x(i, j)S_y(i - k, j - l), \text{ over range of } k \text{ and } l$$



measured TDOA

$$\Delta t_{nm} = \frac{\|\vec{p}_m - \vec{p}_n\|}{c}$$

modeled TDOA

$$\boxed{\Delta \hat{t}_{nm}(\vec{q}) = \hat{t}_n(\vec{q}) - \hat{t}_m(\vec{q})} \text{ where } \hat{t}_m(\vec{q}) = \frac{\|\vec{q} - \vec{p}_m\|}{c}$$

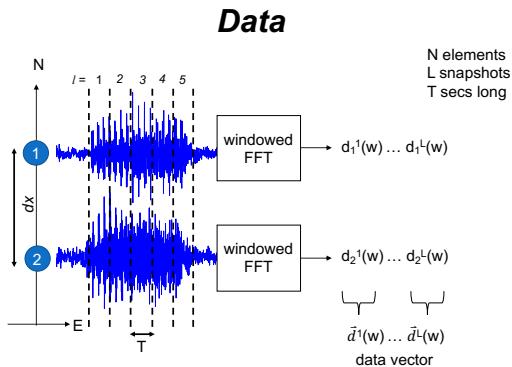
**Maximum Likelihood Estimate
of the True Position**

$$\boxed{LS(\vec{q}) \propto \prod_{n,m} \left\{ \max_k \left(\exp \left[\frac{-1}{2\sigma_{nm}^2} (\Delta t_{nm}(k) - \Delta \hat{t}_{nm}(\vec{q}))^2 \right] \right) \right\}}$$

Methods

Frequency-Domain Beamforming

search in bearing Θ , elevation ϕ and range R
for plane- or curve-wavefront signal



$$K(\omega_i) = \frac{1}{L} \sum_{l=1}^L \vec{d}_l(\omega_i) \vec{d}_l^*(\omega_i)$$

is the cross-spectral density matrix where $\vec{d}(\omega_i)$ is the complex data vector for the i th frequency bin

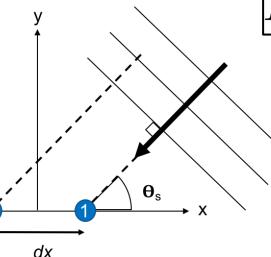
Model

replica vector for **plane-wavefront**

$$\vec{r}_m(\omega, \theta, \phi) = \exp \left(i \frac{2\pi f}{c} \vec{p}_m \cdot \vec{q} \right)$$

where the source position vector is

$$\vec{q}(\theta_s, \phi_s) = \begin{bmatrix} \cos(\theta_s) \cos(\phi_s) \\ \sin(\theta_s) \cos(\phi_s) \\ \sin(\phi_s) \end{bmatrix}$$



Beamformer

$$B_{\text{Bartlett}}(\omega) = \vec{r}^* K(\omega) \vec{r}$$

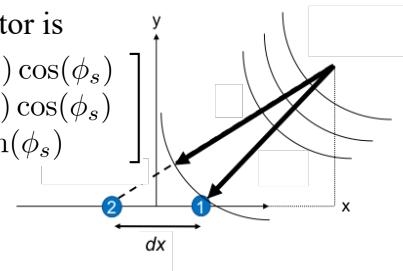
linear (Bartlett) beamformer output magnitude squared

replica vector for **curved-wavefront**

$$\vec{r}_m(\omega, \theta, \phi, R) = \frac{1}{\|\vec{q} - \vec{p}_m\|} \exp \left(i \frac{2\pi f}{c} \|\vec{q} - \vec{p}_m\| \right)$$

where the source position vector is

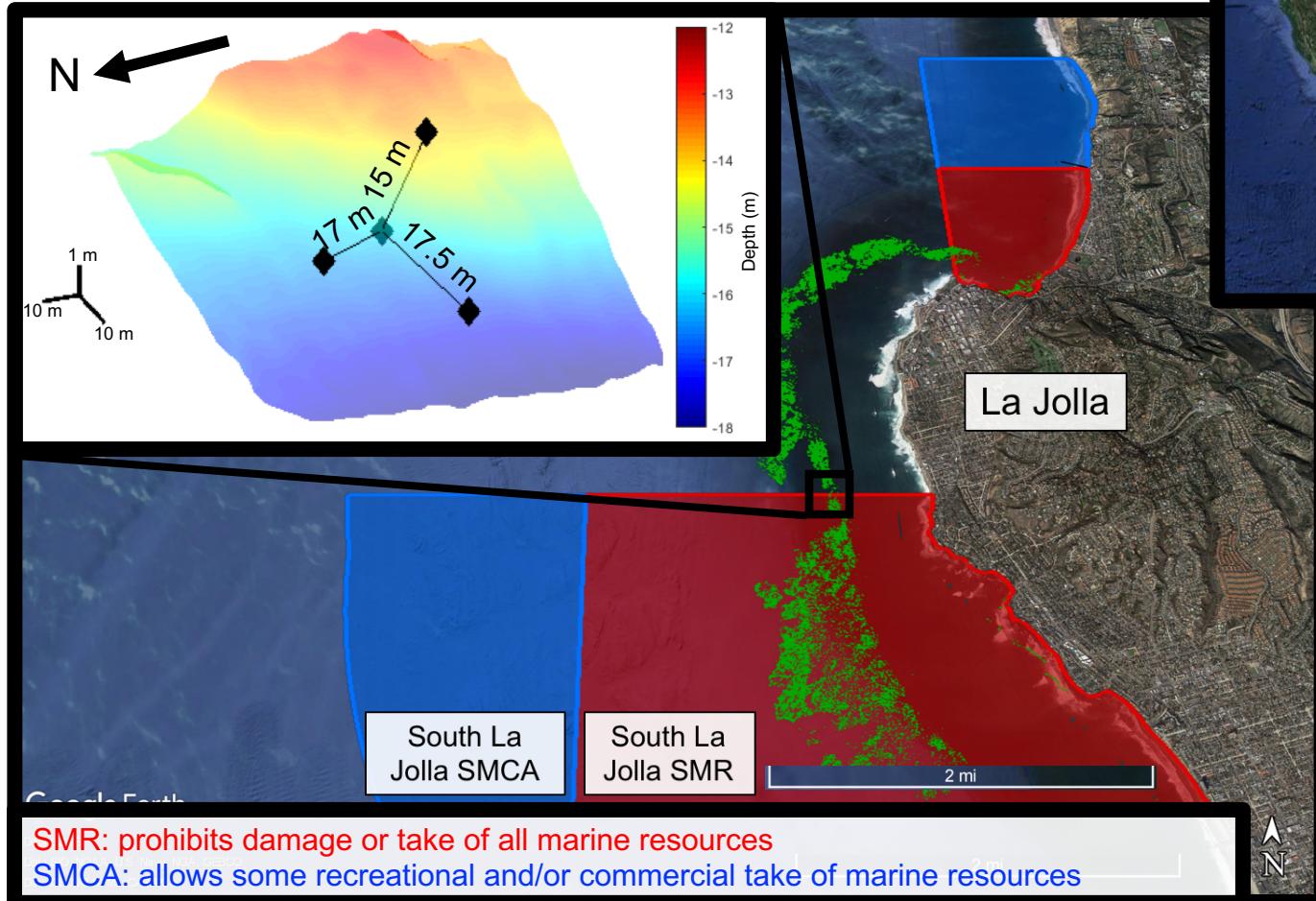
$$\vec{q}(\theta_s, \phi_s, R_s) = \begin{bmatrix} R_s \cos(\theta_s) \cos(\phi_s) \\ R_s \sin(\theta_s) \cos(\phi_s) \\ R_s \sin(\phi_s) \end{bmatrix}$$



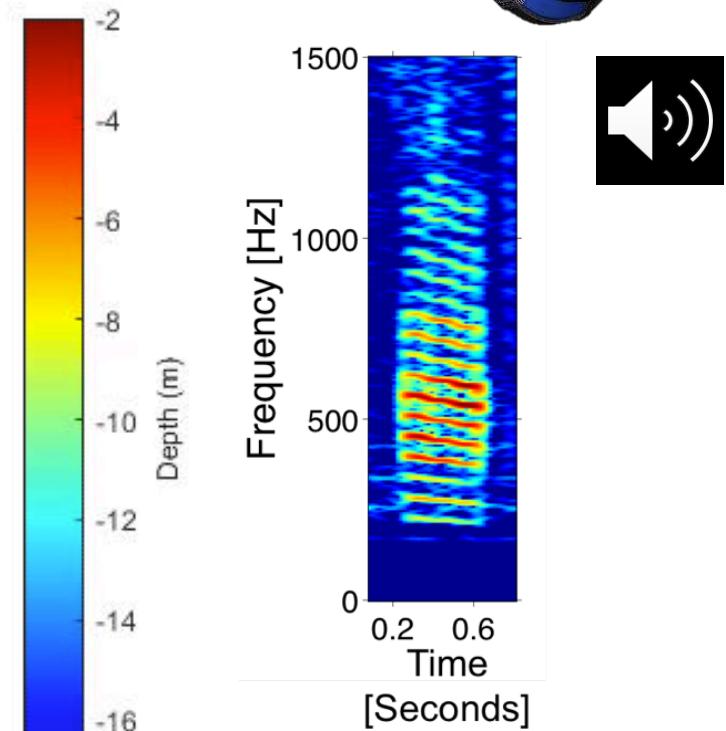
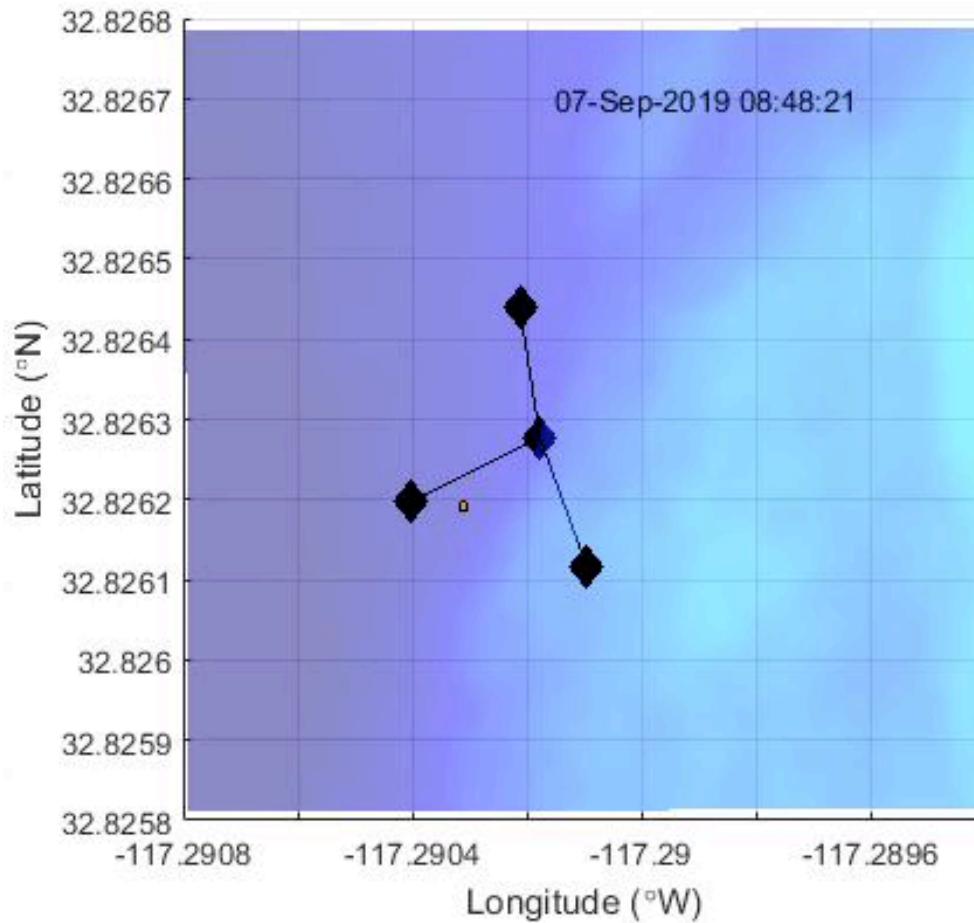
Objective

- **quantitatively compare the performance of four methods:**
 - 1) TDOAs using waveform cross-correlation
 - 2) TDOAs using spectrogram cross-correlation
 - 3) curved-wavefront frequency-domain beamforming
 - 4) plane-wavefront frequency-domain beamforming
- determine the most effective localization approach, given the present array geometry and environment, to estimate the positions and track (hopefully) individual soniferous fish to better understand their small-scale spawning movements and reproductive behavior

Experimental Setup



Experimental Setup



Source Level:

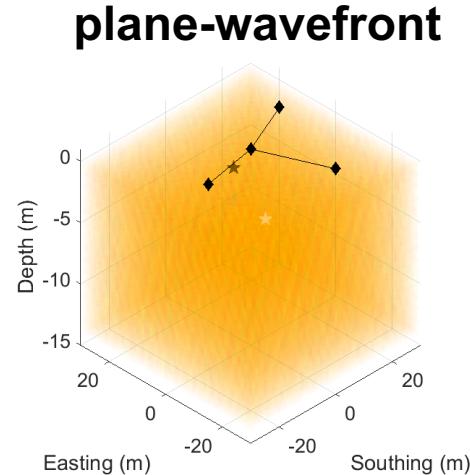
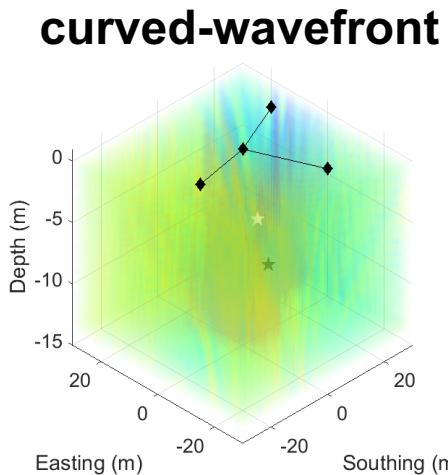
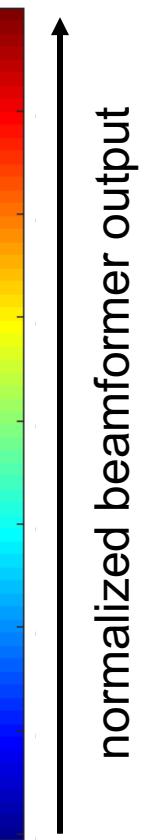
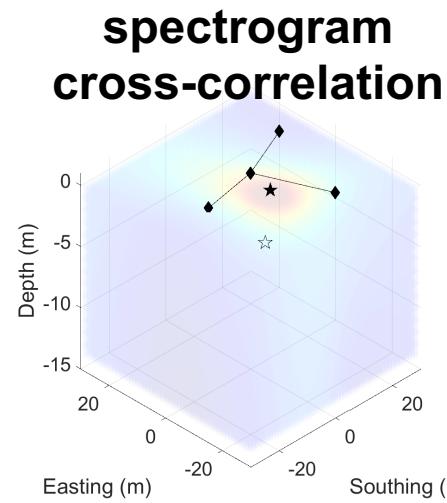
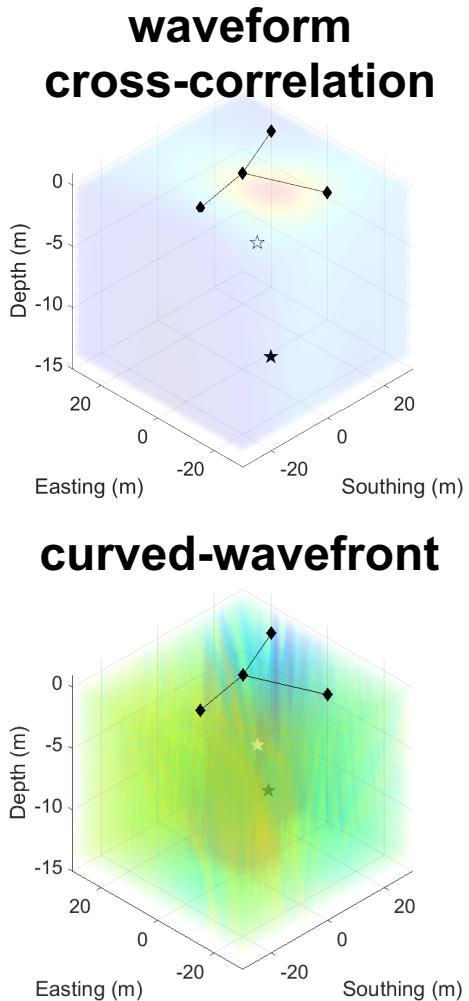
- 155.7 dB re 1 μ Pa RMS
- 174.4 dB re 1 μ Pa peak-to-peak
- 168.4 dB re 1 μ Pa 0-to-peak

Ambiguity Surfaces

★ GPS- and Ambient Pressure-derived “true” position

★ localization-derived estimated position

frequency-domain
time-domain
beamforming



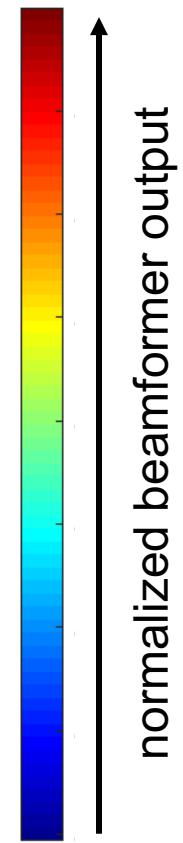
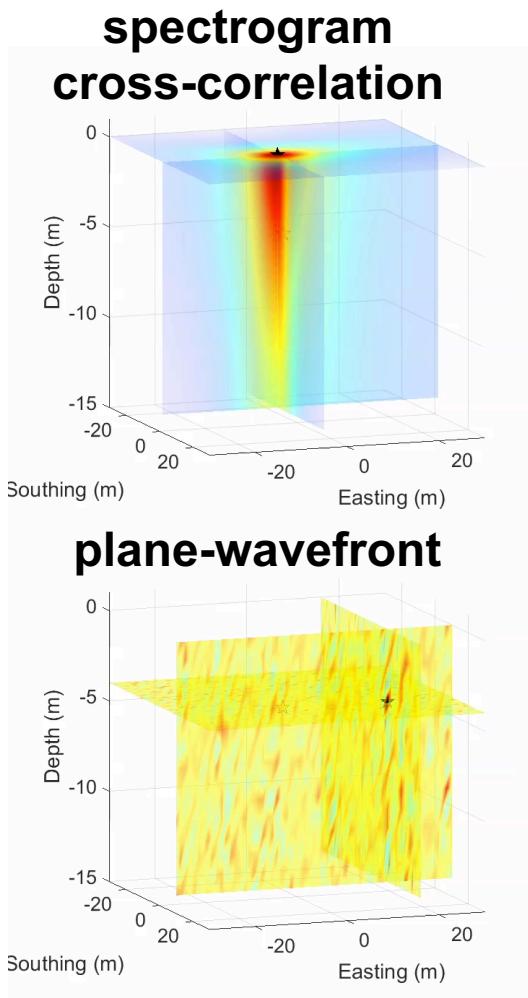
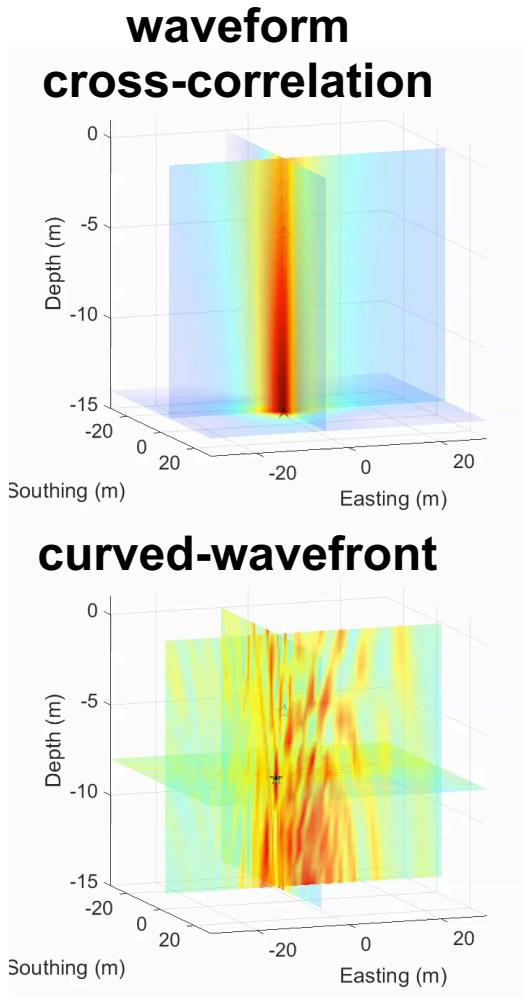
frequency-domain beamforming

time-domain beamforming

Ambiguity Surfaces

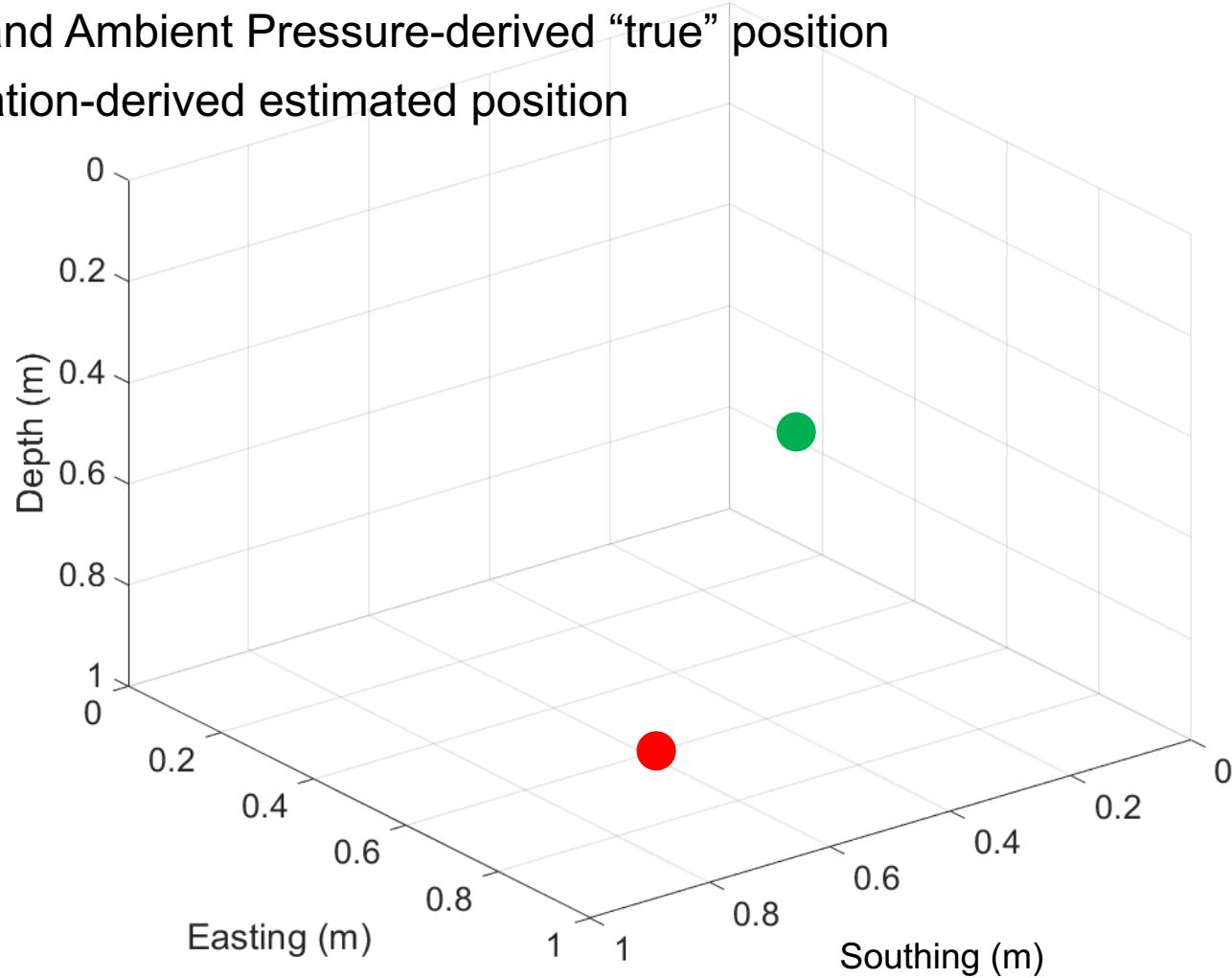
★ GPS- and Ambient Pressure-derived “true” position

★ localization-derived estimated position



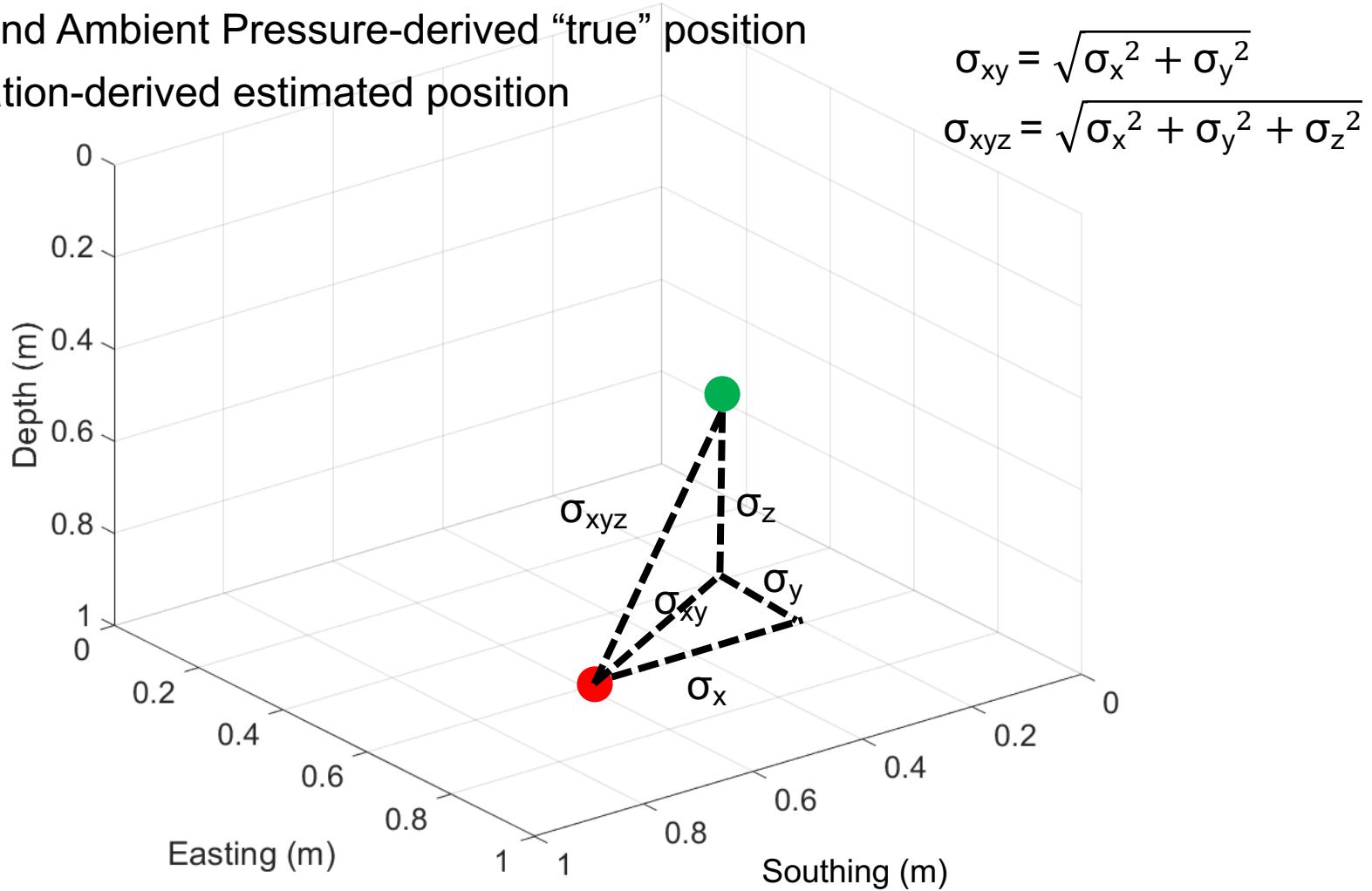
Performance Metrics

- GPS- and Ambient Pressure-derived “true” position
- localization-derived estimated position



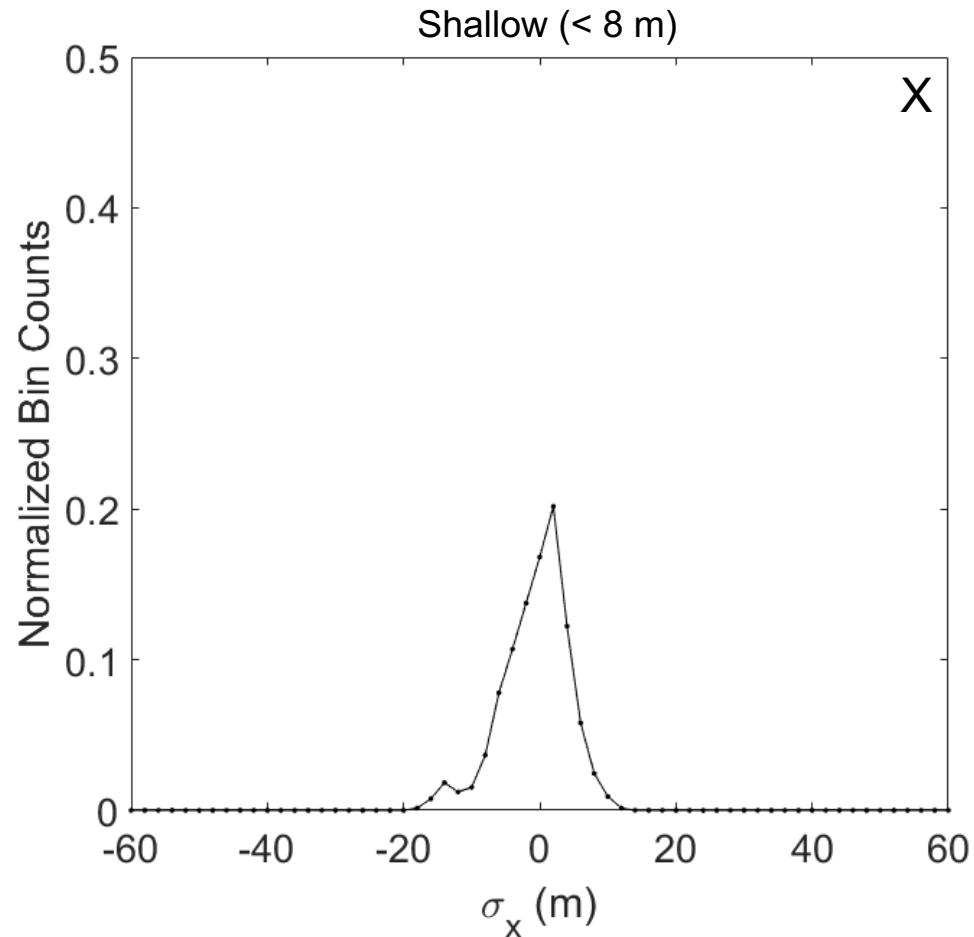
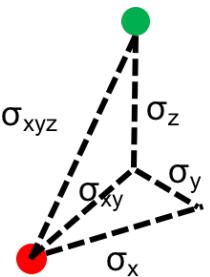
Performance Metrics

- GPS- and Ambient Pressure-derived “true” position
- localization-derived estimated position



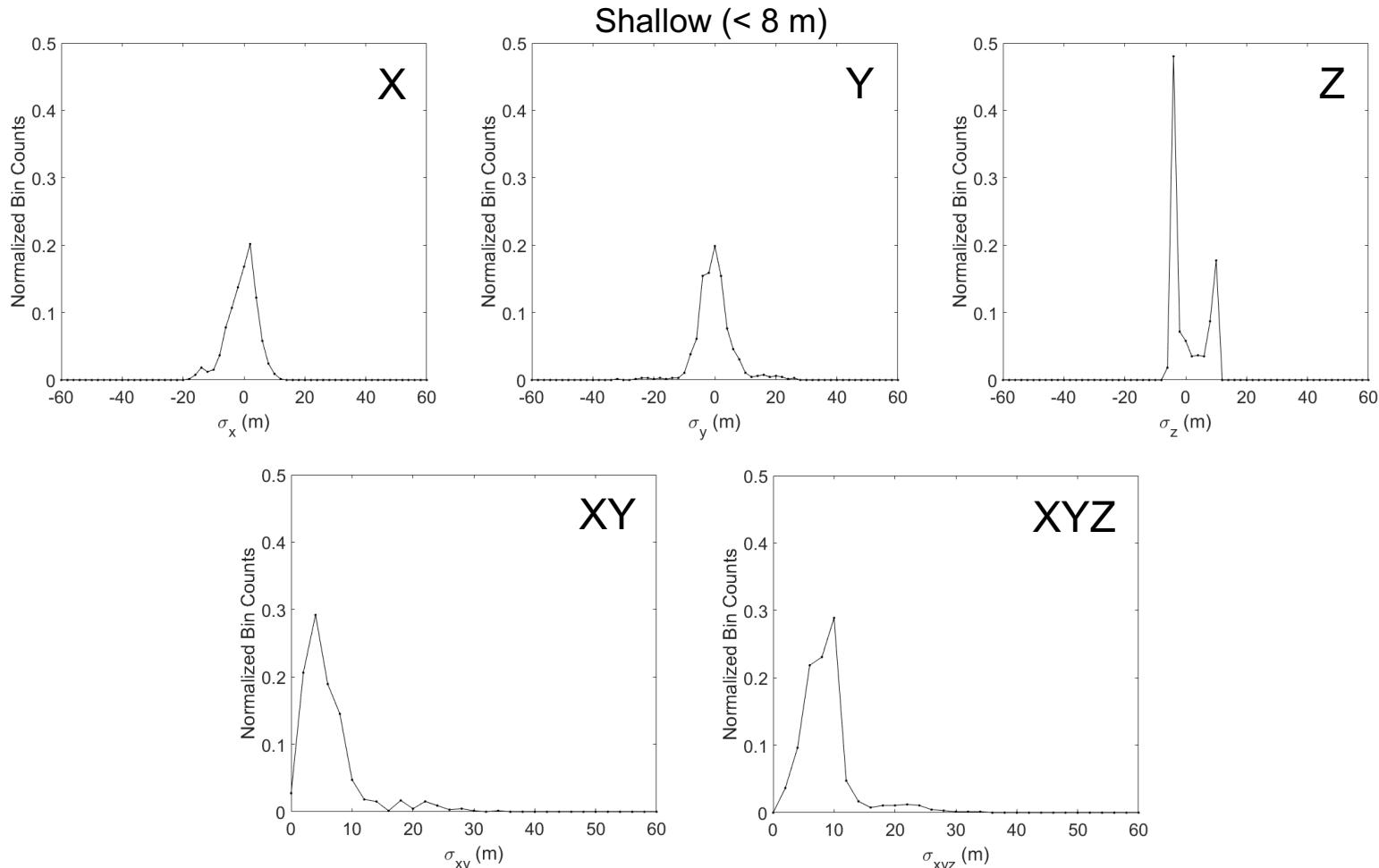
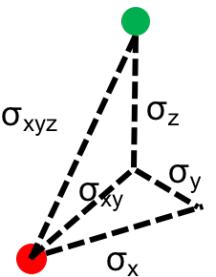
Error Distributions

Method: TDOAs using waveform cross-correlation (no interpolation)



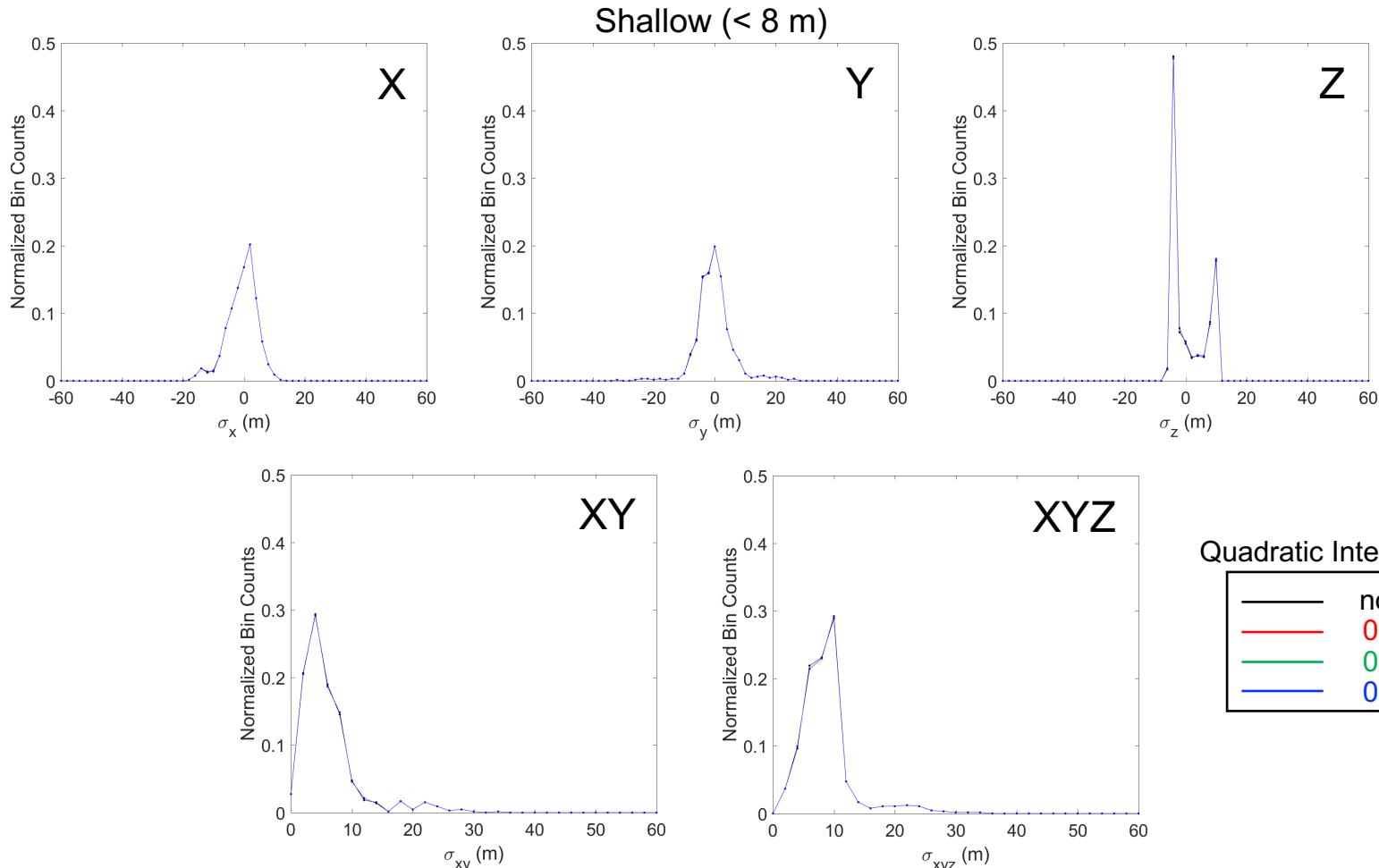
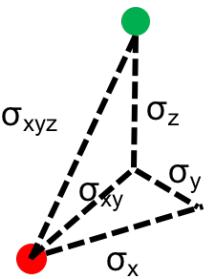
Error Distributions

Method: TDOAs using waveform cross-correlation (no interpolation)



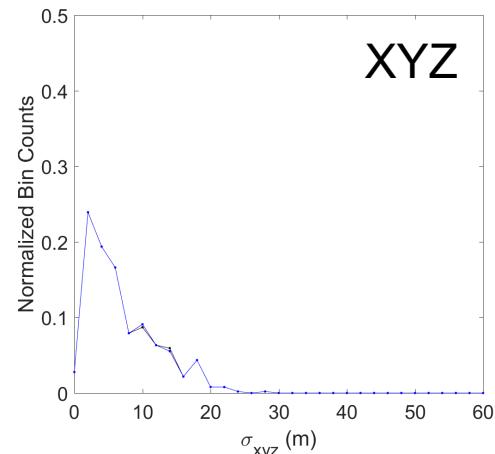
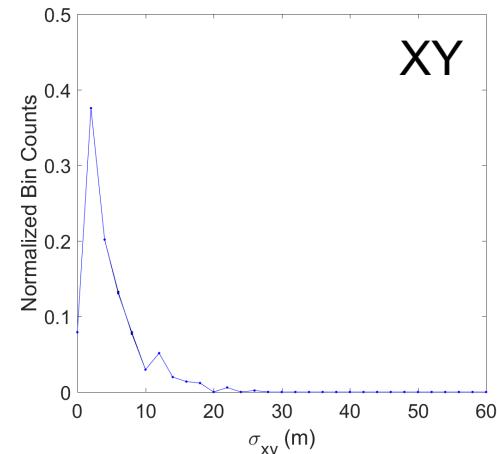
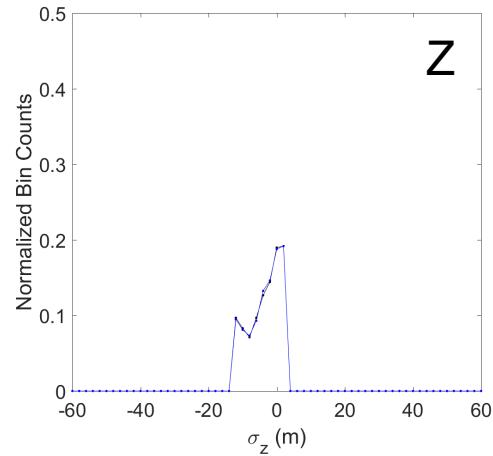
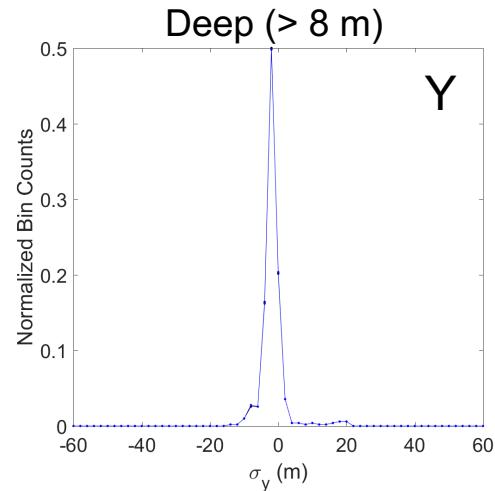
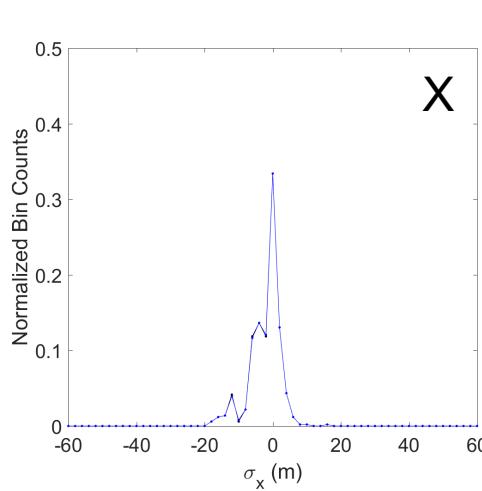
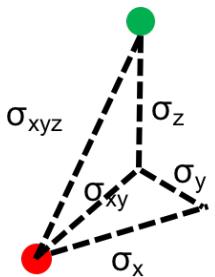
Parameter Selection

Method: TDOAs using waveform cross-correlation



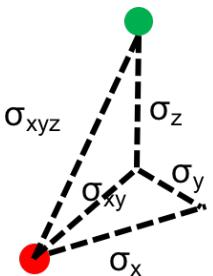
Parameter Selection

Method: TDOAs using waveform cross-correlation



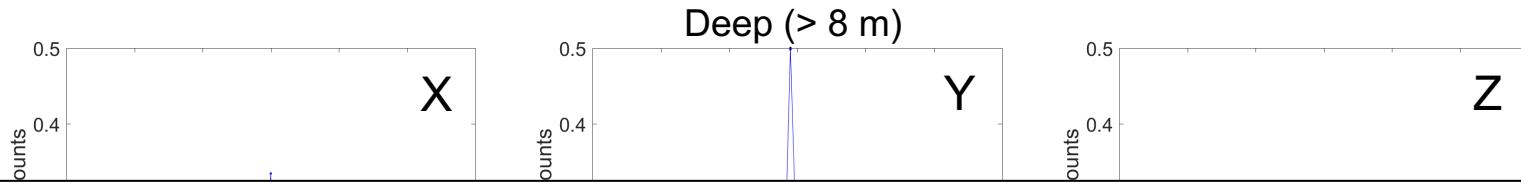
Quadratic Interpolation

| | |
|---|-------|
| — | none |
| — | 0.1 |
| — | 0.01 |
| — | 0.001 |

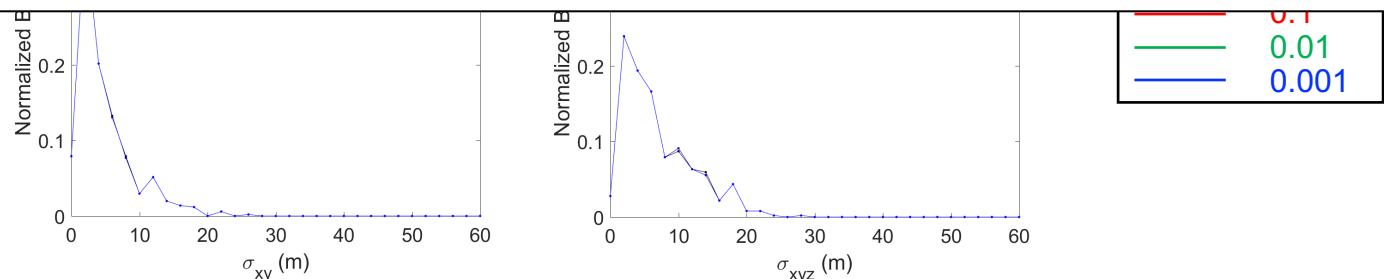


Parameter Selection

Method: TDOAs using waveform cross-correlation

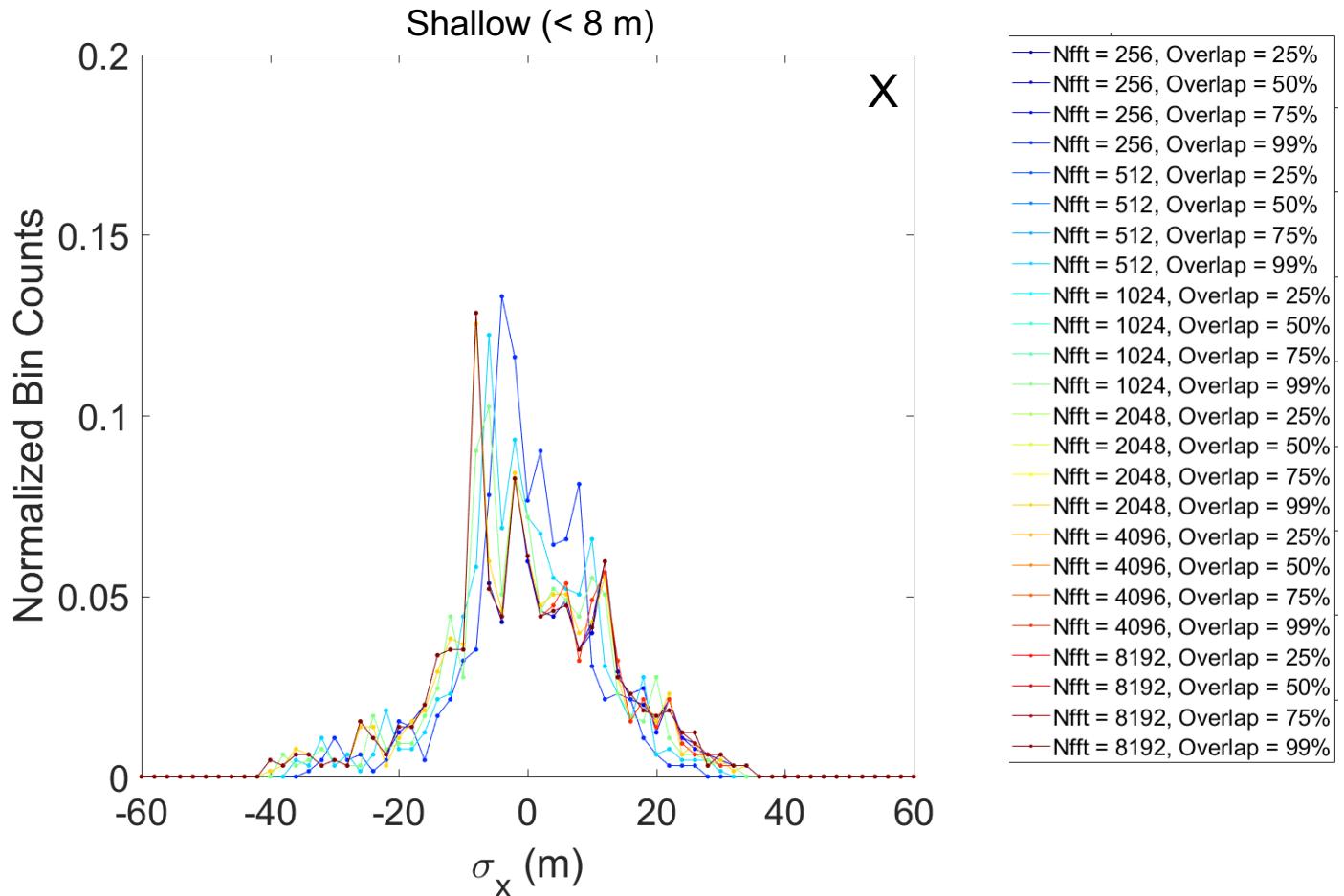
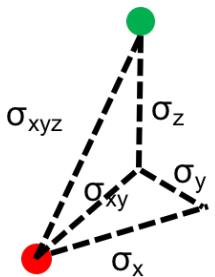


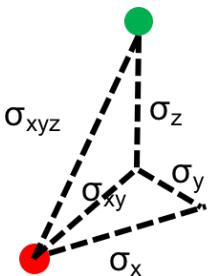
for TDOAs using waveform cross-correlation:
quadratic interpolation of the cross-correlation output has zero effect on localization performance for both shallow and deep sources



Parameter Selection

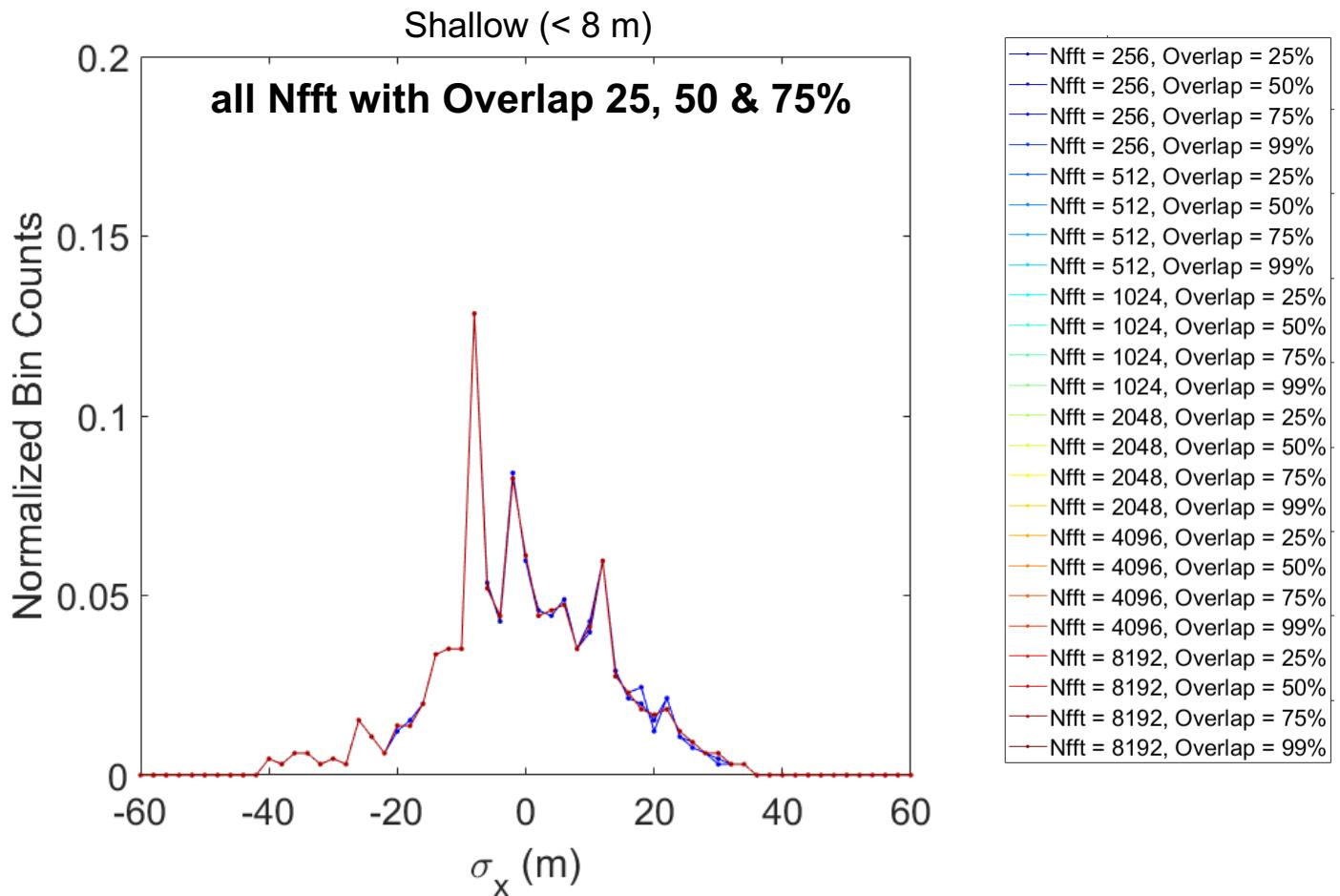
Method: TDOAs using spectrogram cross-correlation





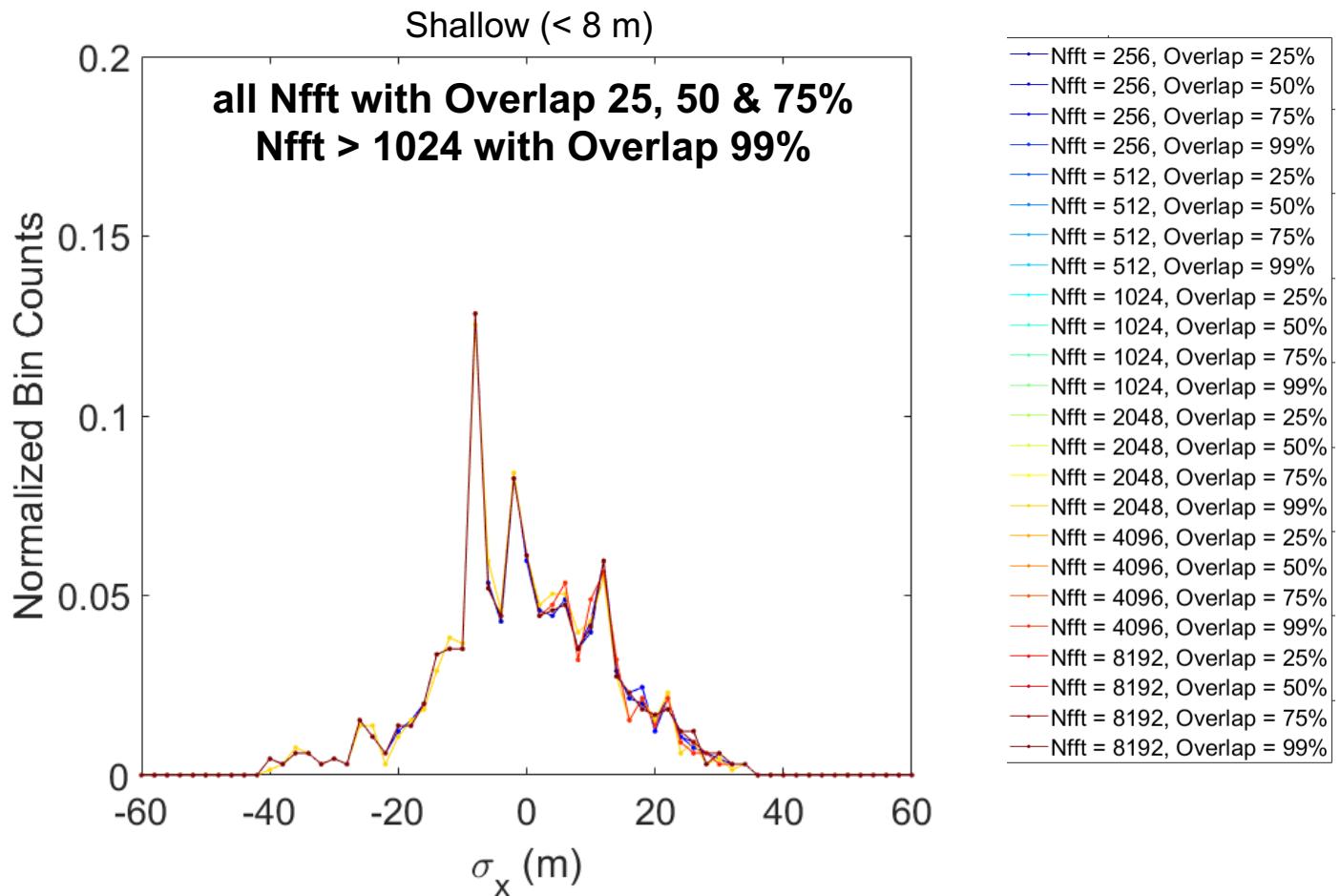
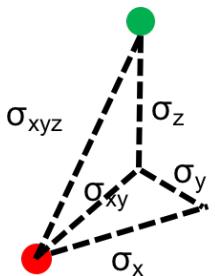
Parameter Selection

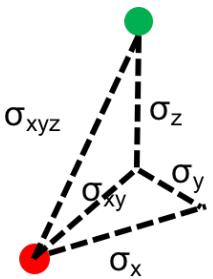
Method: TDOAs using spectrogram cross-correlation



Parameter Selection

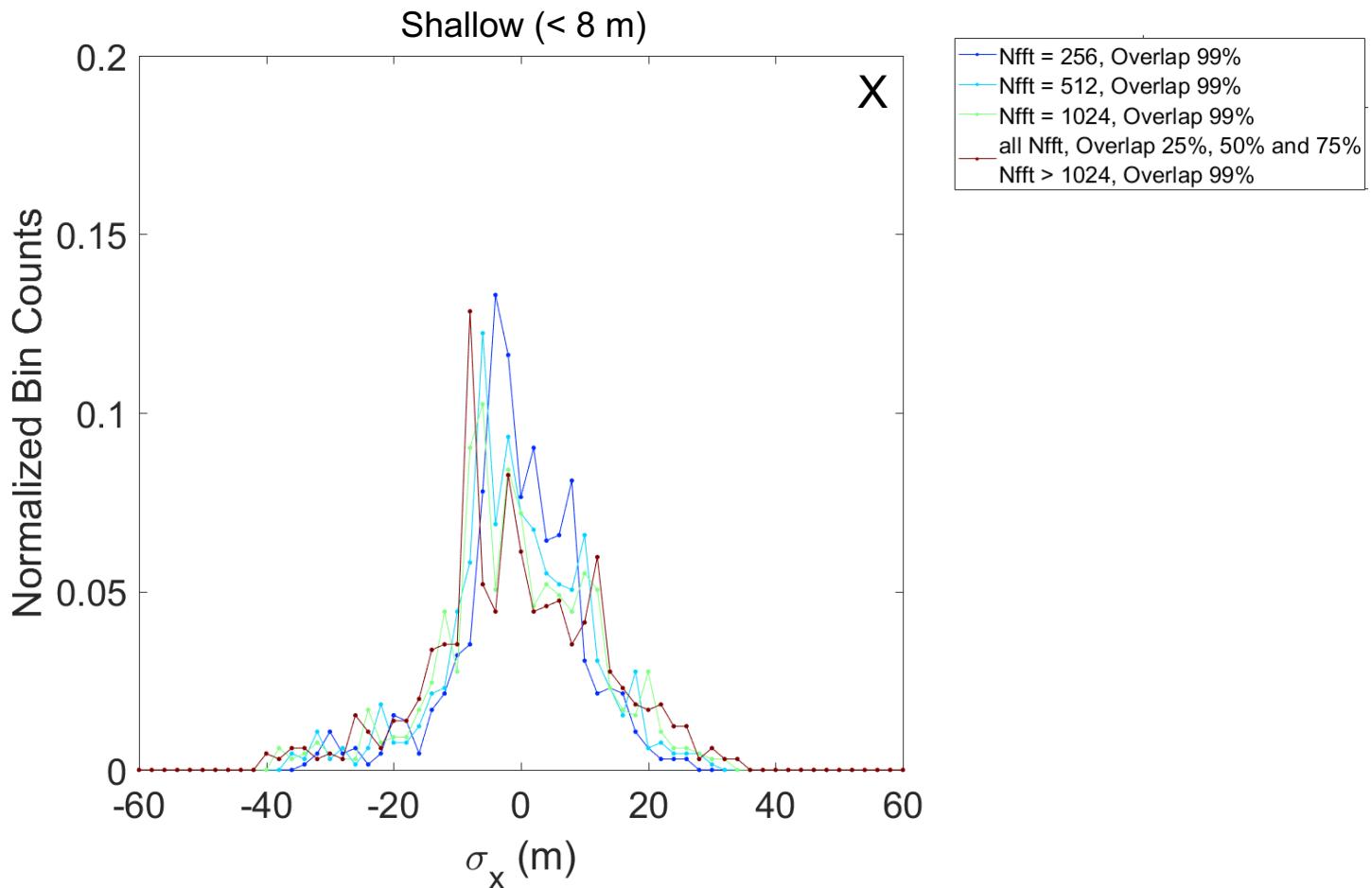
Method: TDOAs using spectrogram cross-correlation





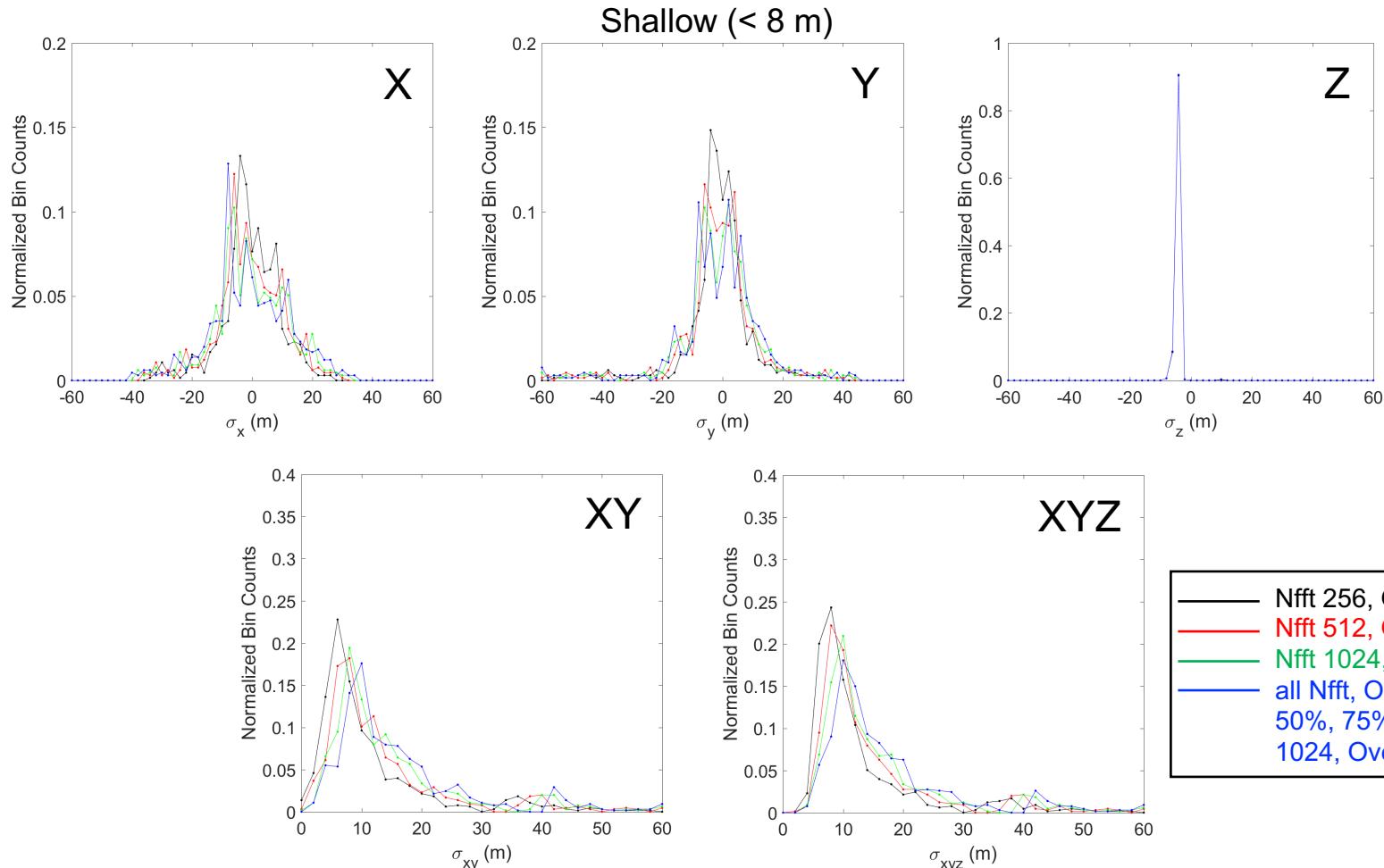
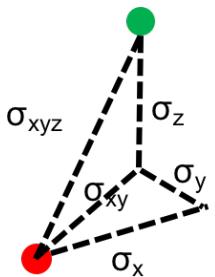
Parameter Selection

Method: TDOAs using spectrogram cross-correlation



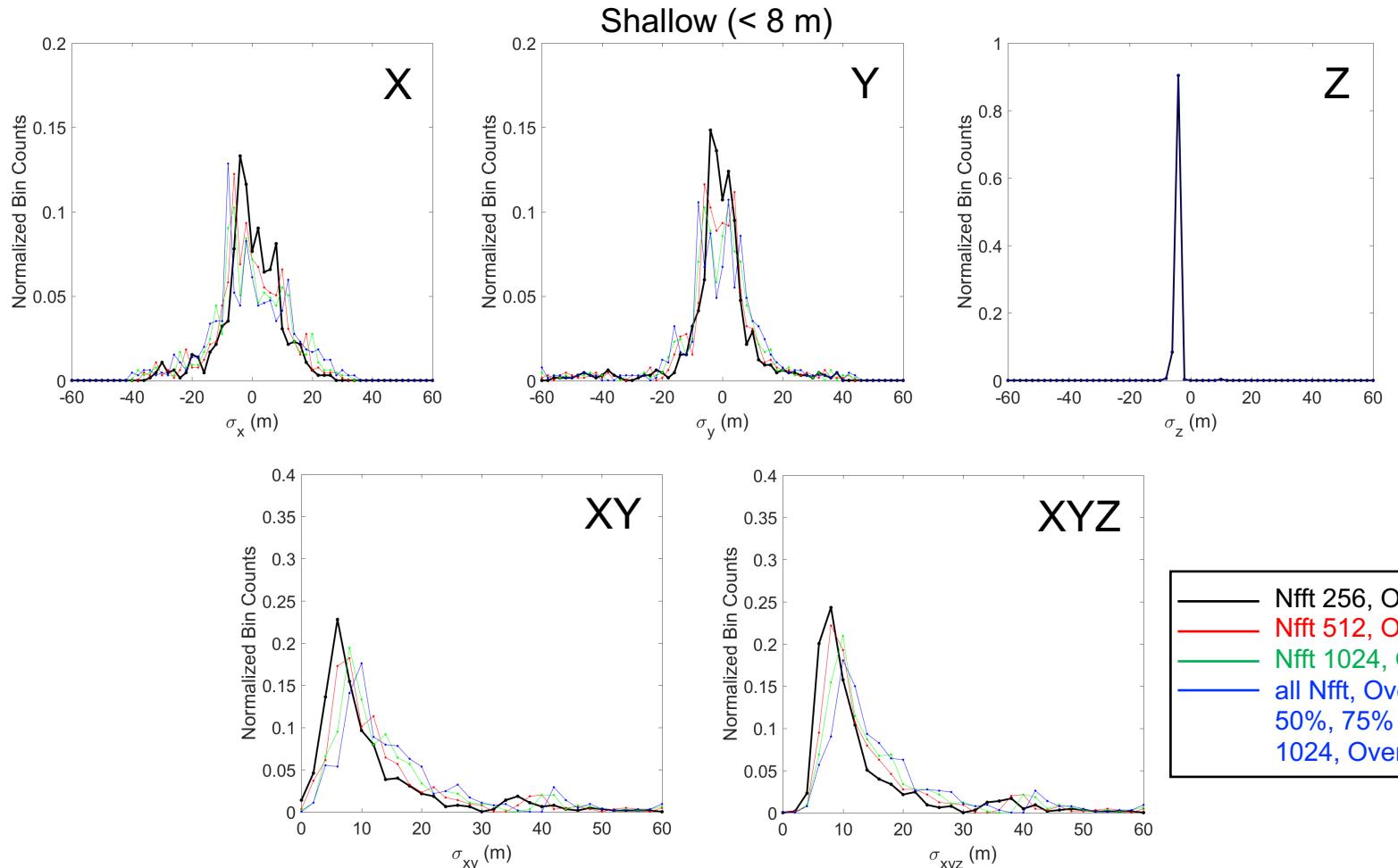
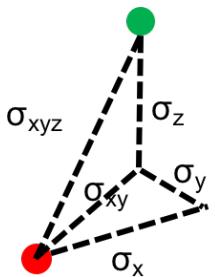
Parameter Selection

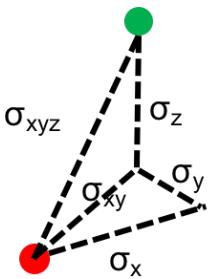
Method: TDOAs using spectrogram cross-correlation



Parameter Selection

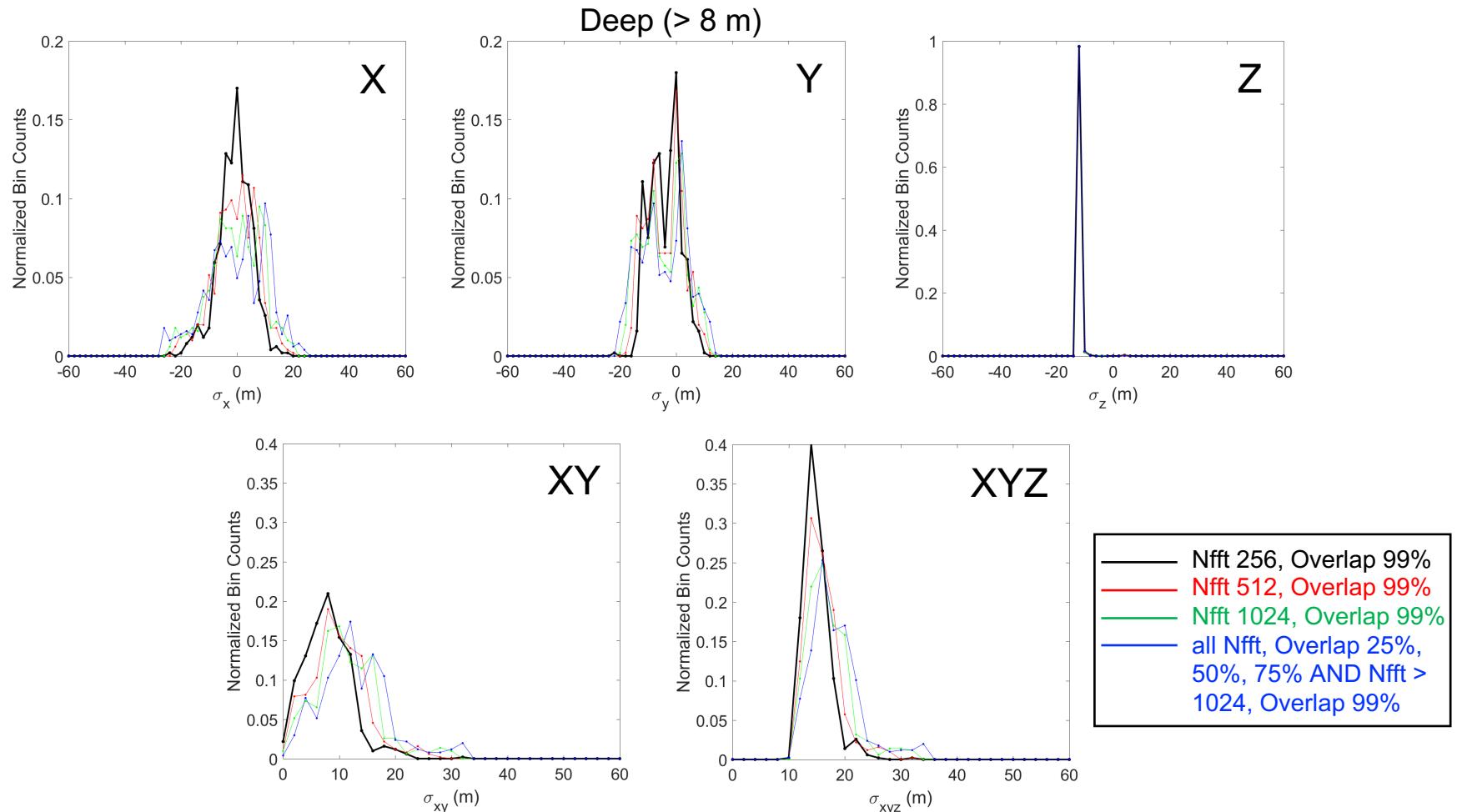
Method: TDOAs using spectrogram cross-correlation

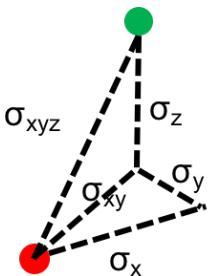




Parameter Selection

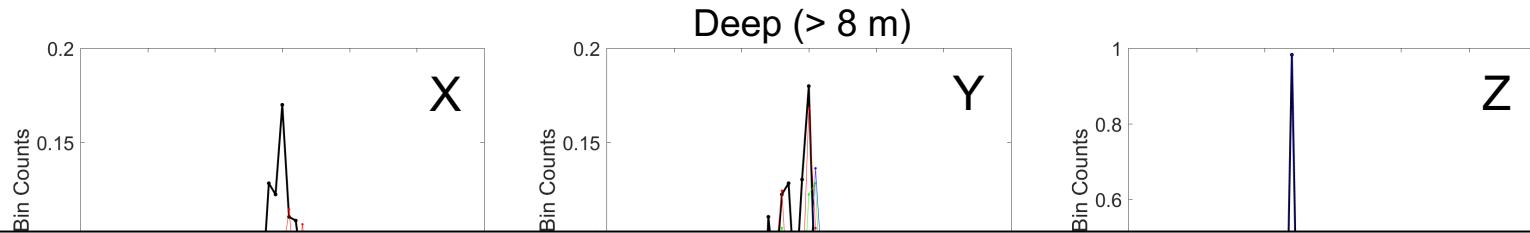
Method: TDOAs using spectrogram cross-correlation



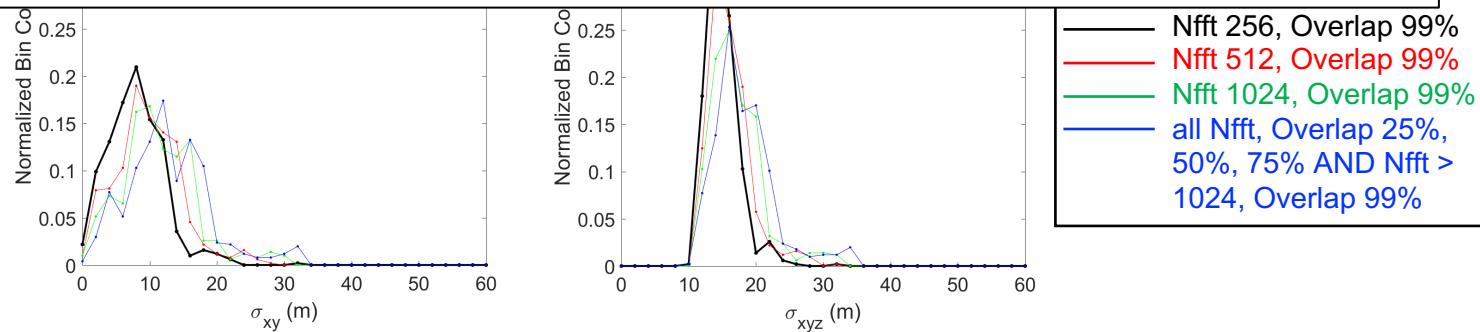


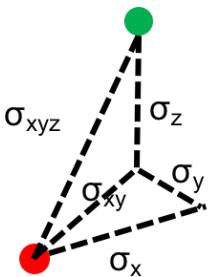
Parameter Selection

Method: TDOAs using spectrogram cross-correlation



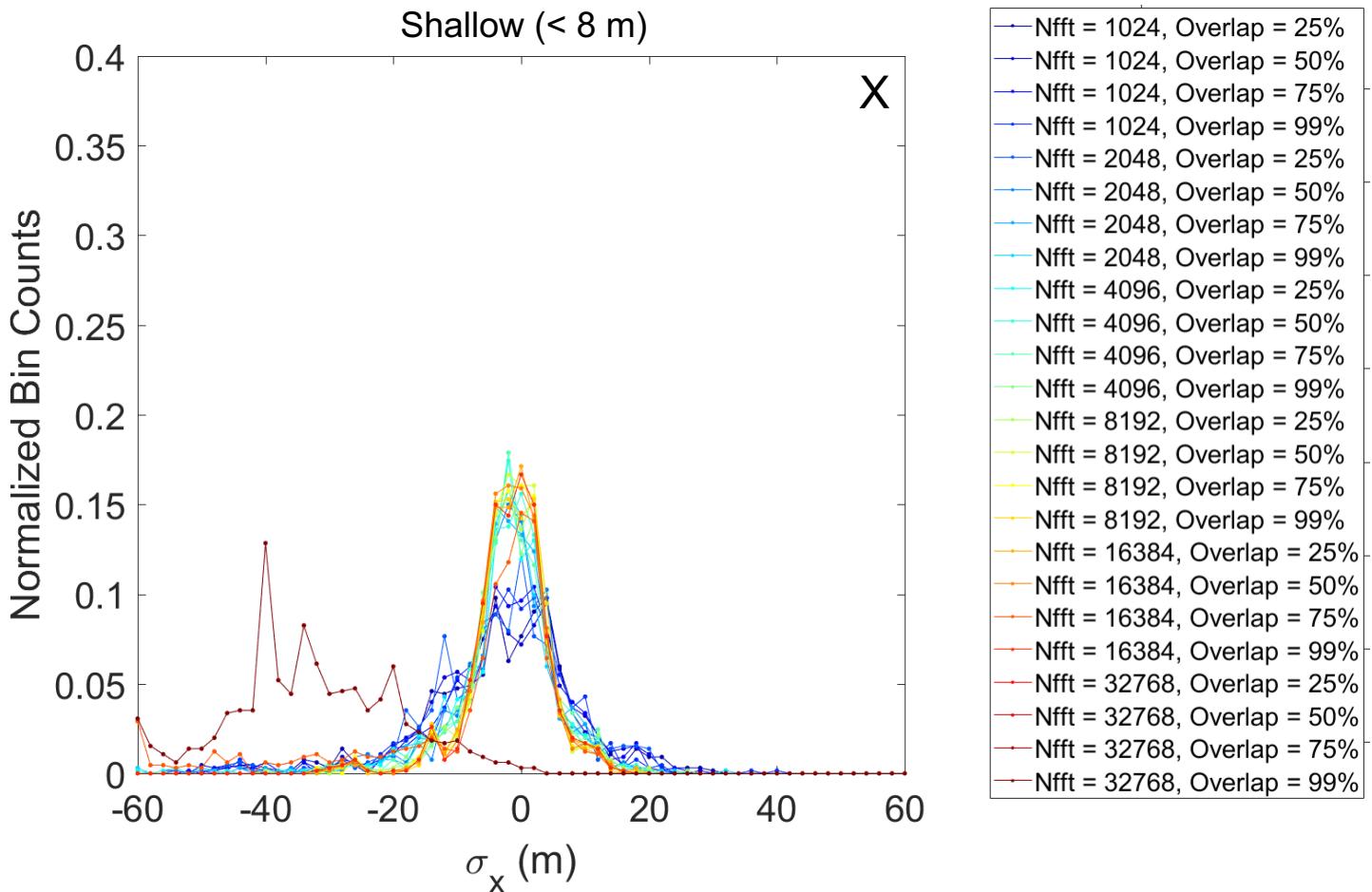
for TDOAs using spectrogram cross-correlation:
Nfft 256, Overlap 99%
minimizes localization error
for both shallow and deep sources





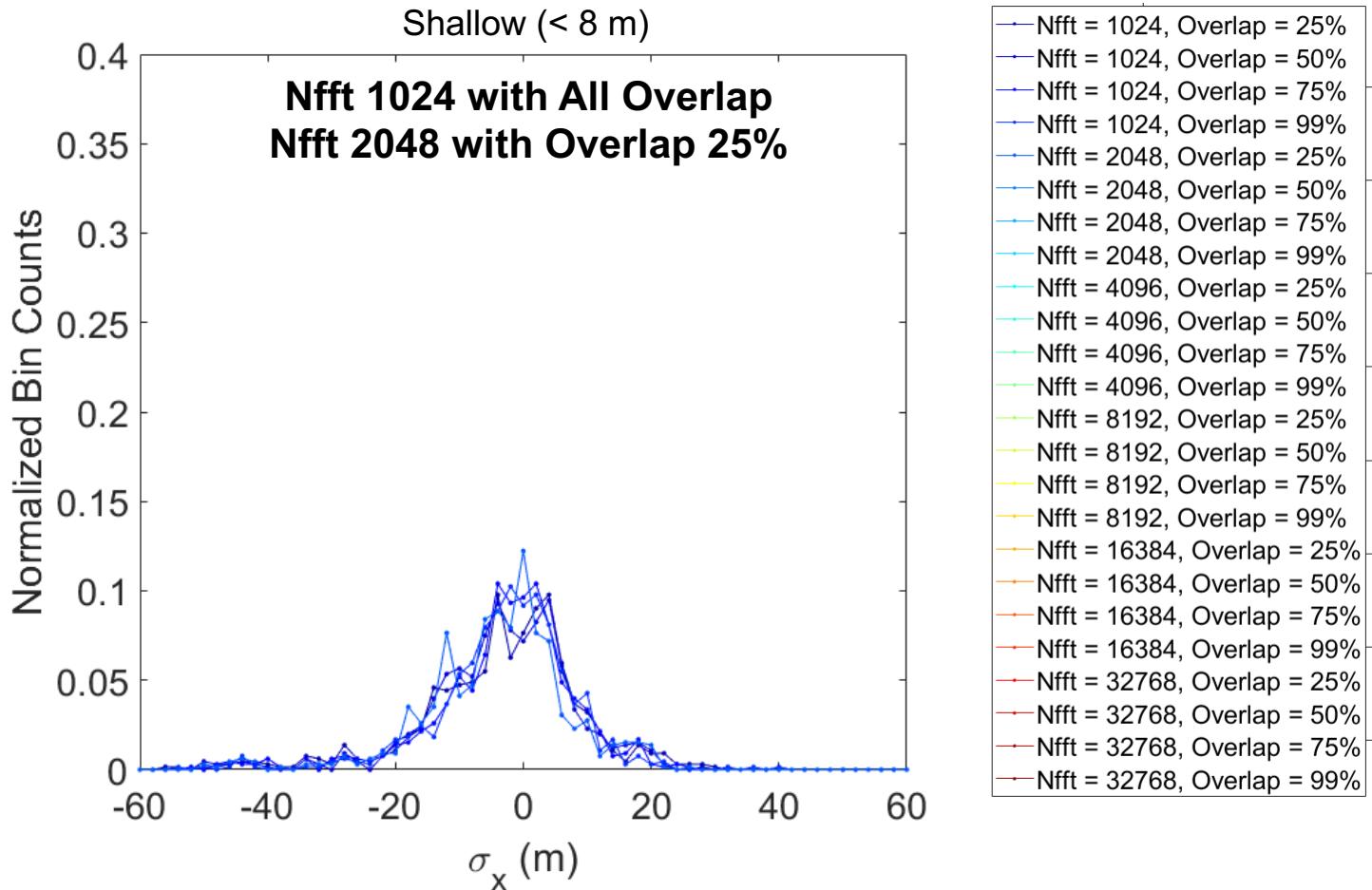
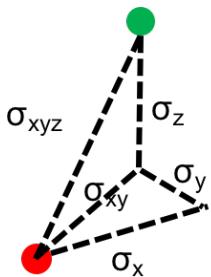
Parameter Selection

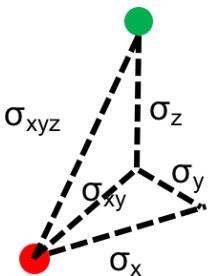
Method: curved-wavefront frequency-domain beamforming



Parameter Selection

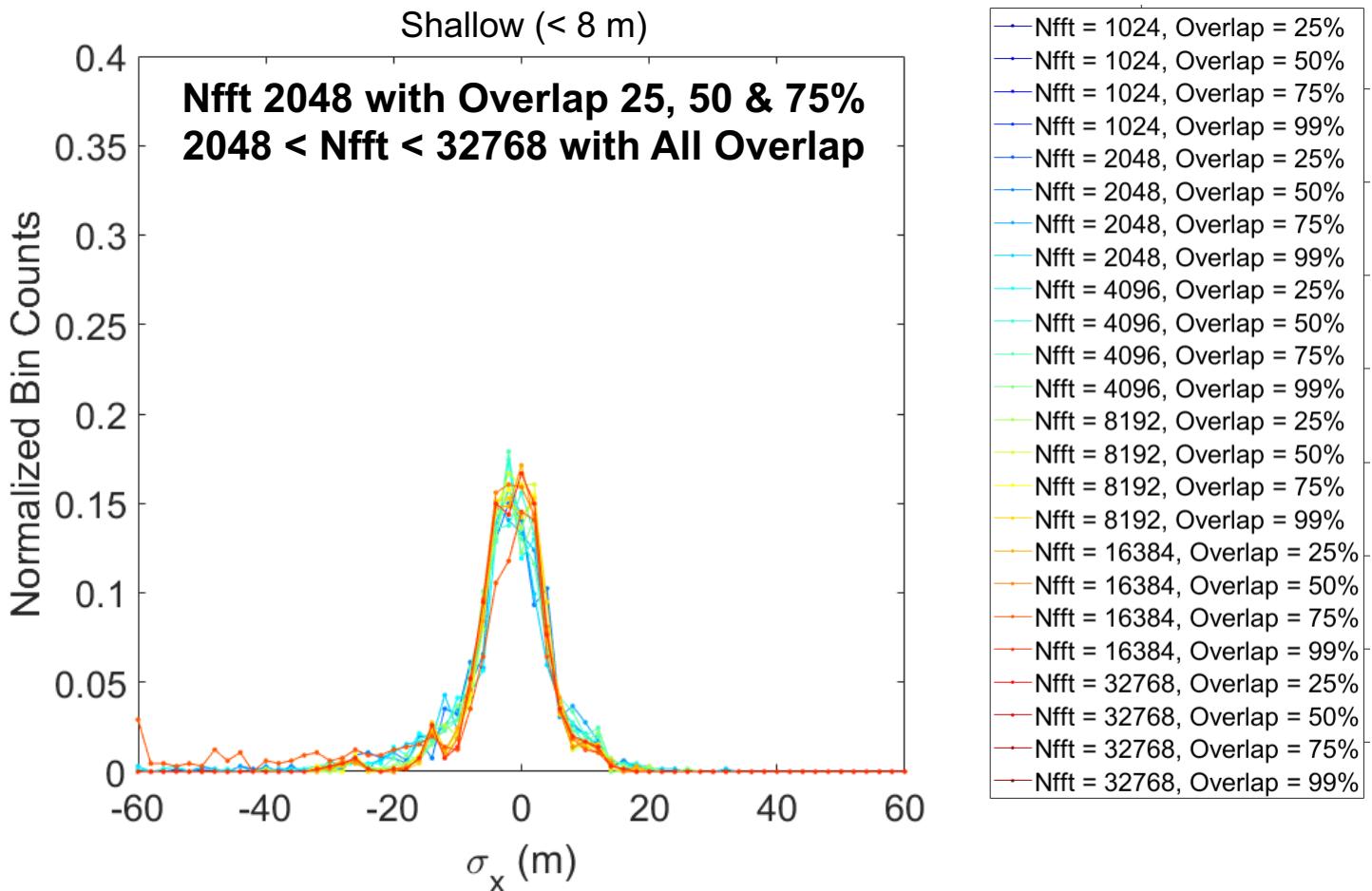
Method: curved-wavefront frequency-domain beamforming

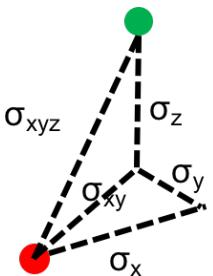




Parameter Selection

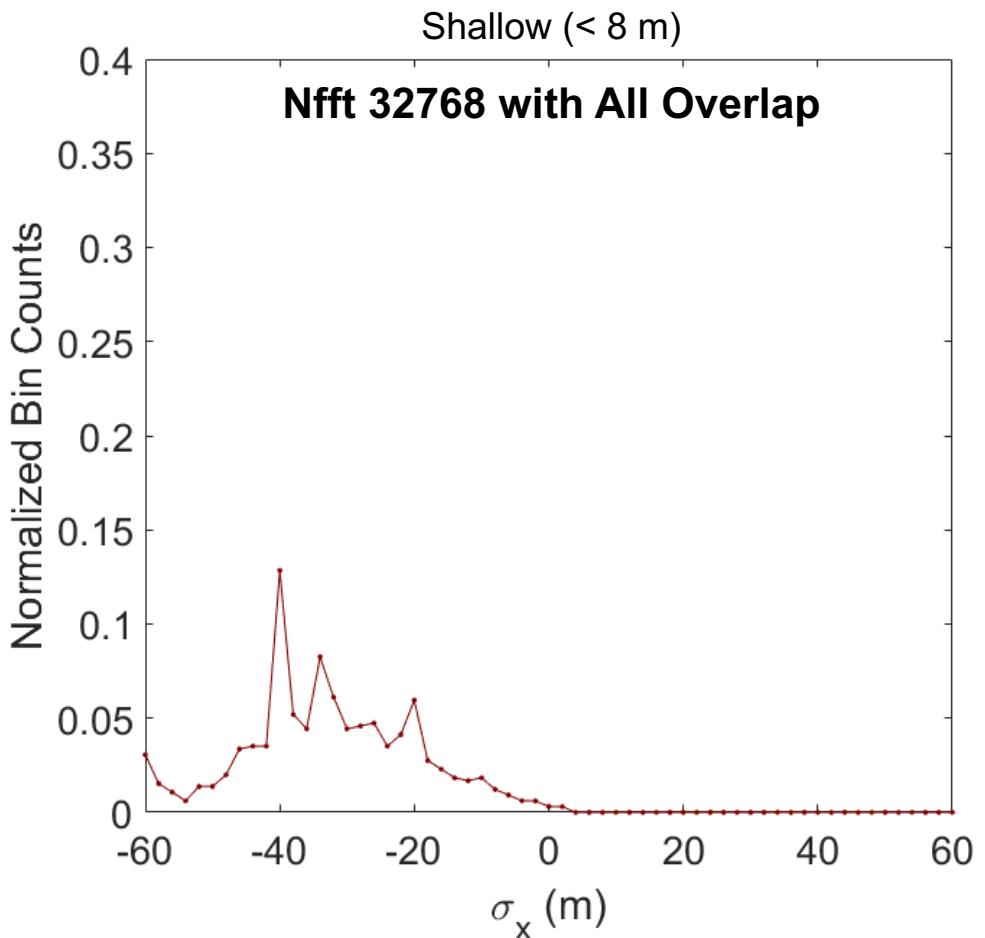
Method: curved-wavefront frequency-domain beamforming



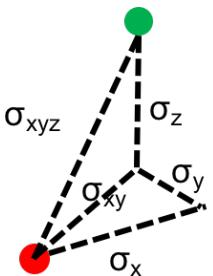


Parameter Selection

Method: curved-wavefront frequency-domain beamforming

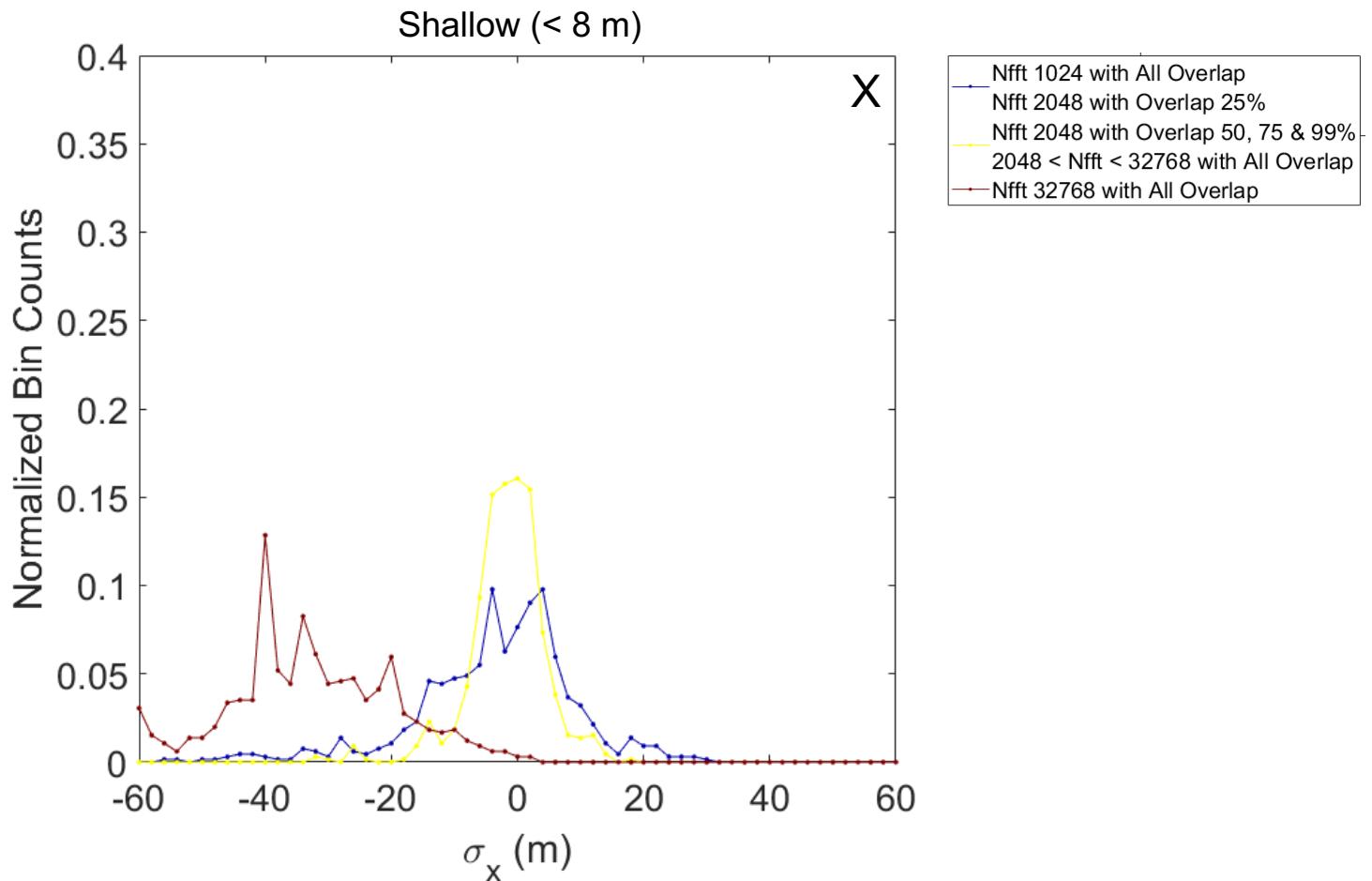


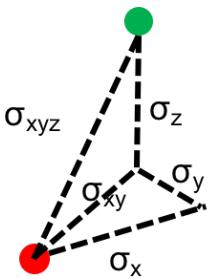
- Nfft = 1024, Overlap = 25%
- Nfft = 1024, Overlap = 50%
- Nfft = 1024, Overlap = 75%
- Nfft = 1024, Overlap = 99%
- Nfft = 2048, Overlap = 25%
- Nfft = 2048, Overlap = 50%
- Nfft = 2048, Overlap = 75%
- Nfft = 2048, Overlap = 99%
- Nfft = 4096, Overlap = 25%
- Nfft = 4096, Overlap = 50%
- Nfft = 4096, Overlap = 75%
- Nfft = 4096, Overlap = 99%
- Nfft = 8192, Overlap = 25%
- Nfft = 8192, Overlap = 50%
- Nfft = 8192, Overlap = 75%
- Nfft = 8192, Overlap = 99%
- Nfft = 16384, Overlap = 25%
- Nfft = 16384, Overlap = 50%
- Nfft = 16384, Overlap = 75%
- Nfft = 16384, Overlap = 99%
- Nfft = 32768, Overlap = 25%
- Nfft = 32768, Overlap = 50%
- Nfft = 32768, Overlap = 75%
- Nfft = 32768, Overlap = 99%



Parameter Selection

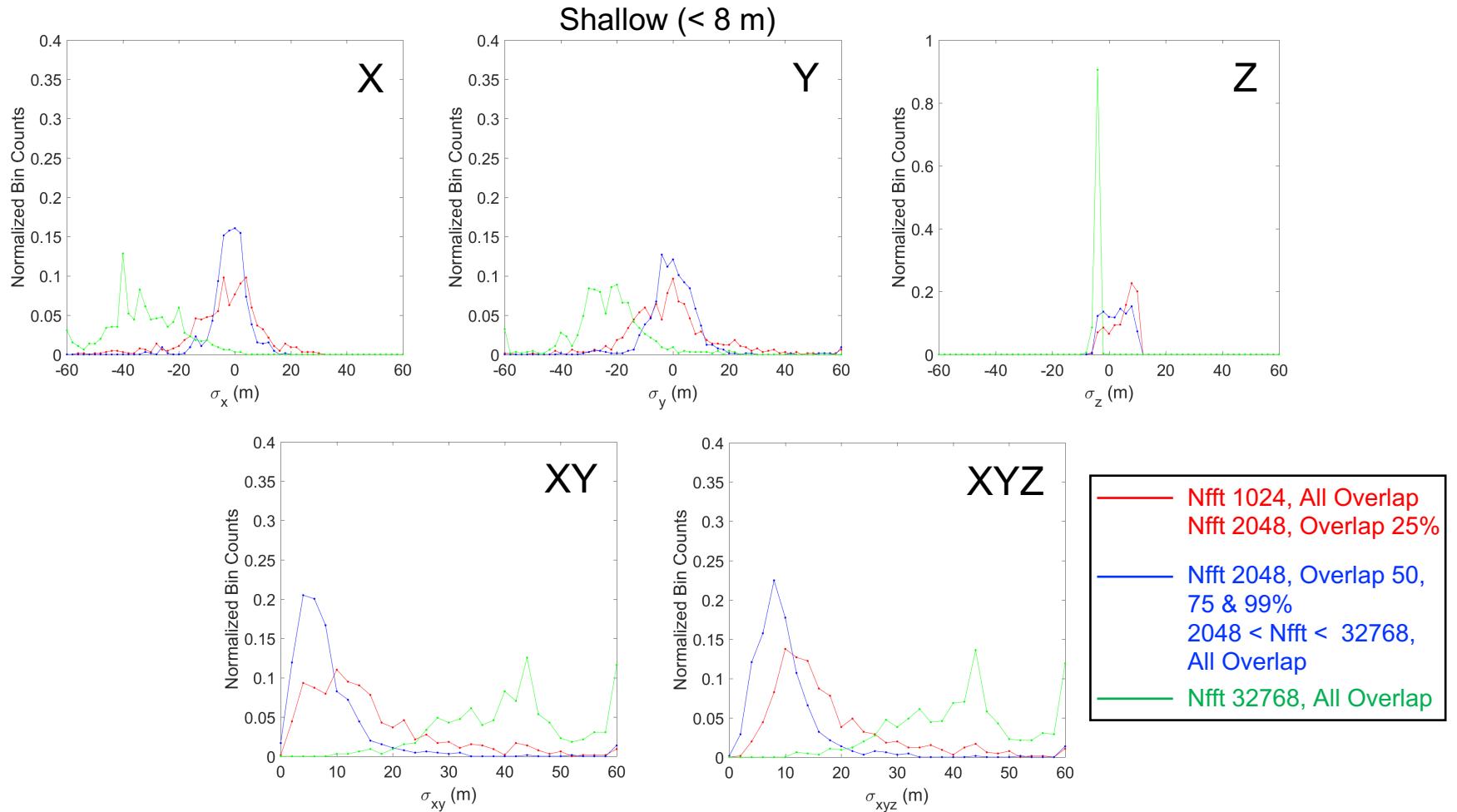
Method: curved-wavefront frequency-domain beamforming





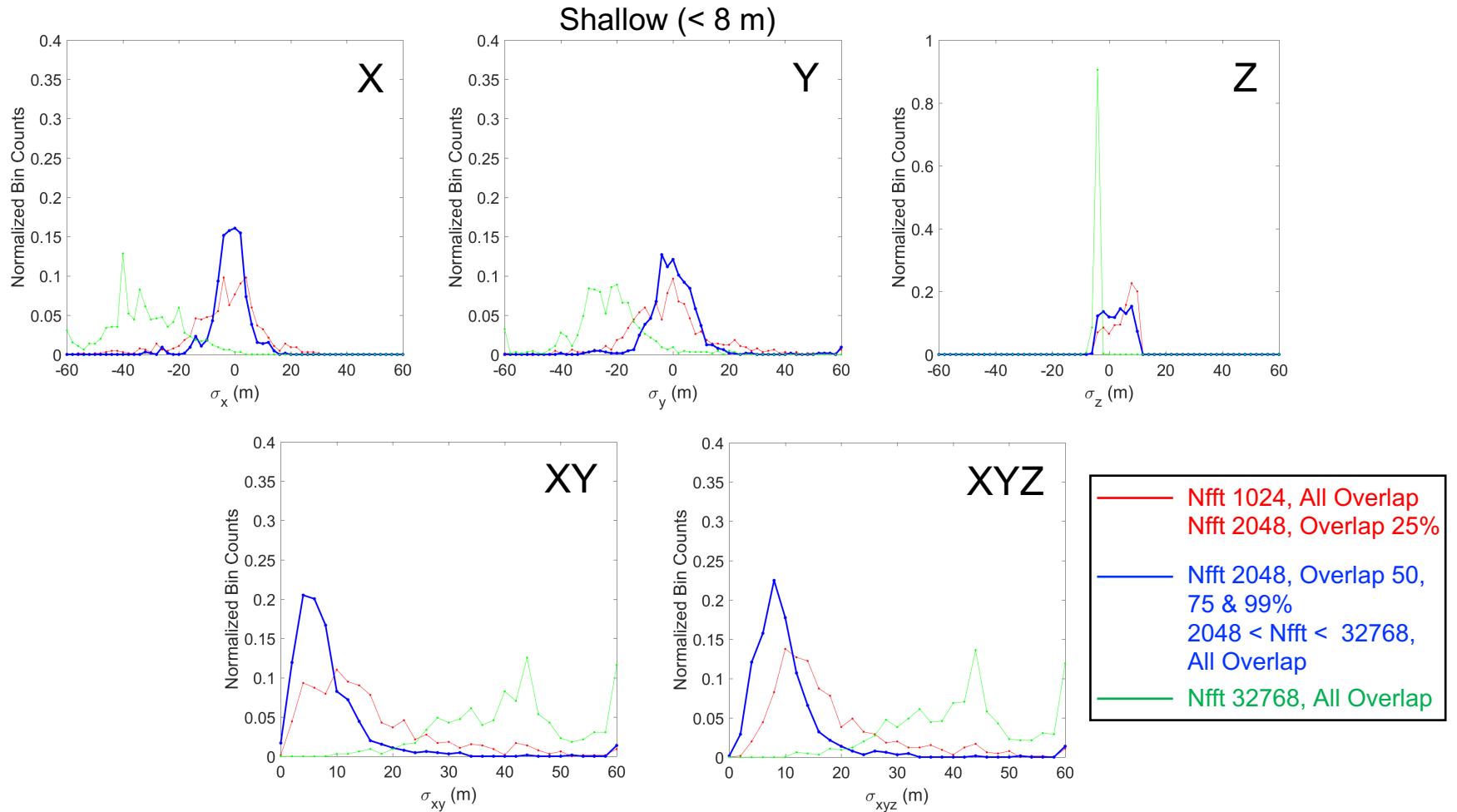
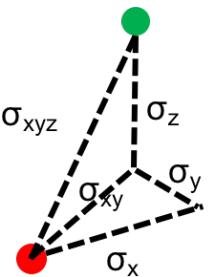
Parameter Selection

Method: curved-wavefront frequency-domain beamforming



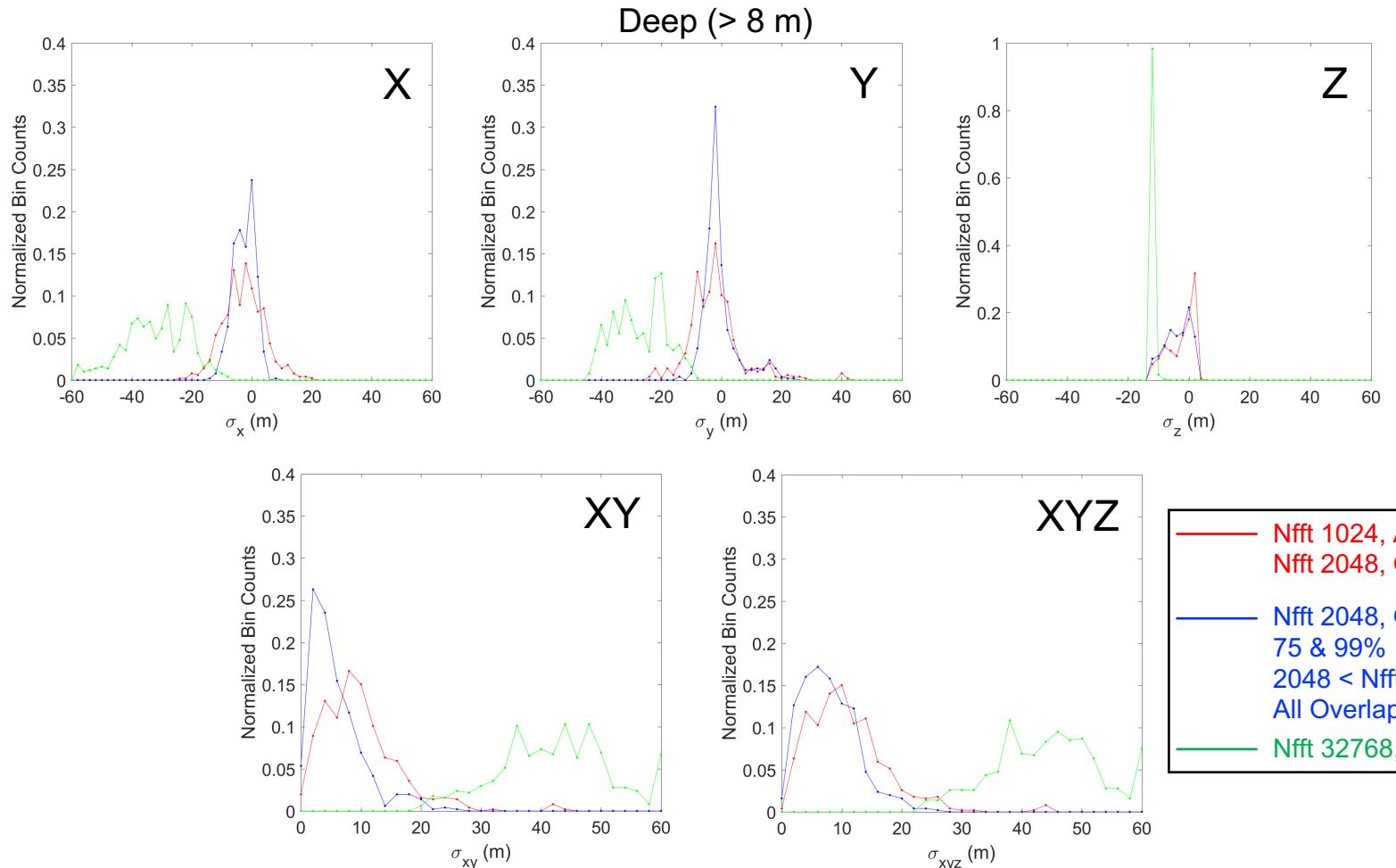
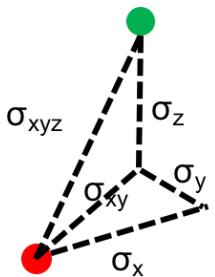
Parameter Selection

Method: curved-wavefront frequency-domain beamforming



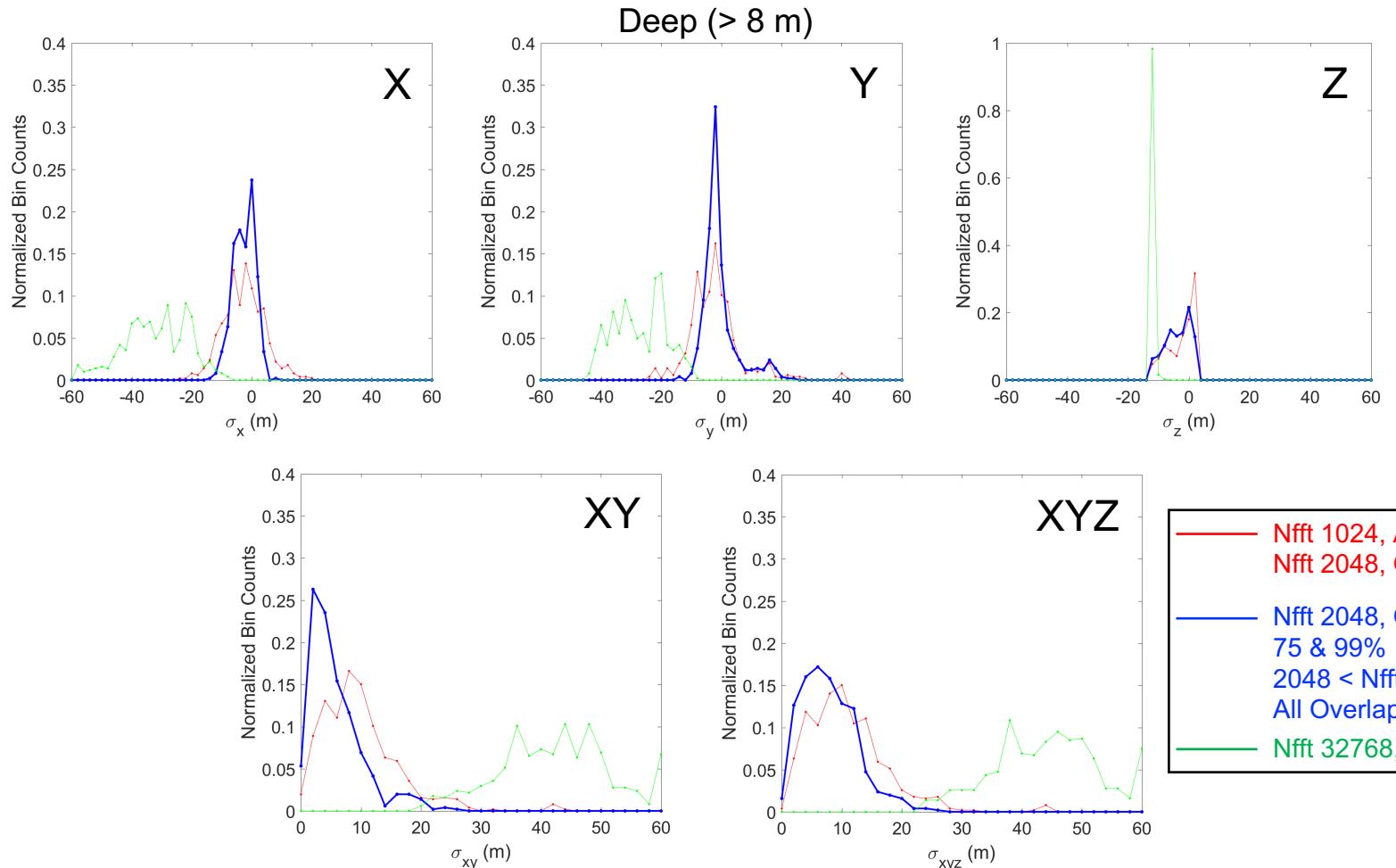
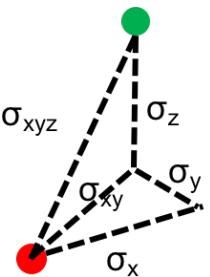
Parameter Selection

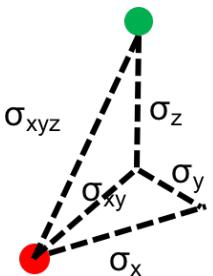
Method: curved-wavefront frequency-domain beamforming



Parameter Selection

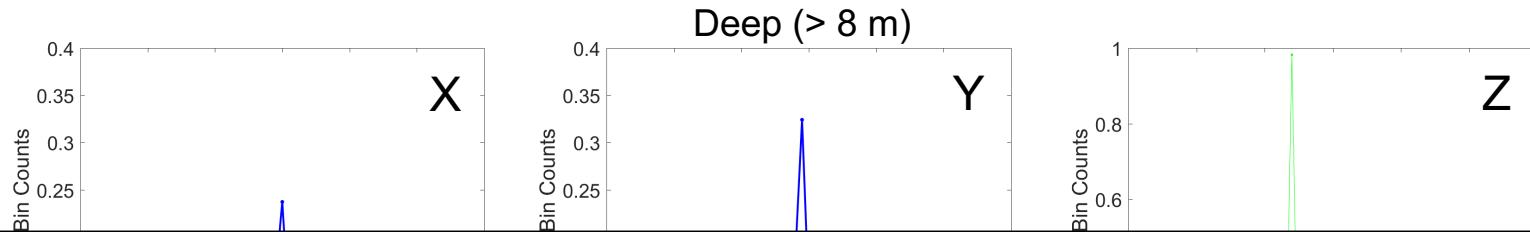
Method: curved-wavefront frequency-domain beamforming





Parameter Selection

Method: curved-wavefront frequency-domain beamforming

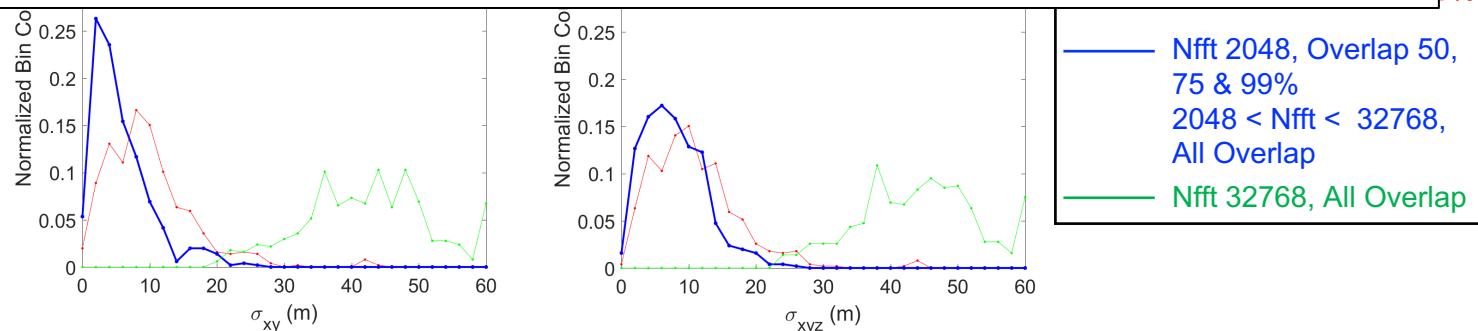


for curved-wavefront frequency-domain beamforming:

Nfft 8192, Overlap 75%

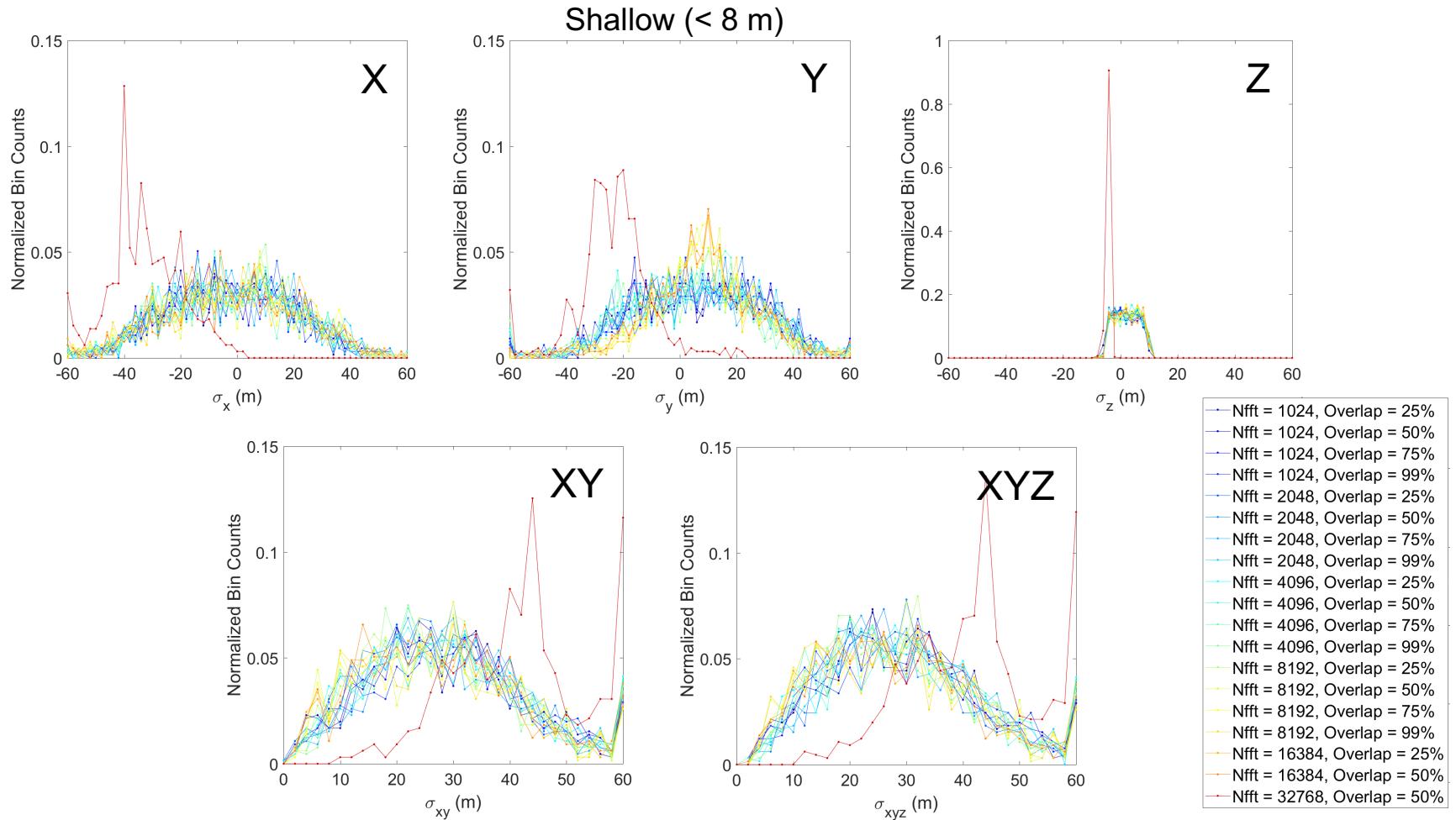
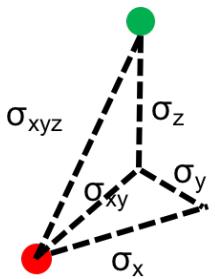
minimizes localization error

for both shallow and deep sources



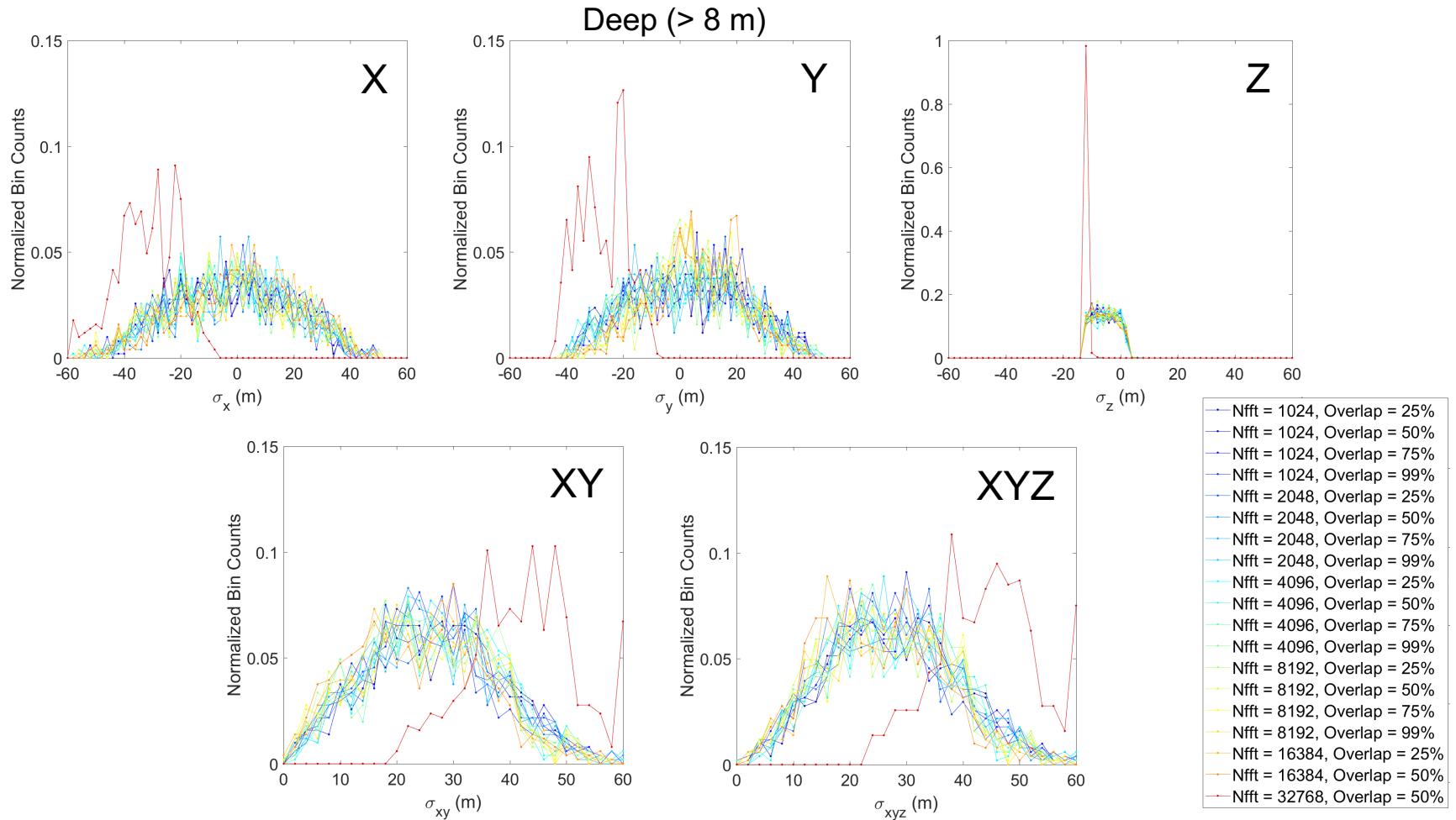
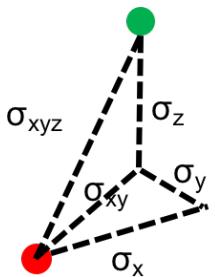
Parameter Selection

Method: plane-wavefront frequency-domain beamforming



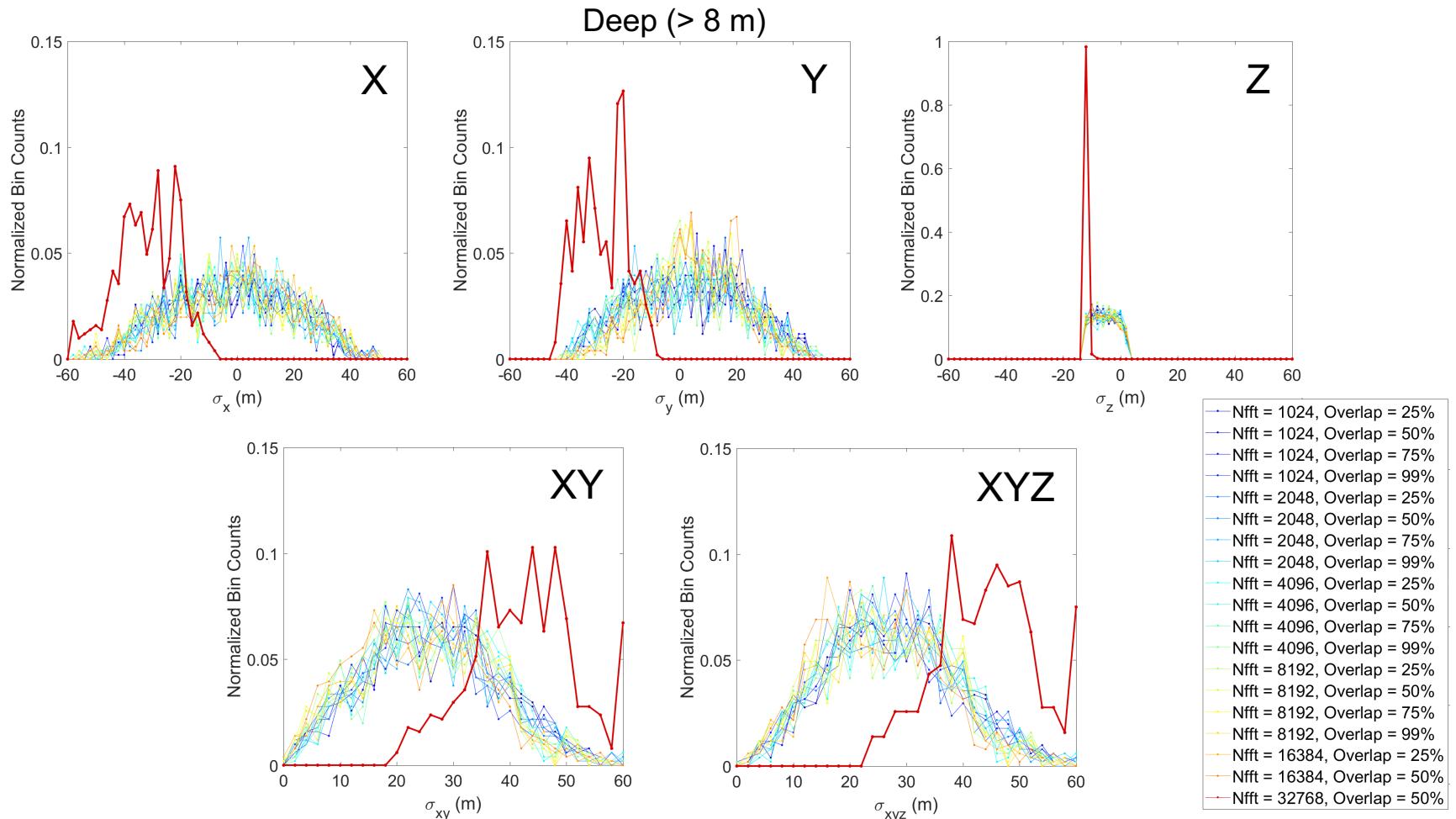
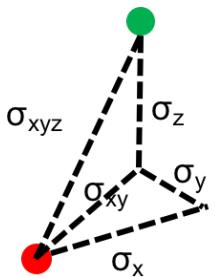
Parameter Selection

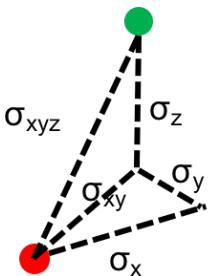
Method: plane-wavefront frequency-domain beamforming



Parameter Selection

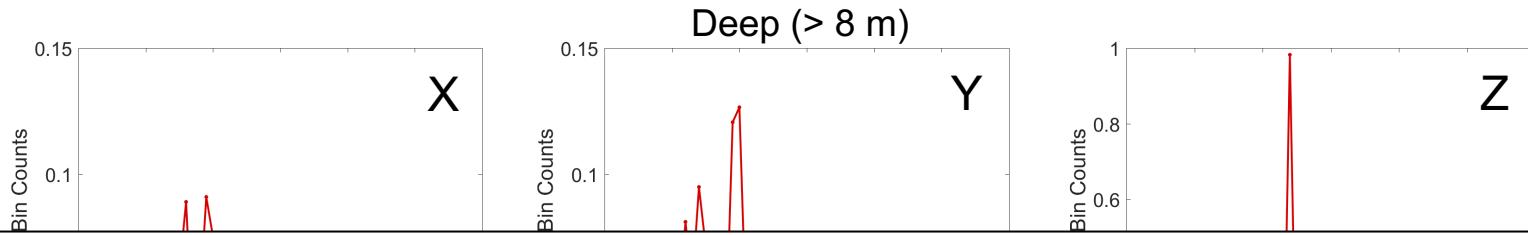
Method: plane-wavefront frequency-domain beamforming





Parameter Selection

Method: plane-wavefront frequency domain beamforming

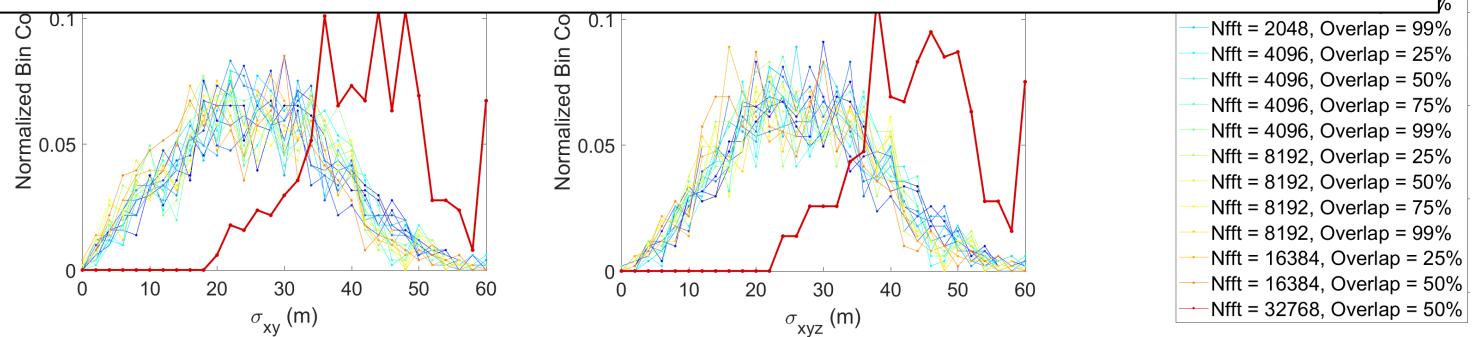


for plane-wavefront frequency-domain beamforming:

Nfft 32768, Overlap 50%

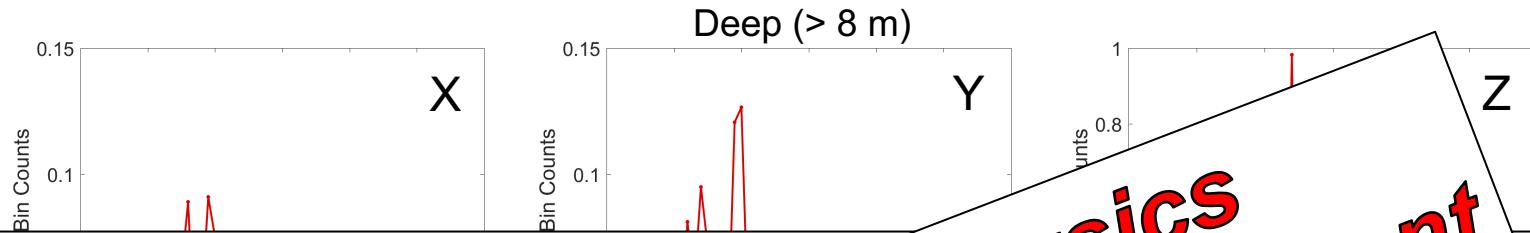
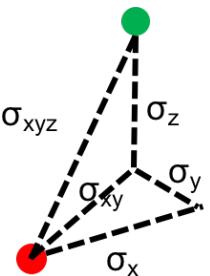
high bias, *lowest* variance

for both shallow and deep sources

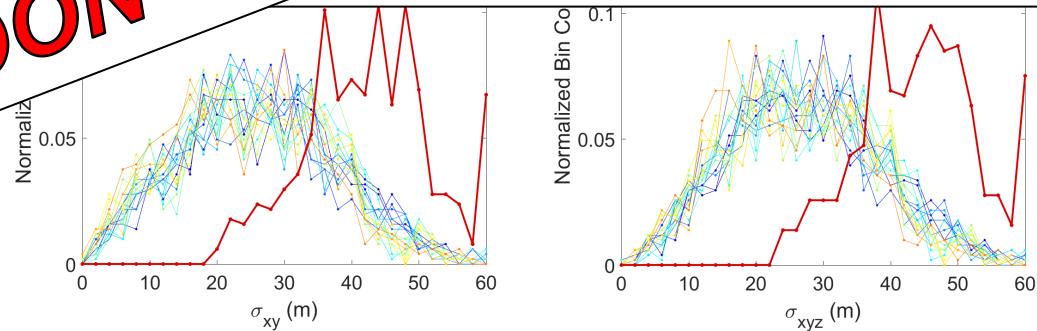


Parameter Selection

Method: plane-wavefront frequency domain beamforming

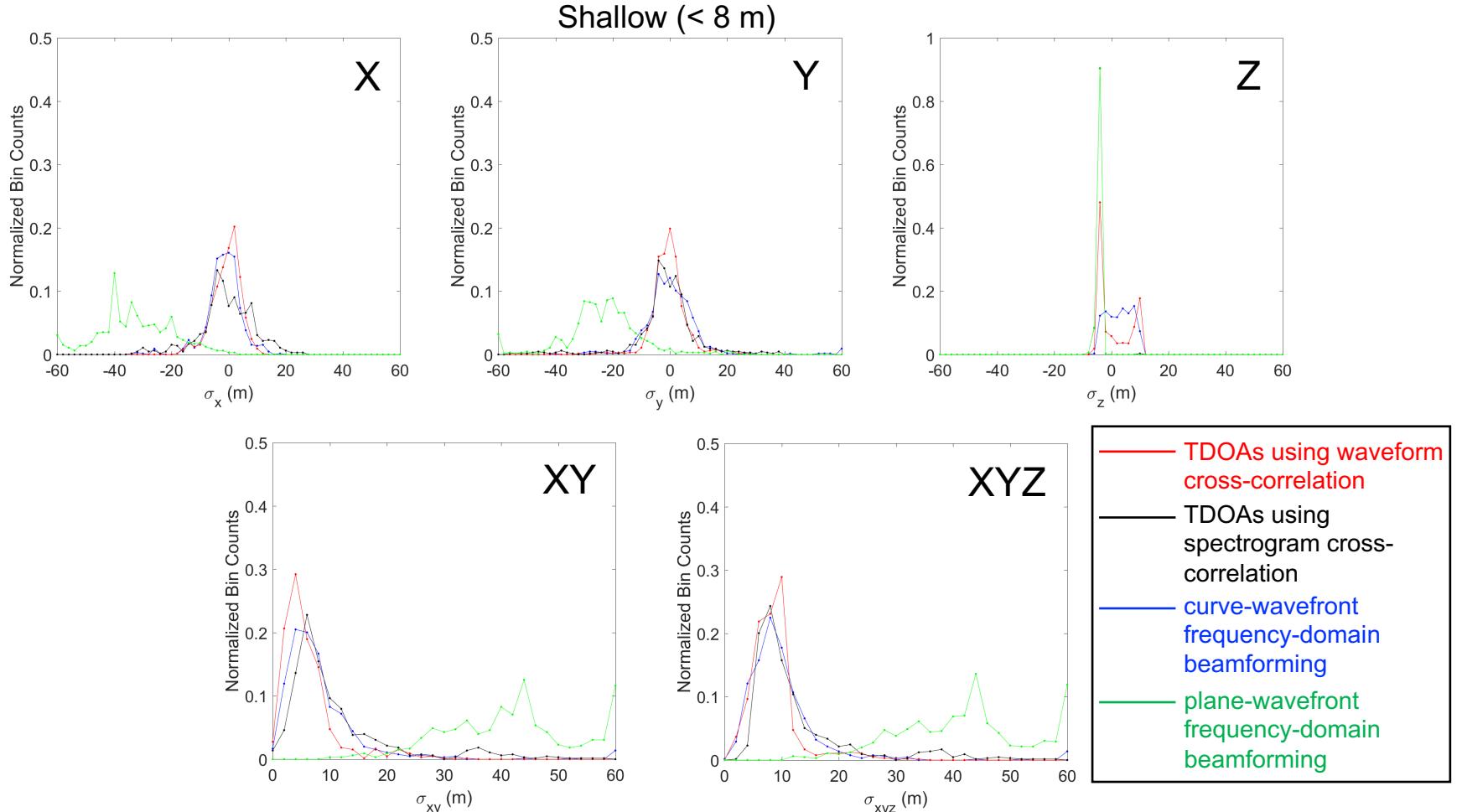
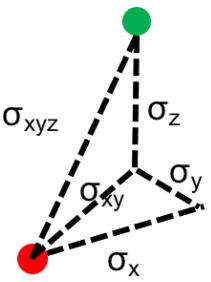


for plane-wavefront frequency domain beamforming:
Nfft = 2048, Overlap = 99%
propagation physics
DON'T match plane-wavefront variance
for shallow and deep sources



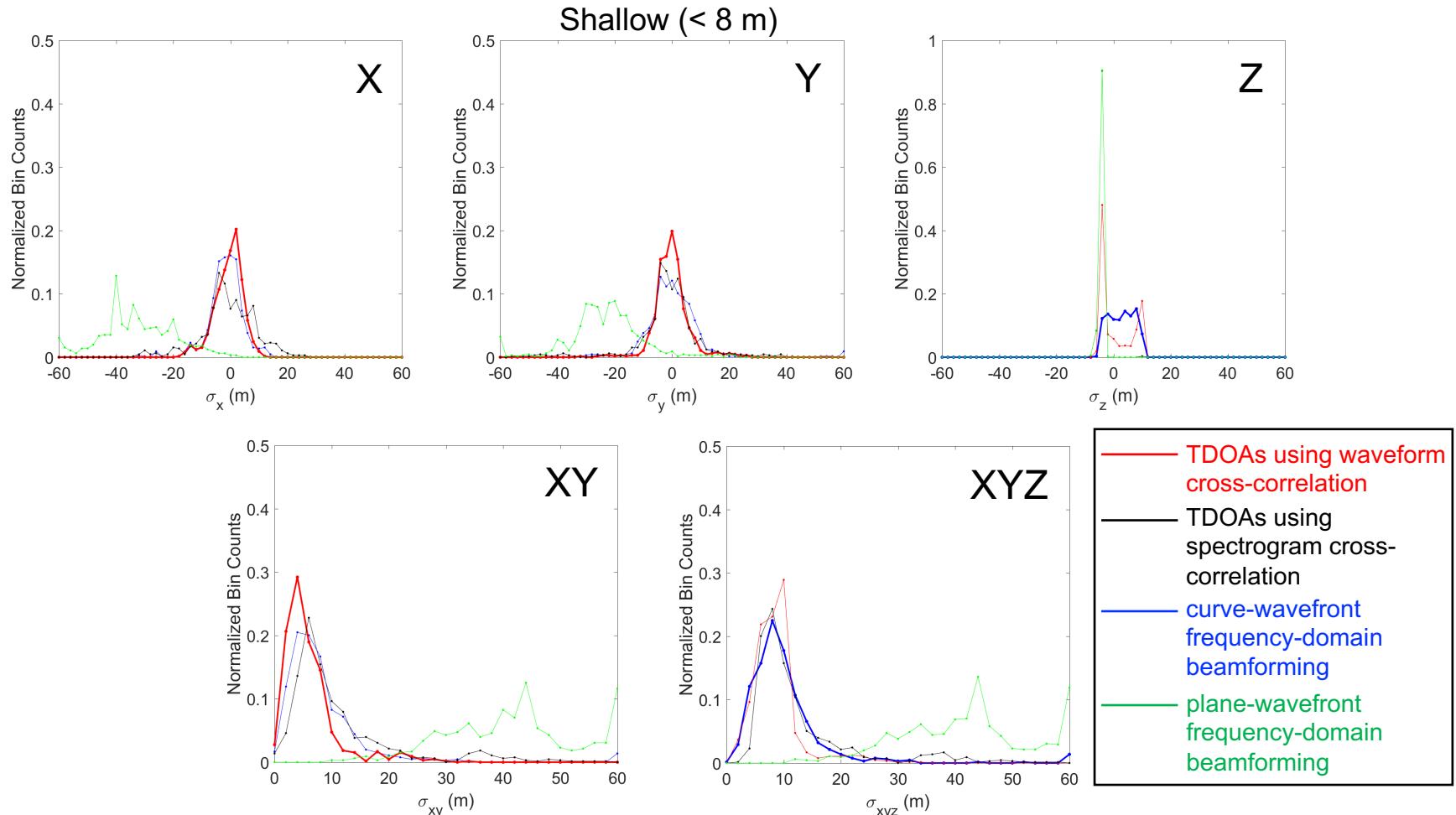
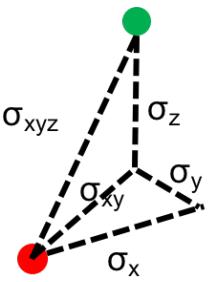
Localization Performance

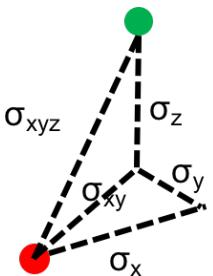
Comparison of Error Distributions between Methods



Localization Performance

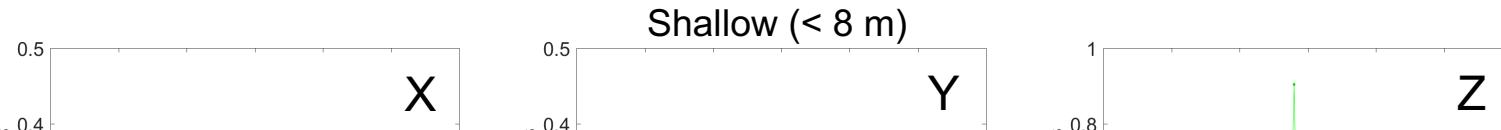
Comparison of Error Distributions between Methods





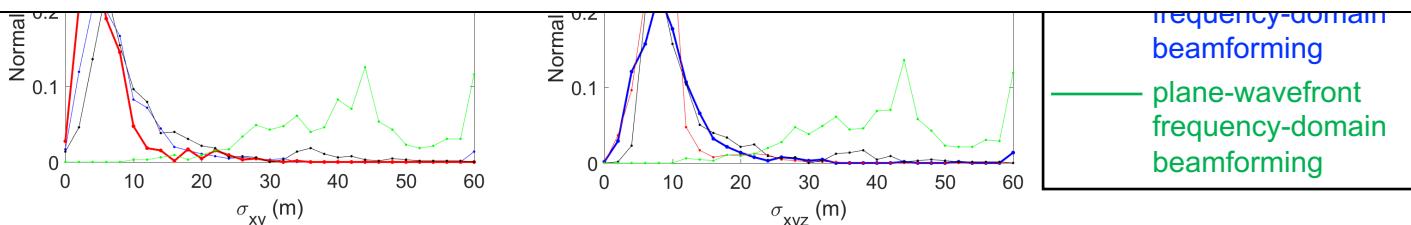
Localization Performance

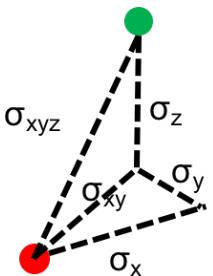
Comparison of Error Distributions between Methods



when the source is shallow:

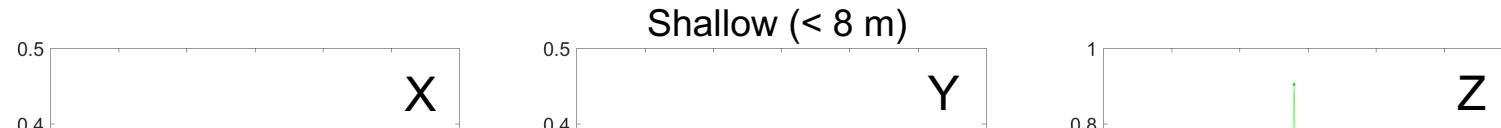
**TDOAs using waveform cross-correlation
best at estimating xy-position**





Localization Performance

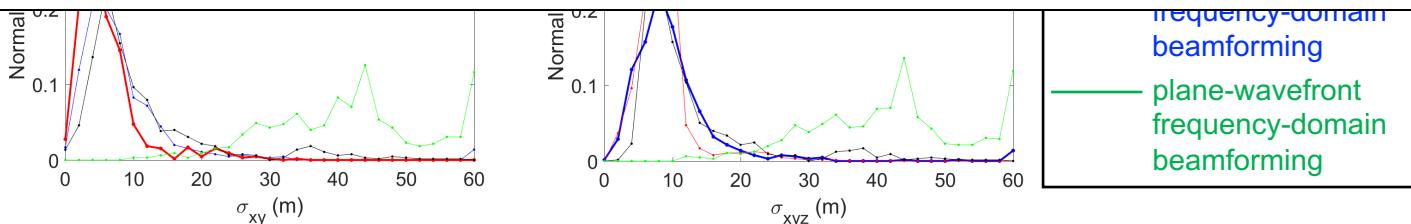
Comparison of Error Distributions between Methods



when the source is shallow:

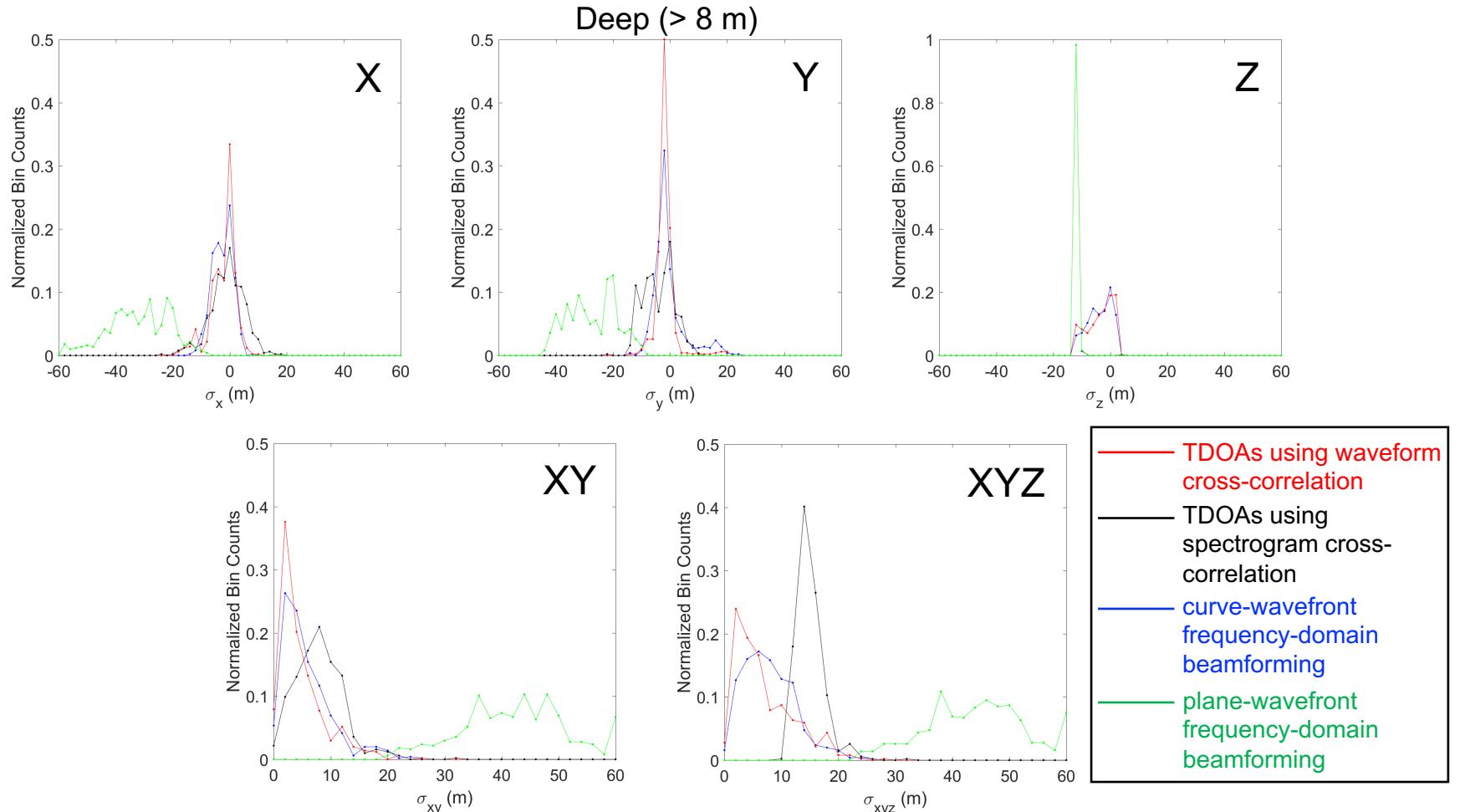
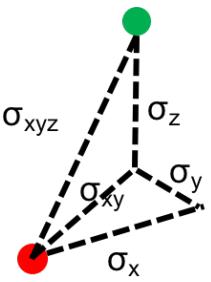
**TDOAs using waveform cross-correlation
best at estimating xy-position**

**curve-wavefront frequency-domain
beamforming best at estimating depth**



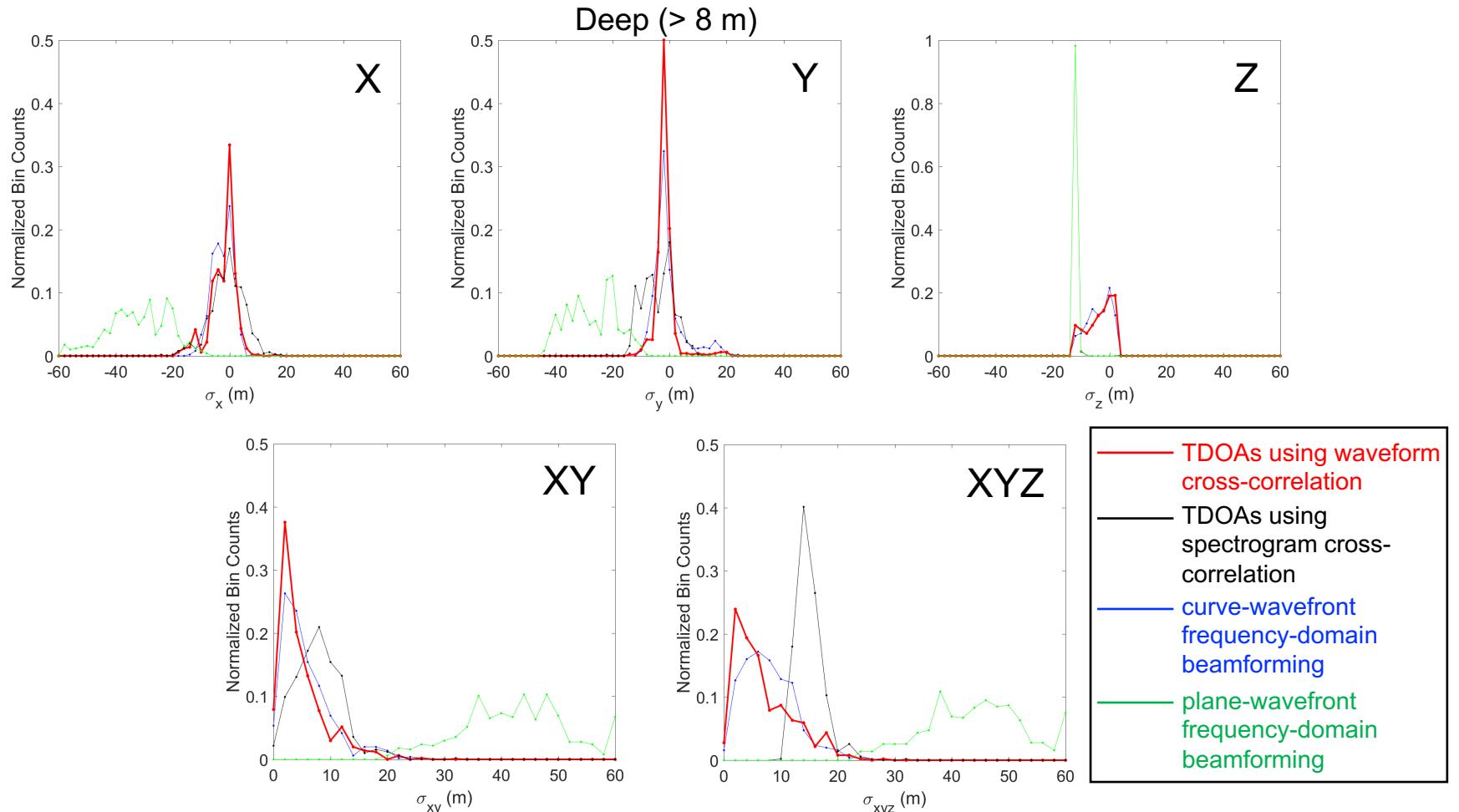
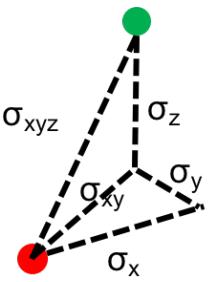
Localization Performance

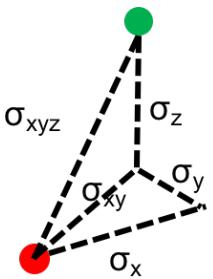
Comparison of Error Distributions between Methods



Localization Performance

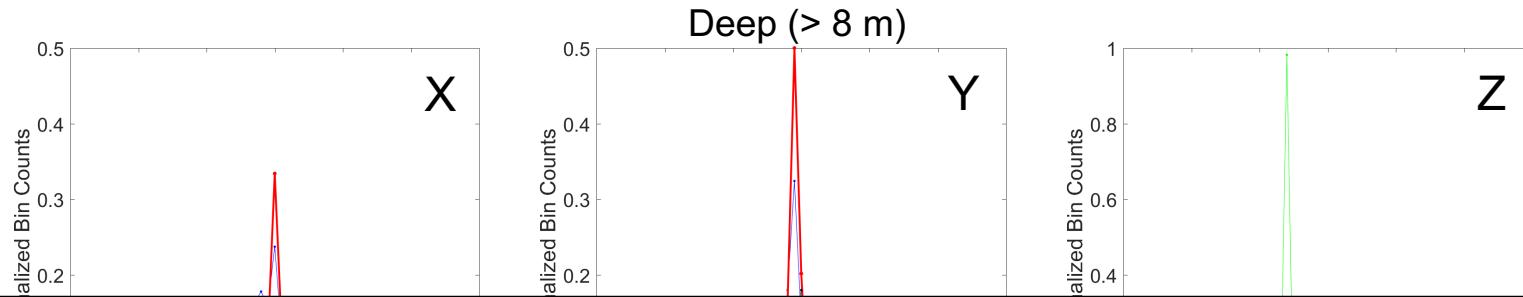
Comparison of Error Distributions between Methods



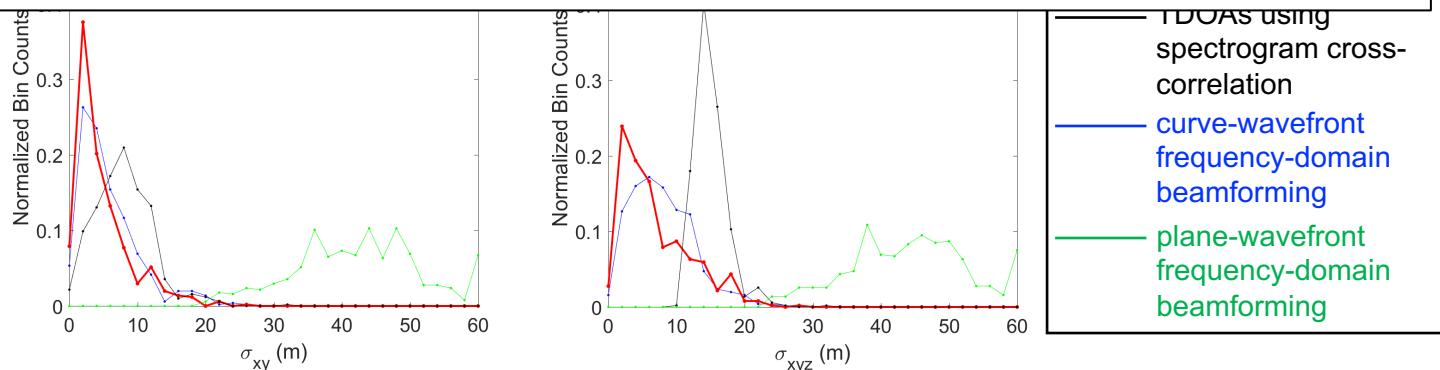


Localization Performance

Comparison of Error Distributions between Methods

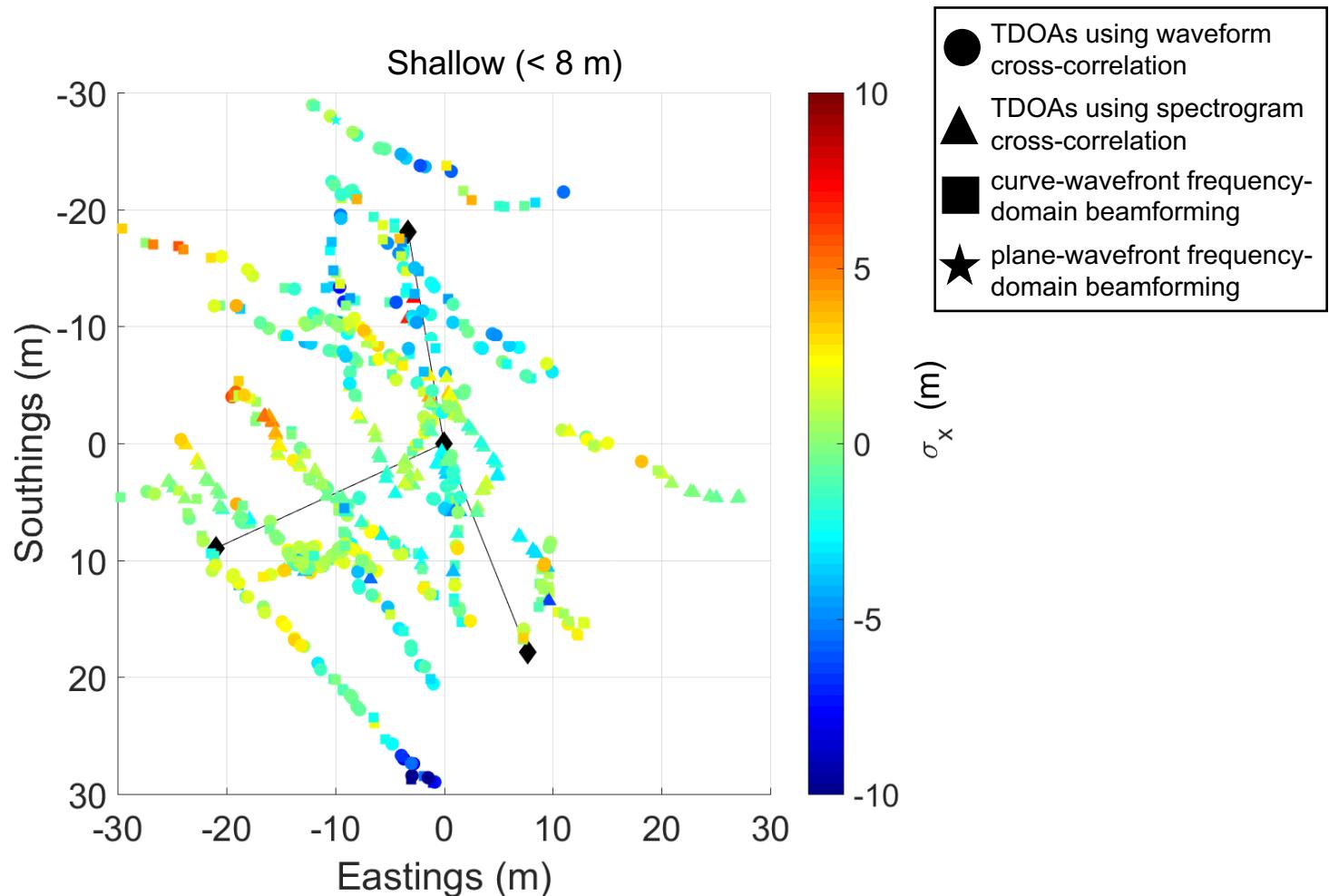
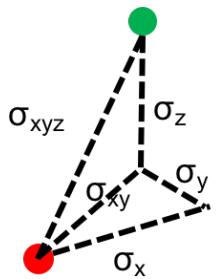


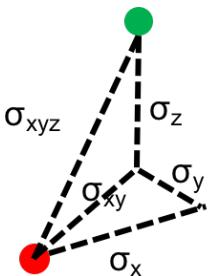
when the source is deep:
**TDOAs using waveform cross-correlation
best at estimating xyz-position**



Localization Performance

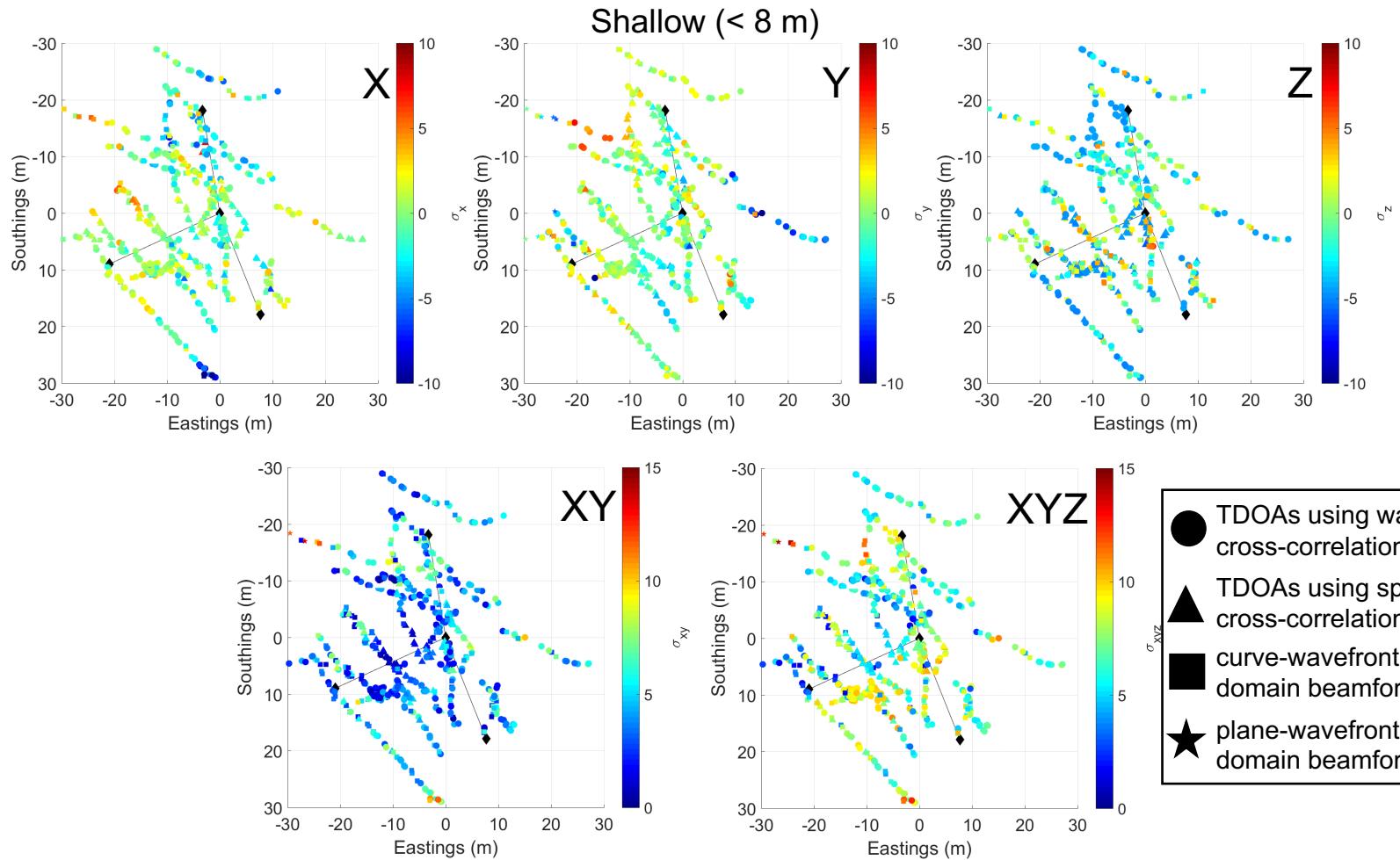
Spatial Patterns of Performance amongst Methods

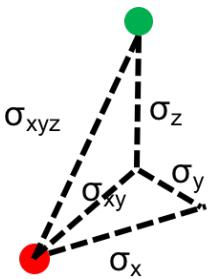




Localization Performance

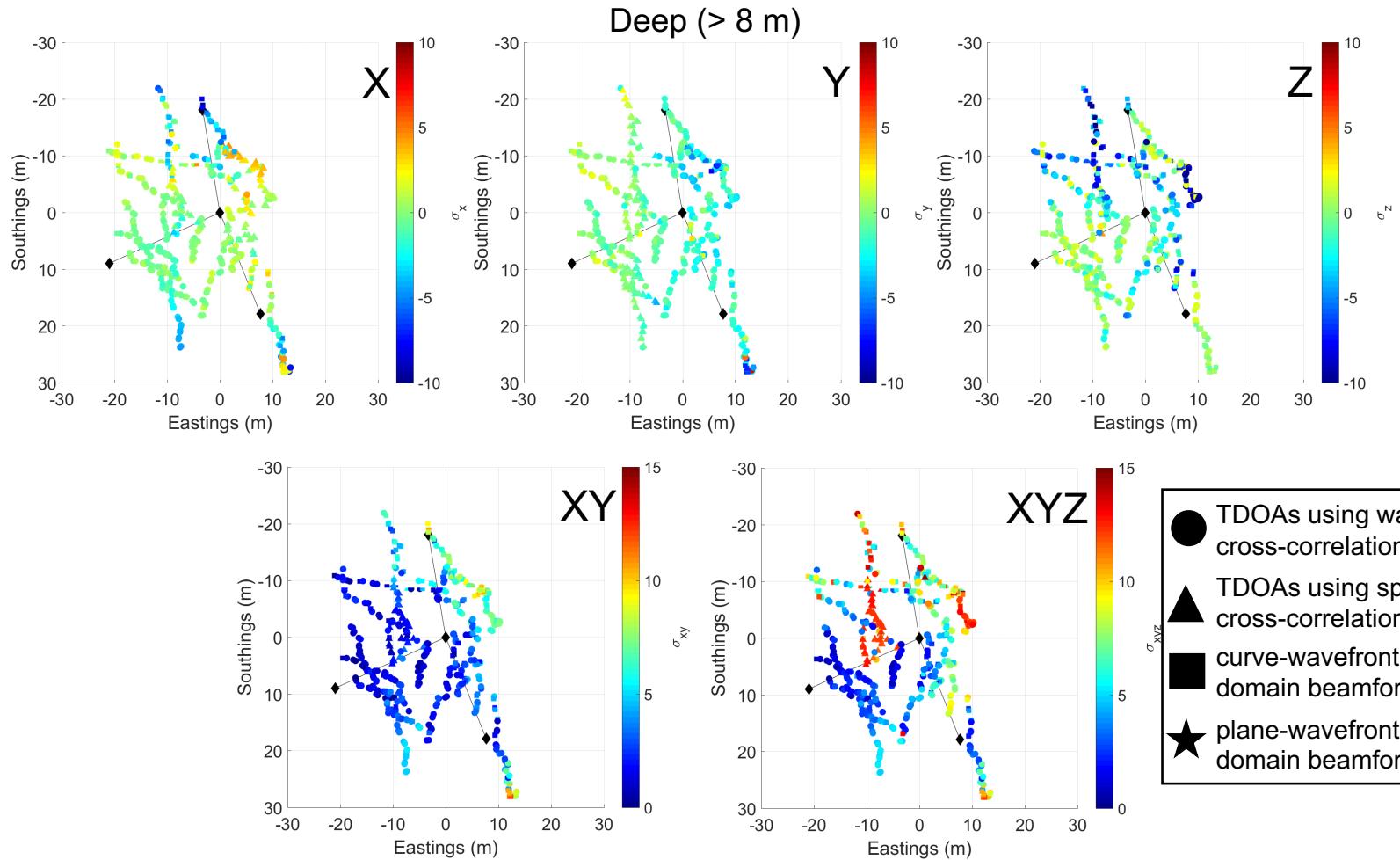
Spatial Patterns of Performance amongst Methods





Localization Performance

Spatial Patterns of Performance amongst Methods



Conclusions and Next Steps

- method with best overall localization performance
TDOAs using waveform cross-correlation
 - but, curved-wavefront frequency-domain beamforming best at resolving **source depth** when **source is shallow**
 - Nfft and overlap greatly influence localization performance
 - no clear spatial pattern as to where each method performs best
-
- how does frequency, duration etc. of fish sounds influence localization performance?
 - if we add more physics to model (e.g., direct path, surface-bounce, bottom-bounce, depth-varying sound-speed profile, kelp distribution etc.), will modeled error distributions match experimental error distributions?

Acknowledgements

- Divers and Experiment Support:
 - D. Bedenko
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 - Fleet Admiral Chester W. Nimitz Fellowship, SIO
 - NSERC PGS D-3



Thank you!



Questions?