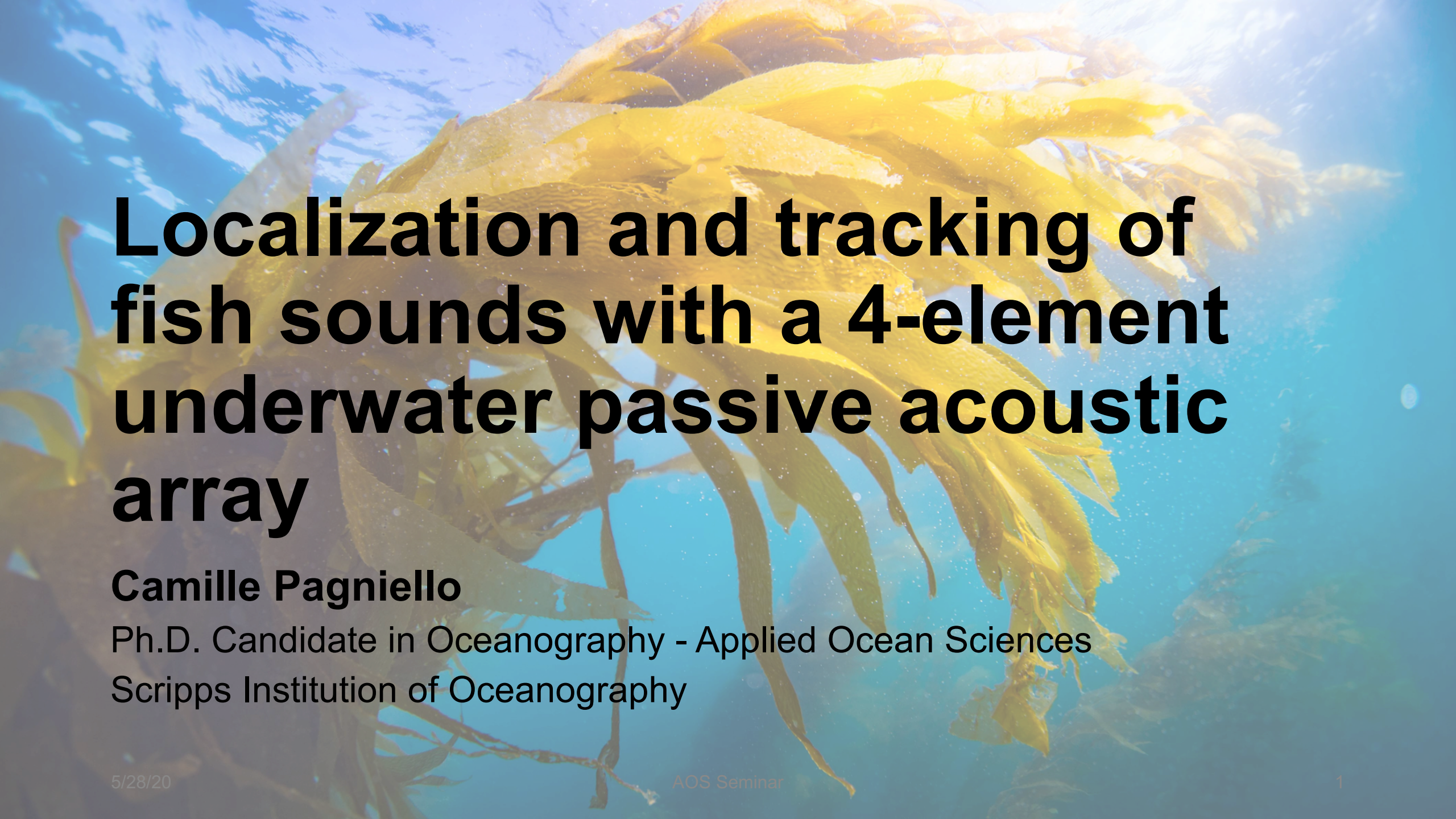

Localization and tracking of fish sounds with a 4-element underwater passive acoustic array

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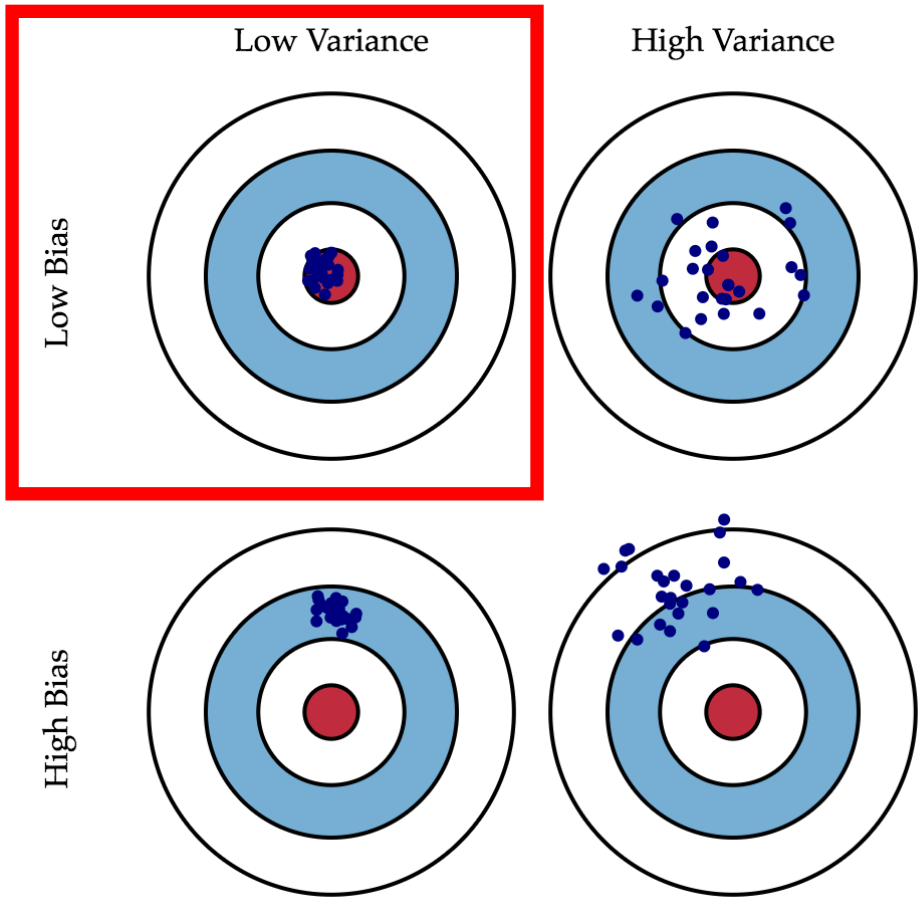
Scripps Institution of Oceanography

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

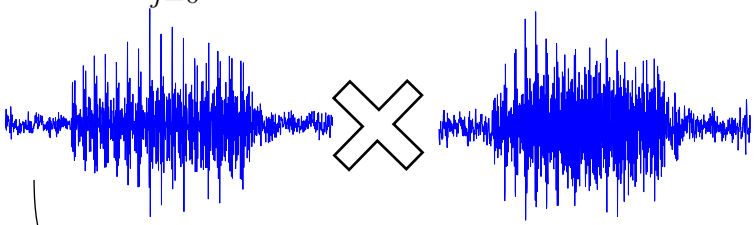


Methods: Time-Domain Beamforming

time difference of arrival (TDOA) of incoming signals

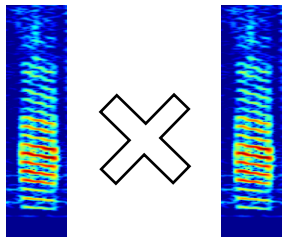
TDOAs from ***waveform*** cross-correlation

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



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

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

modeled TDOA

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

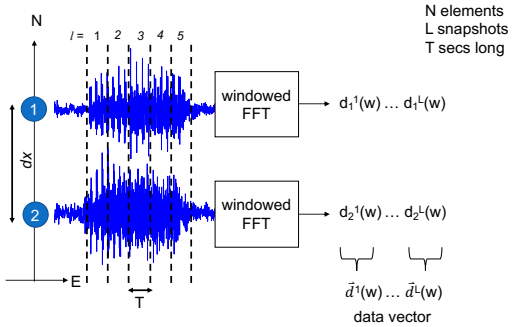
Maximum Likelihood Estimate of the True Position

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

Methods: Frequency-Domain Beamforming

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

Data



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

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

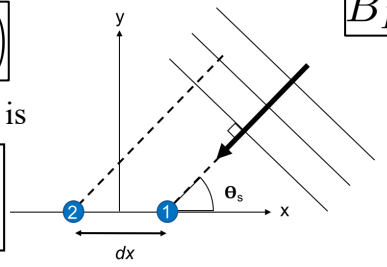
Model

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

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

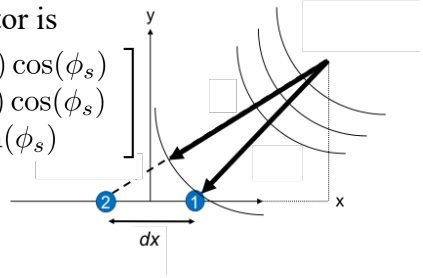


replica vector for **curved-wavefront**

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

where the source position vector is

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



Beamformer

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

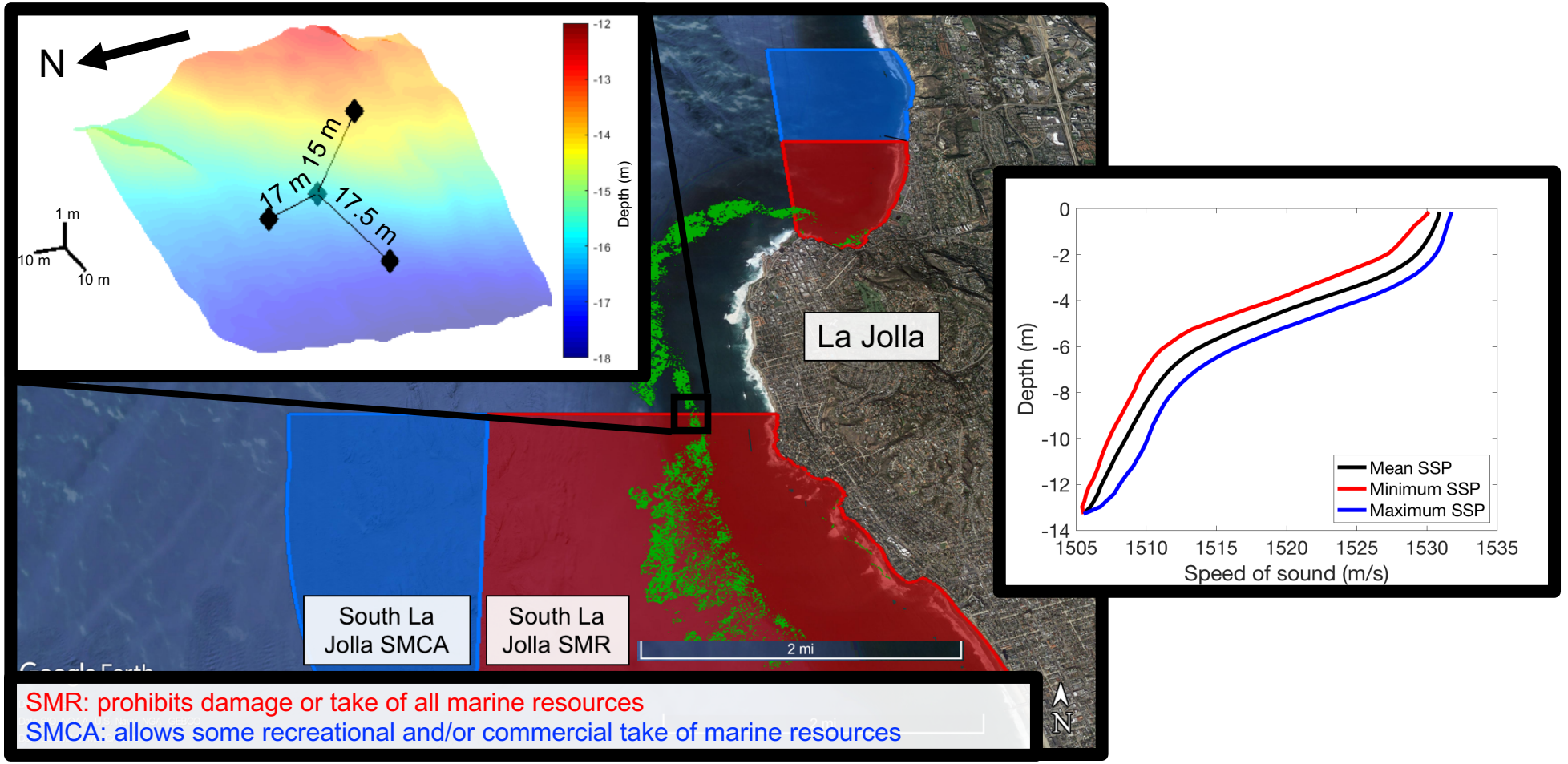
linear (Bartlett) beamformer output magnitude squared

Objective

- **quantitatively compare the performance of three methods**:
  1) TDOAs using waveform cross-correlation (with curved- and plane-wavefront)
  2) TDOAs using spectrogram cross-correlation (with curved- and plane-wavefront)
  3) frequency-domain beamforming (with curved- and plane- wavefront)

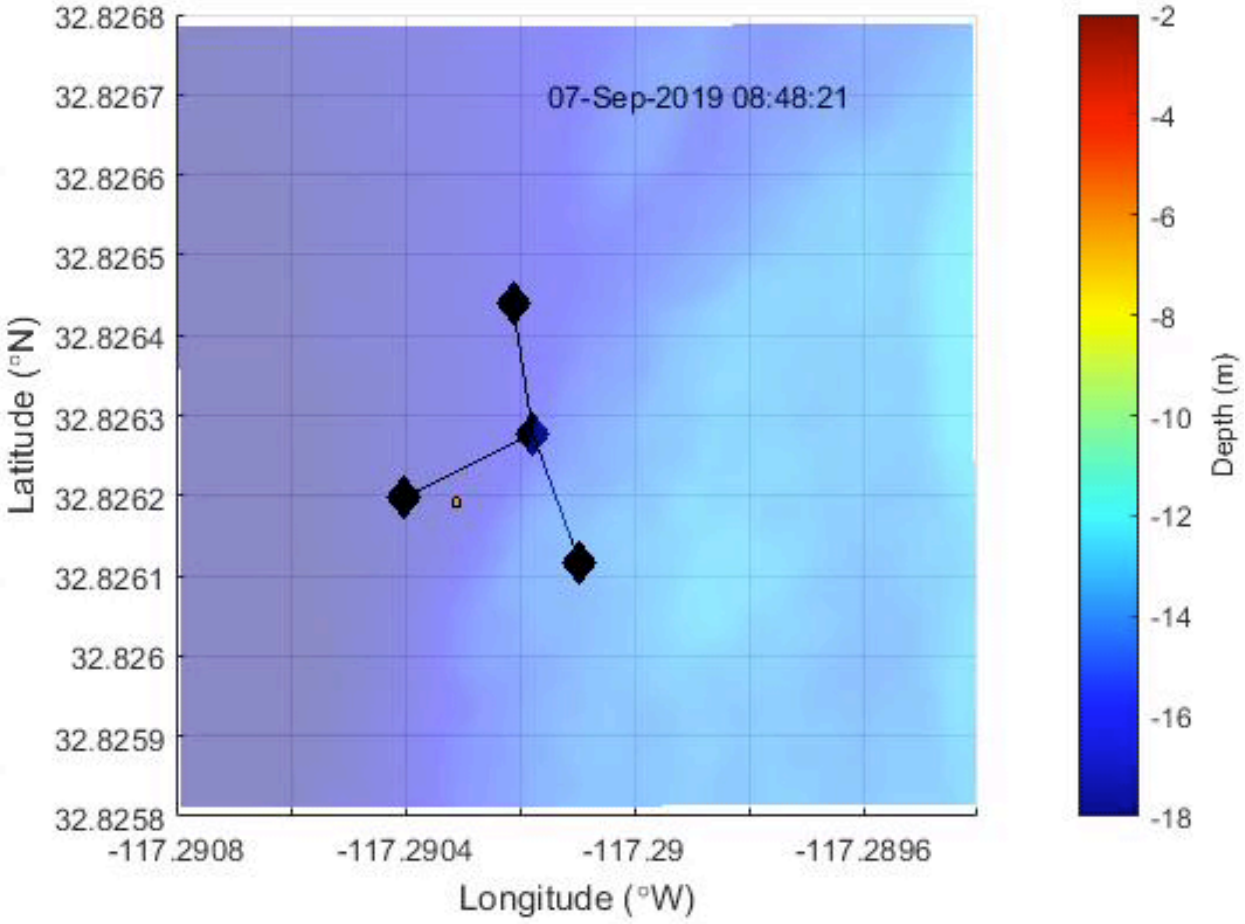
- determine the most effective localization approach, given the present array geometry and environment, to estimate the positions and track (hopefully) individual soniferous fish to better understand their small-scale spawning movements and reproductive behavior

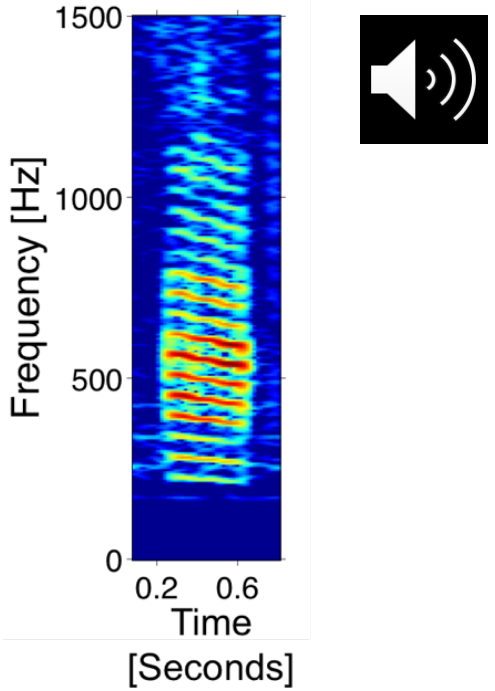
Experimental Setup



SMR: prohibits damage or take of all marine resources
SMCA: allows some recreational and/or commercial take of marine resources

Experimental Setup





Source Level:

155.7 dB re 1 μPa RMS

174.4 dB re 1 μPa peak-to-peak

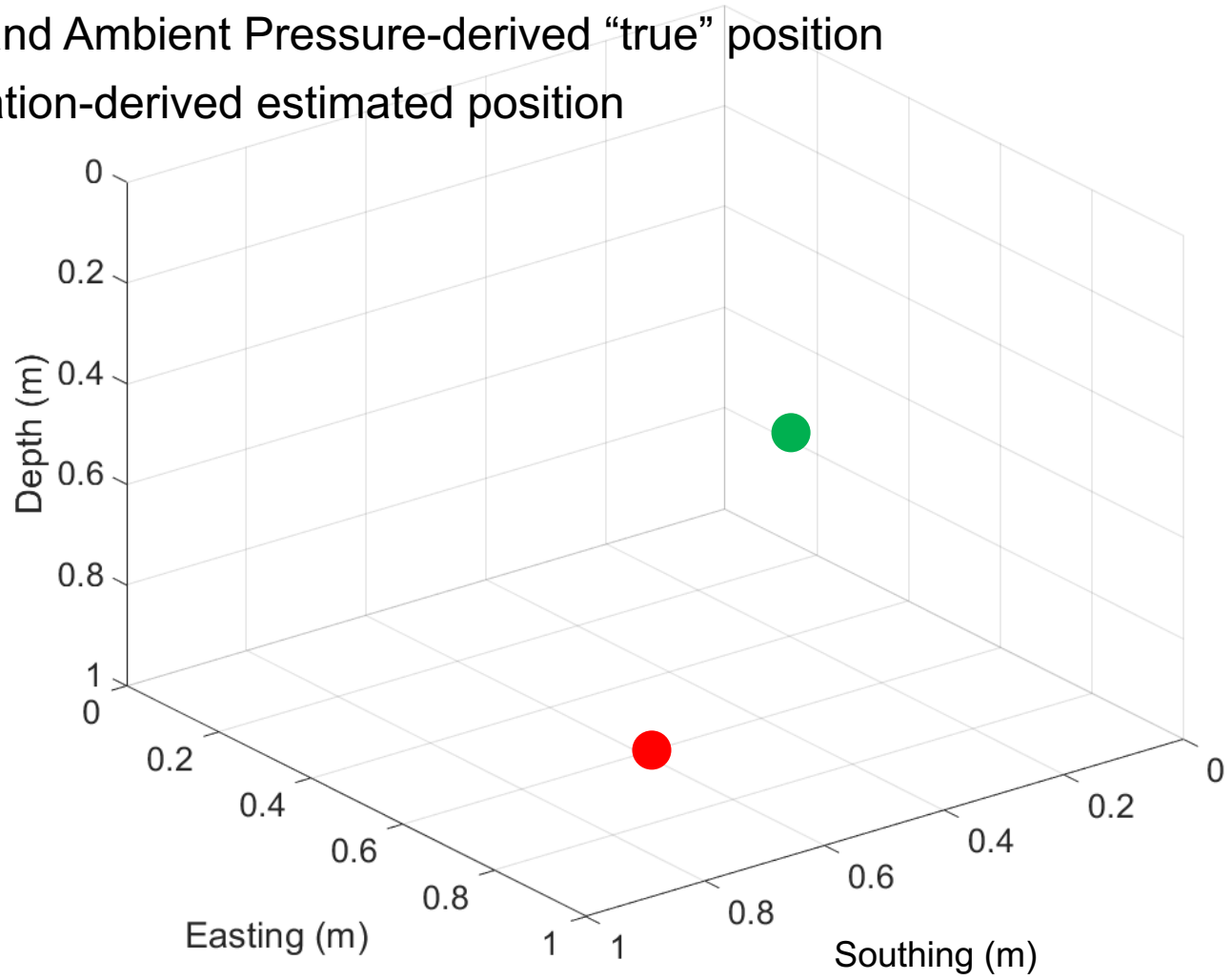
168.4 dB re 1 μPa 0-to-peak

Parameter Selection

Method	Wavefront Shape	Sampling Frequency (kHz)	Signal Amplitude	FFT Length	Percent Overlap (%)	Degree of Quadratic Interpolation
✅ TDOA Waveform	curve, plane	6, 12, 24, 48, 96, 192	native, square	n/a	n/a	1, 0.1, 0.01, 0.001
TDOA Spectrogram	curve, plane	6, 12, 24, 48, 96, 192	n/a	2^2, 2^4, 2^6, 2^8, 2^{10}, 2^{12}	25, 50, 75, 99	1, 0.1, 0.01, 0.001
linear (Bartlett) Frequency-Domain Beamforming	curve, plane	6, 12, 24, 48, 96, 192	n/a	2^{10} to 2^{15}	25, 50, 75, 99	n/a

Performance Metrics

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

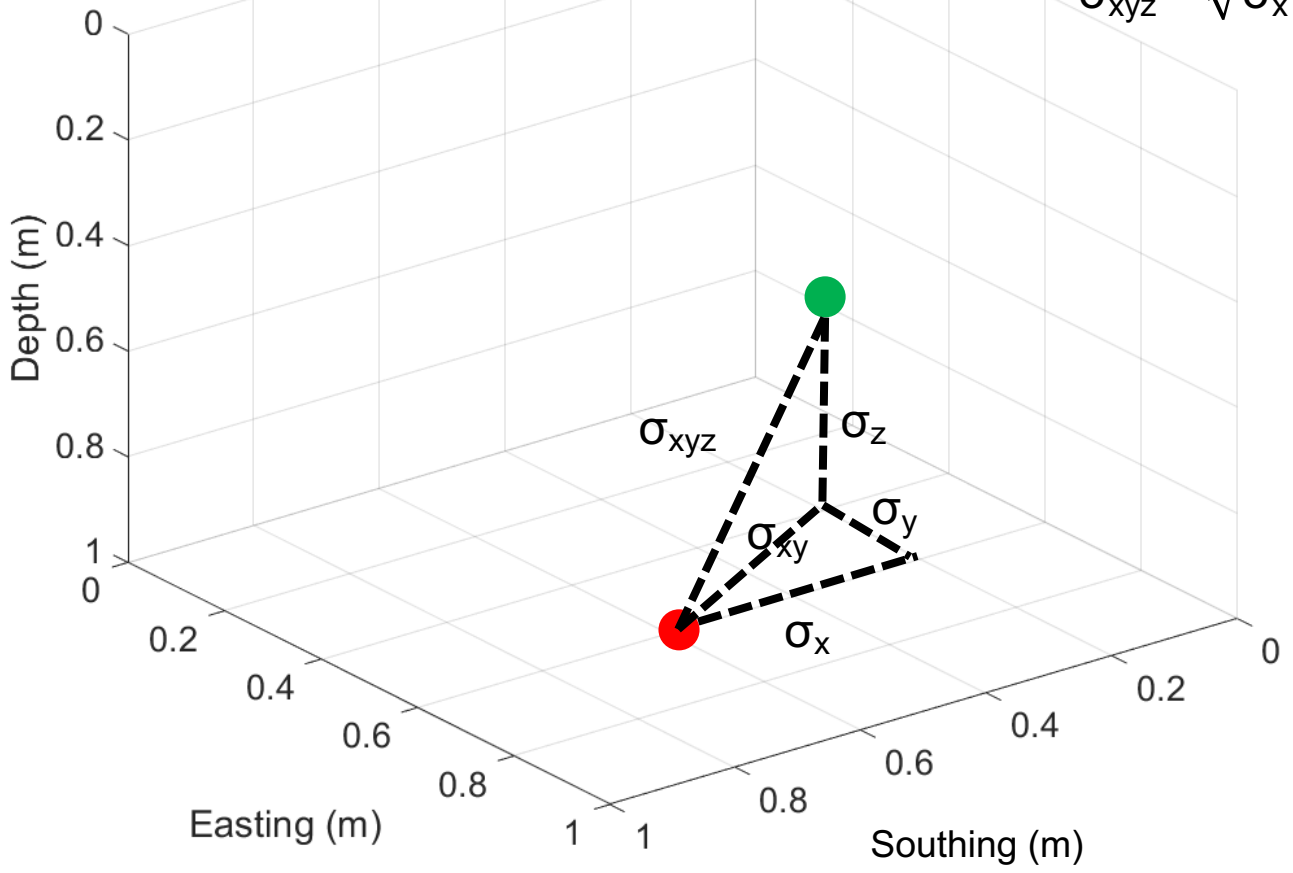


Performance Metrics

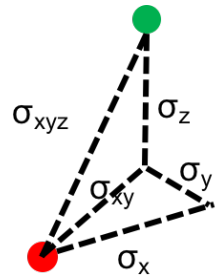
- GPS- and Ambient Pressure-derived “true” position
- localization-derived estimated position

$$\sigma_{xy} = \sqrt{\sigma_x^2 + \sigma_y^2}$$

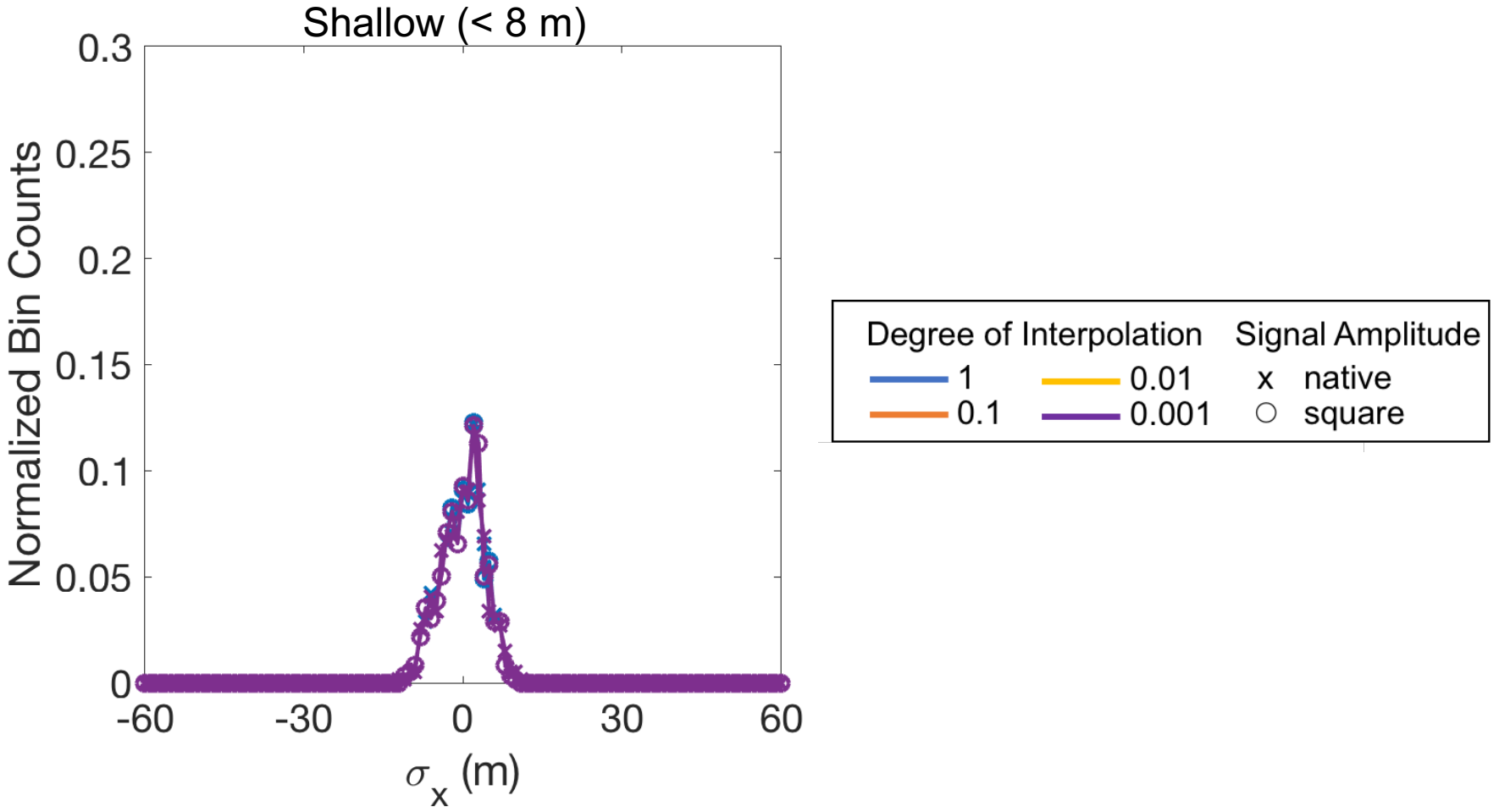
$$\sigma_{xyz} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$$



Error Distributions

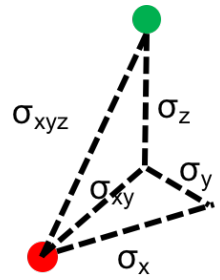


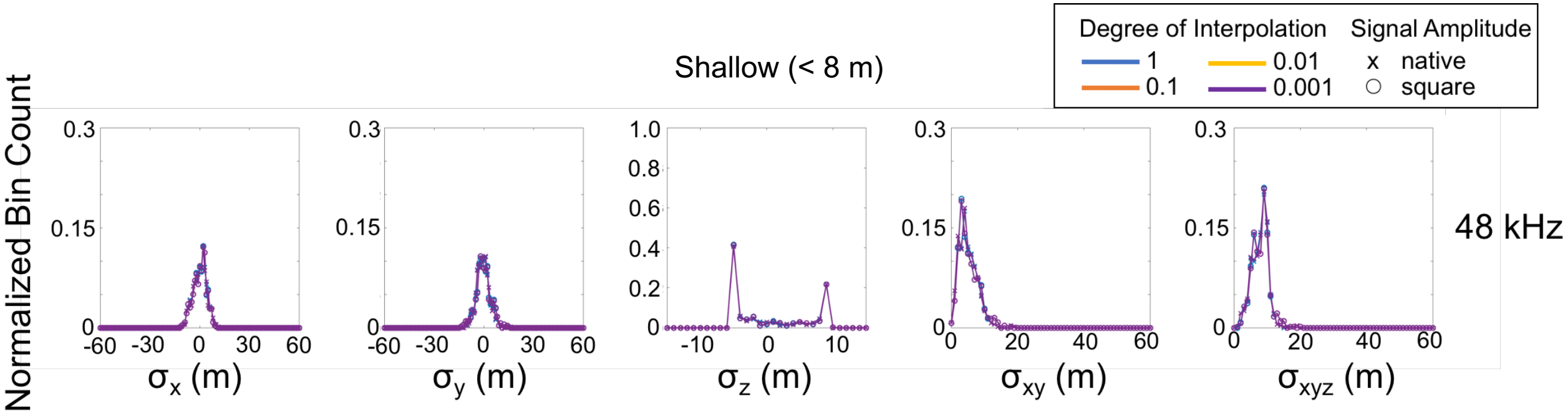
Method: TDOAs using waveform cross-correlation



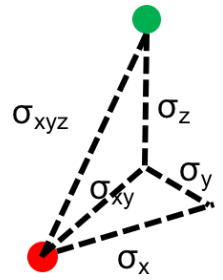
Error Distributions

Method: TDOAs using waveform cross-correlation





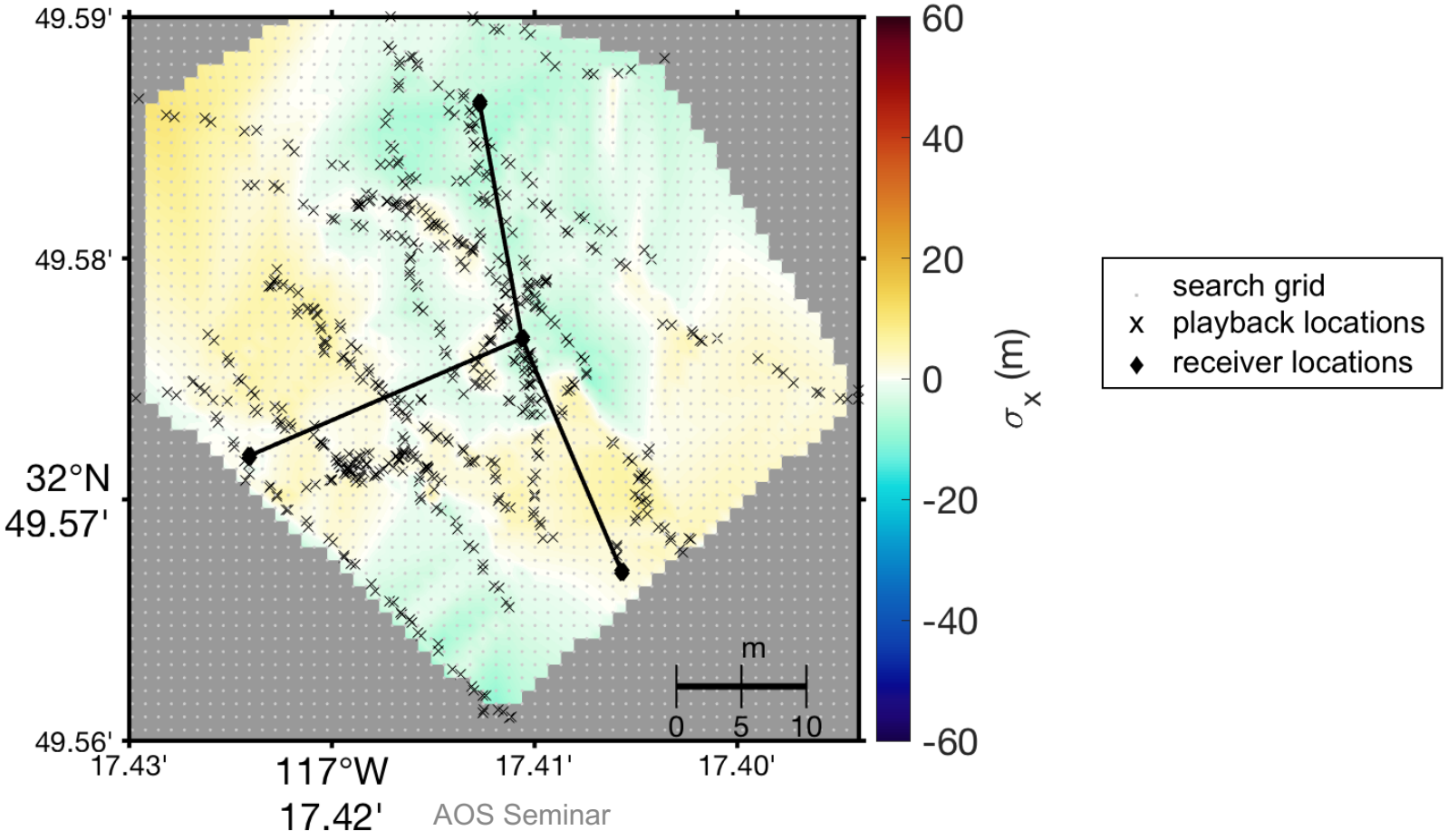
Error Surfaces



Method: TDOAs using waveform cross-correlation

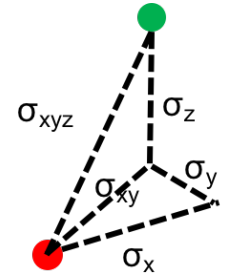
Shallow (< 8 m)

(Signal Amplitude: native, Degree of Interpolation: 1)



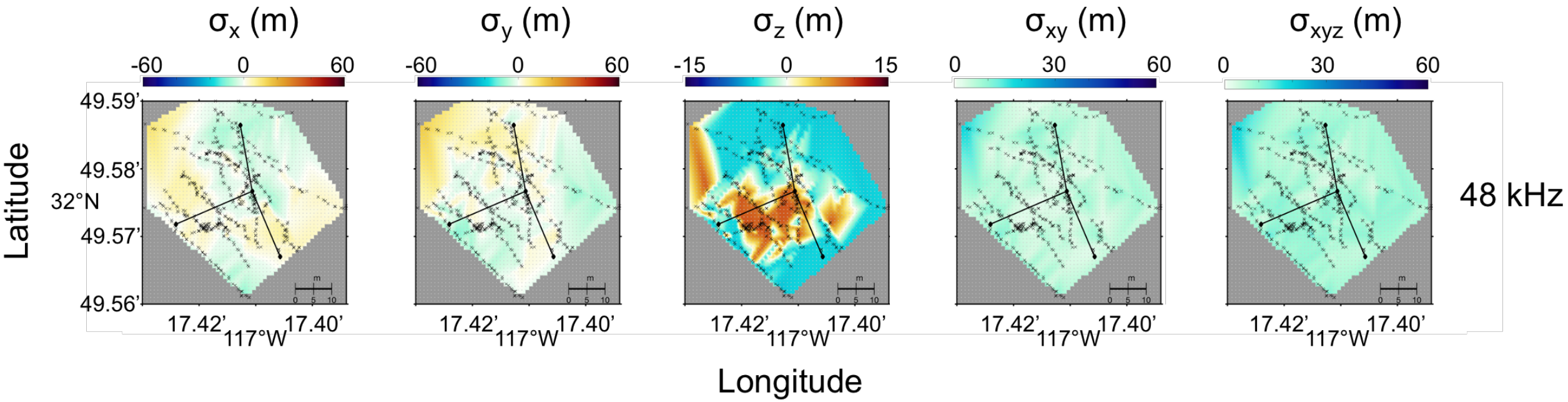
Error Surfaces

Method: TDOAs using waveform cross-correlation



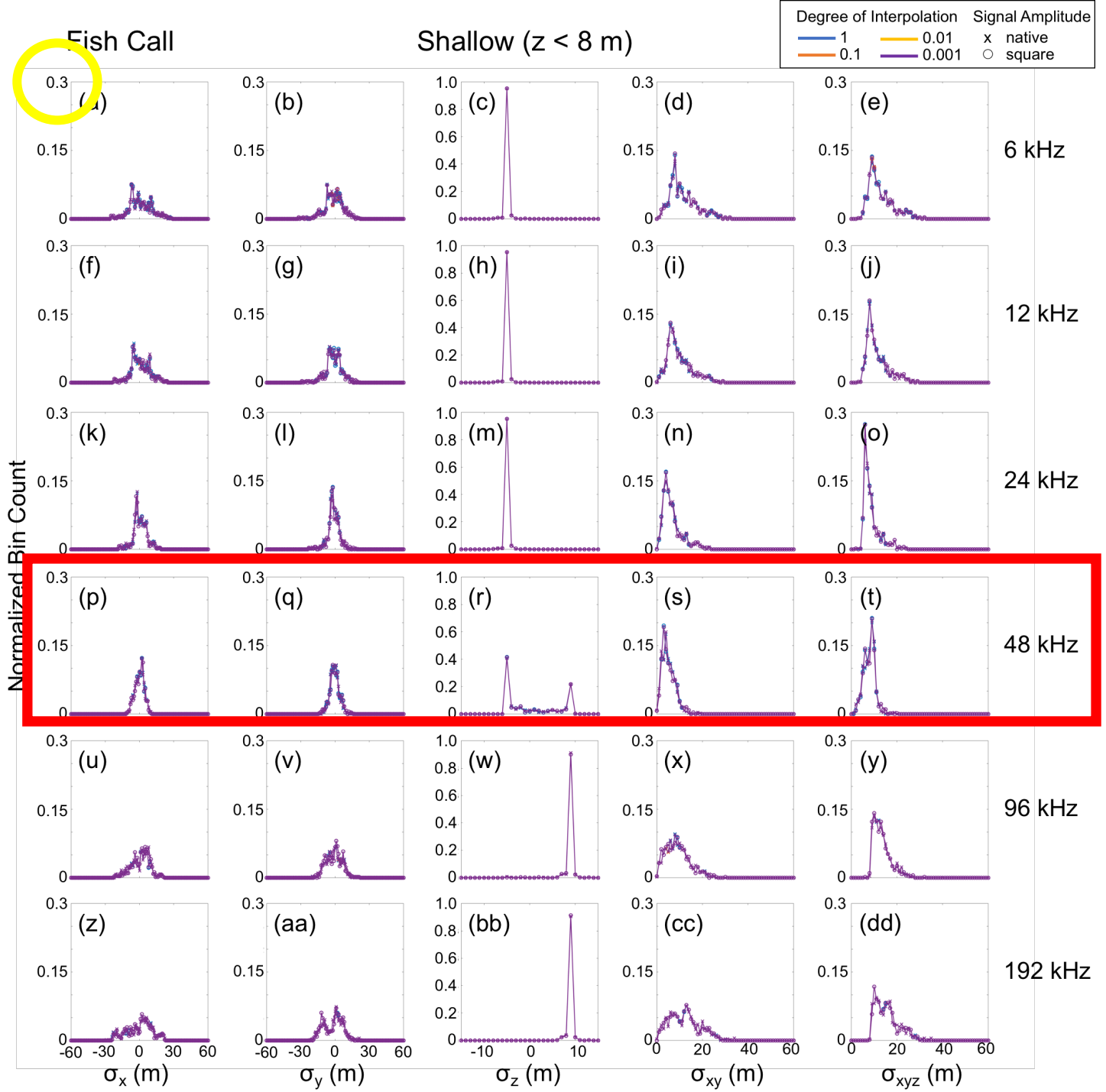
search grid
x playback locations
♦ receiver locations

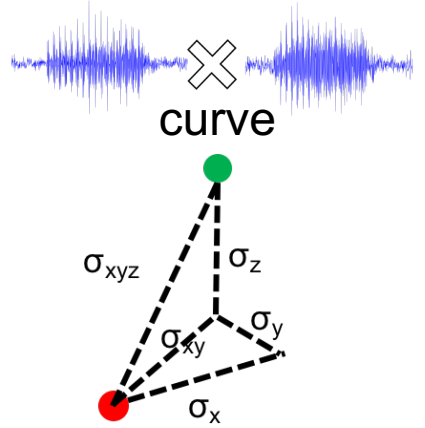
Shallow (< 8 m)
(Signal Amplitude: native, Degree of Interpolation: 1)



Parameter Selection

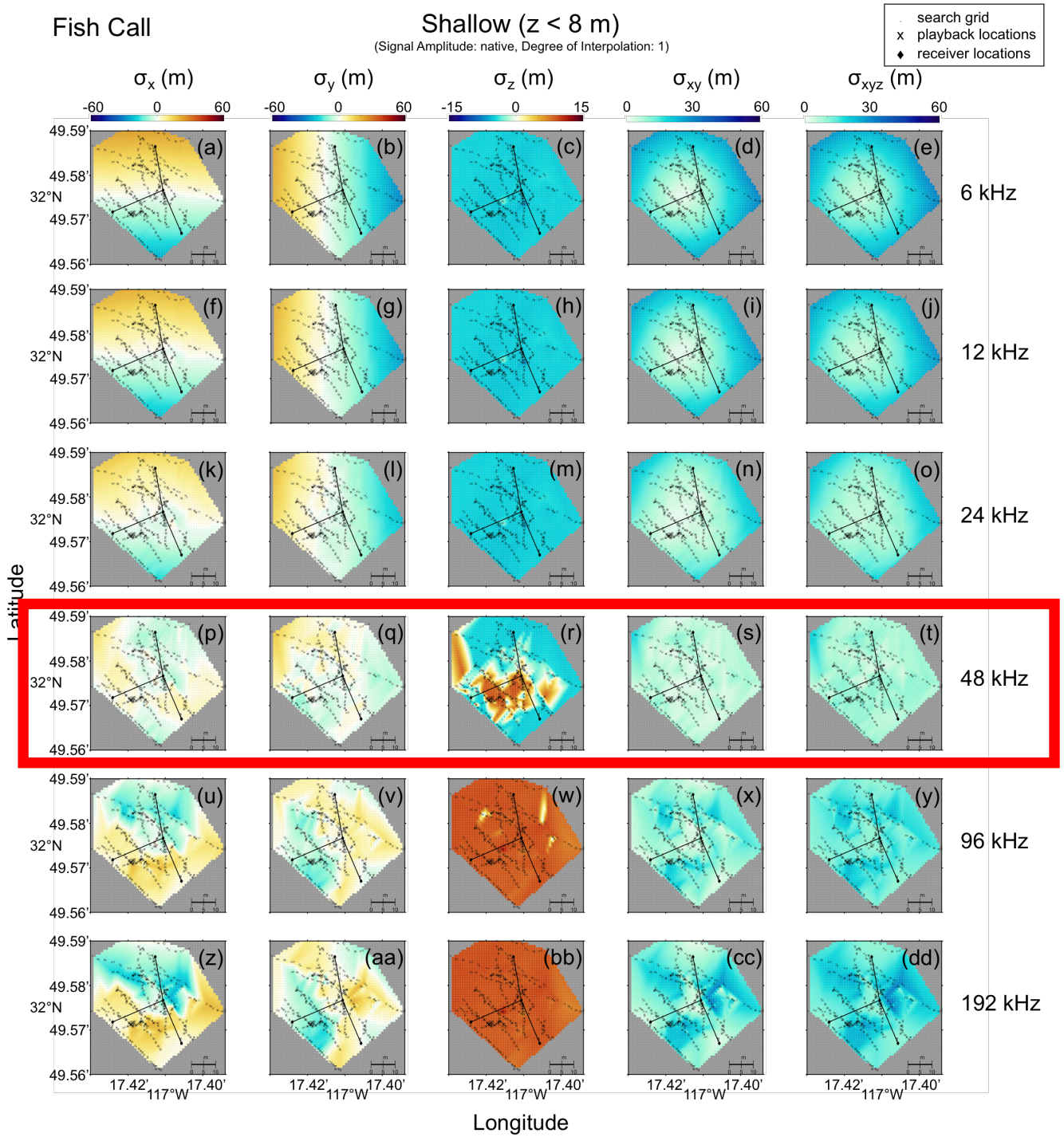
Method: TDOAs using waveform cross-correlation with curve wavefront

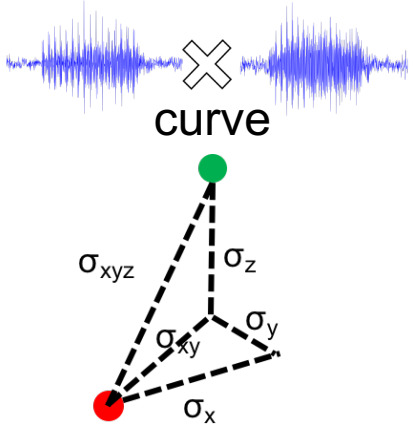




Parameter Selection

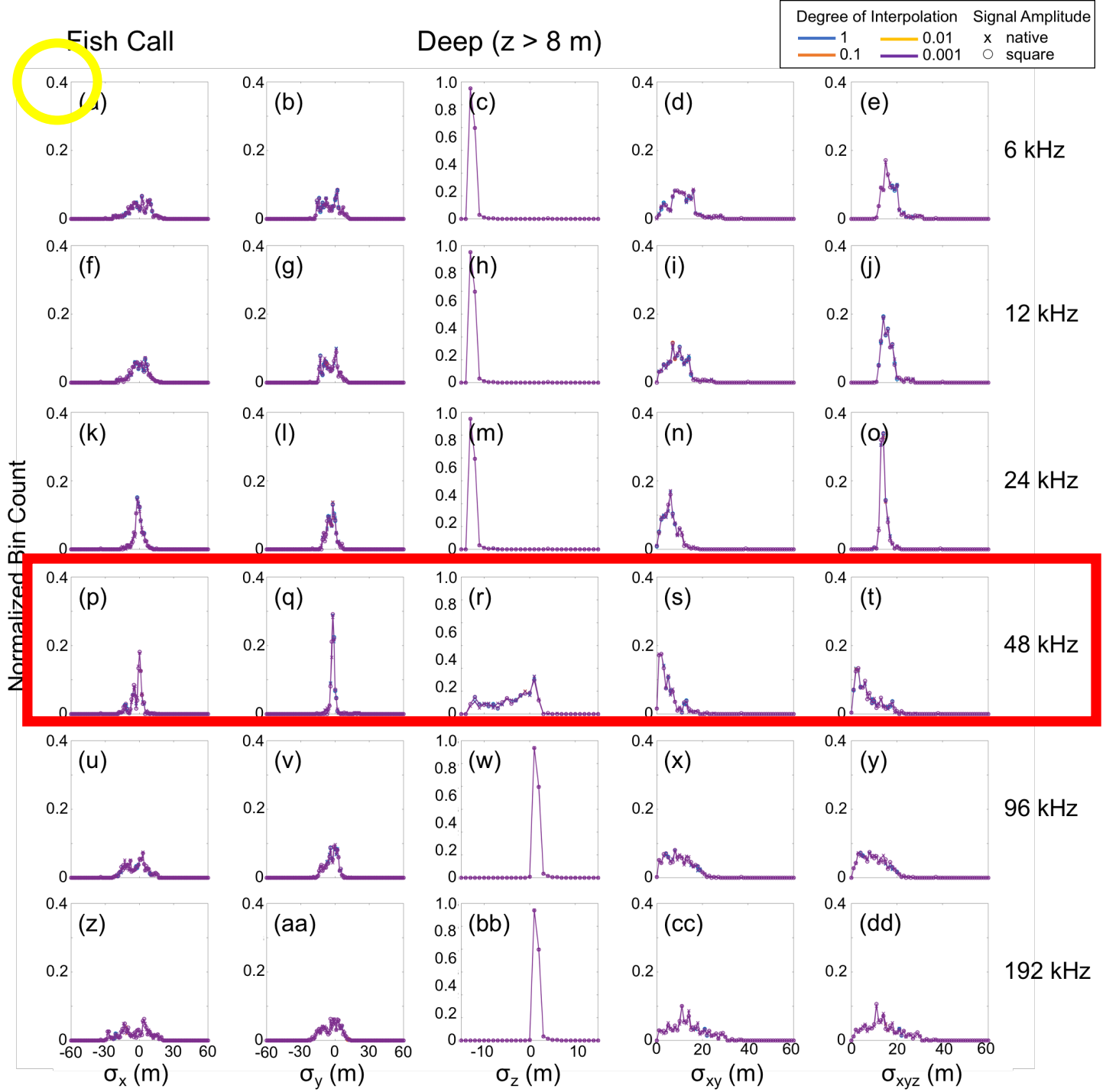
Method: TDOAs using waveform cross-correlation with curve wavefront

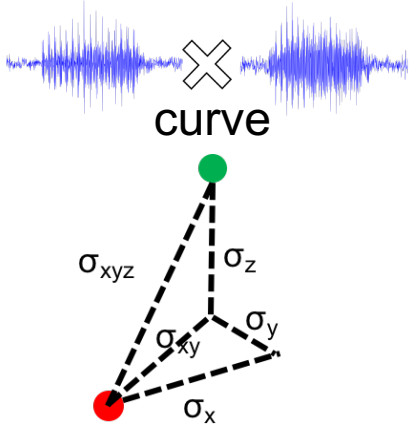




Parameter Selection

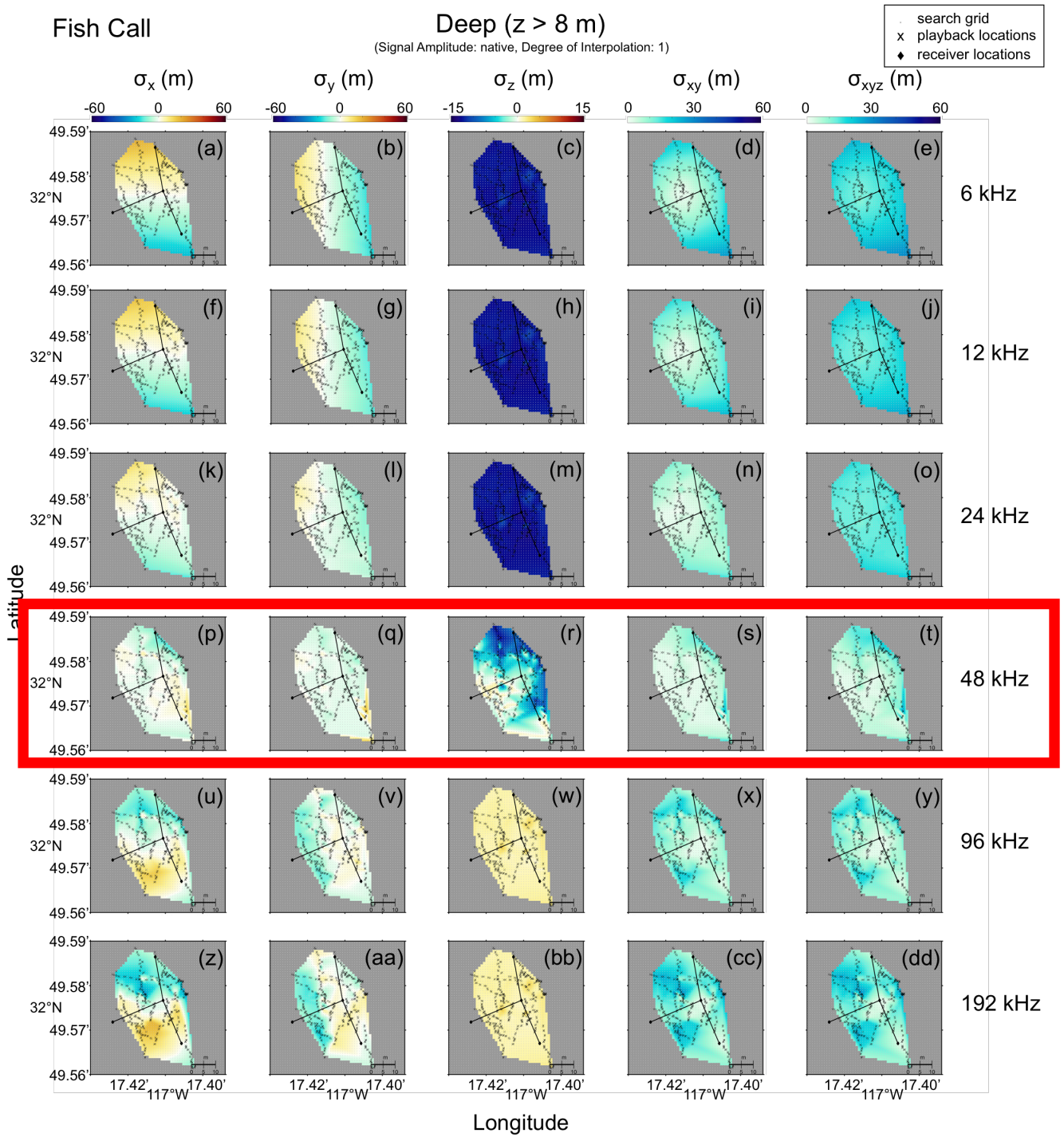
Method: TDOAs using waveform cross-correlation with curve wavefront

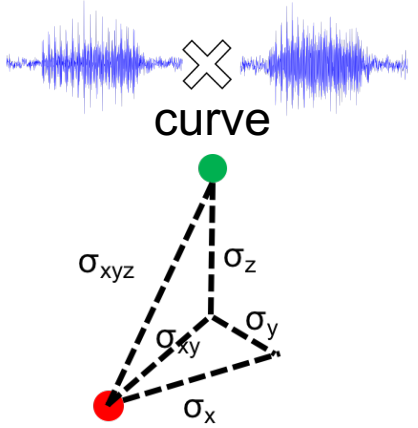


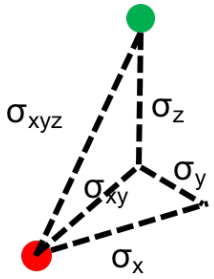


Parameter Selection

Method: TDOAs using waveform cross-correlation with curve wavefront







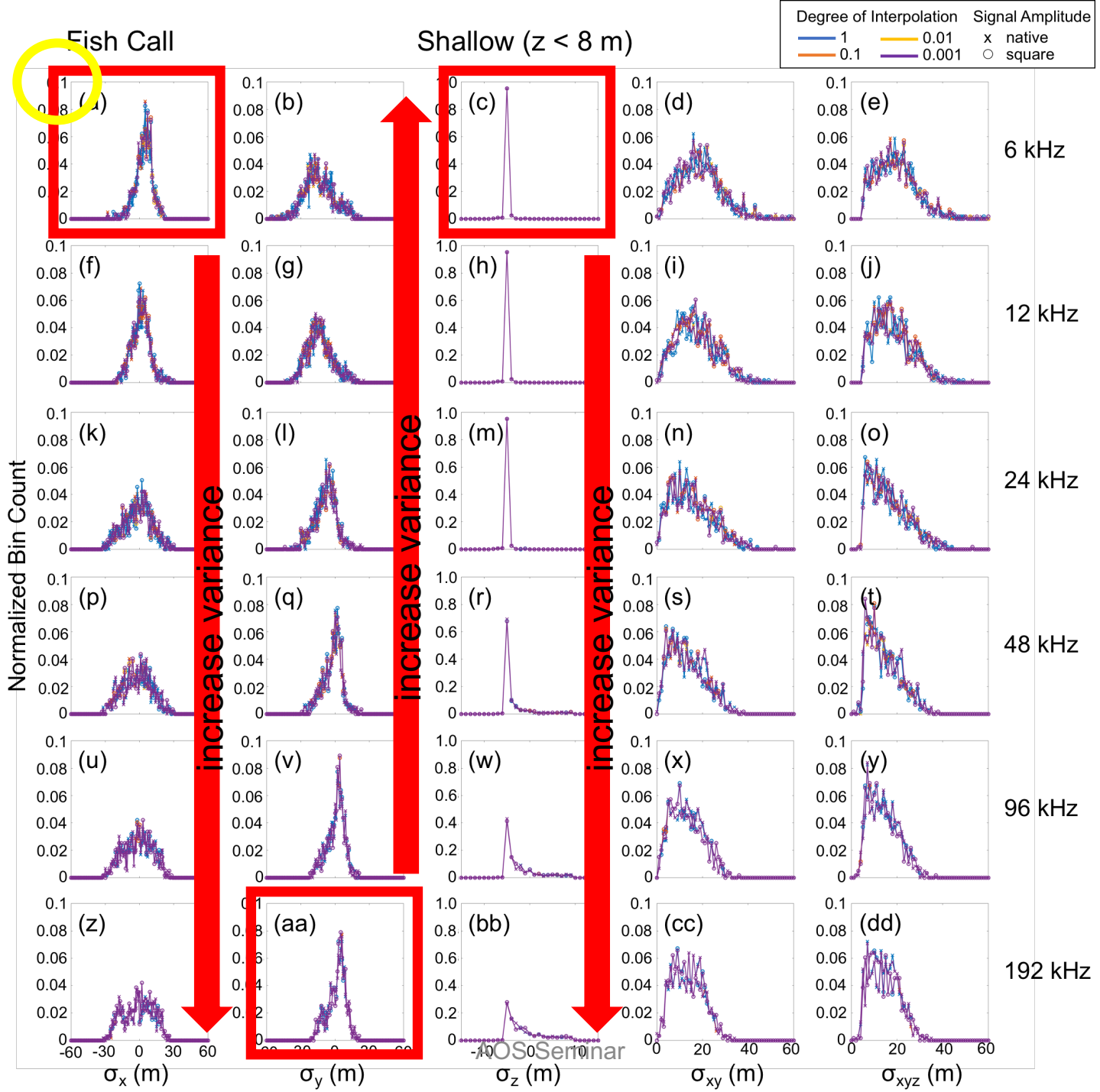
Parameter Selection

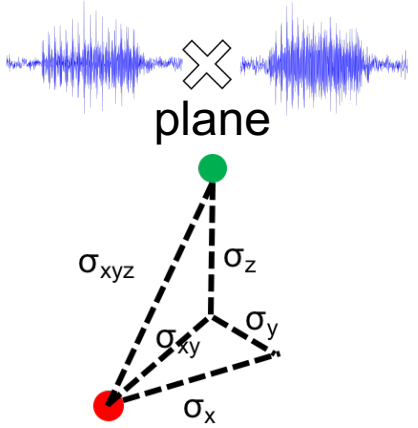
Method: TDOAs using waveform cross-correlation with curve wavefront

- changing the sampling frequency decreases localization performance for both shallow and deep sources
  - possibly related to playback and recording sampling frequency
- degree of quadratic interpolation of the cross-correlation output and signal amplitude have zero effect on localization performance for both shallow and deep sources
  - only increase computation time
- localization performance is higher for deep sources (vs. shallow sources)
  - more direct path to receivers
  - but, fewer playbacks for deep sources

Parameter Selection

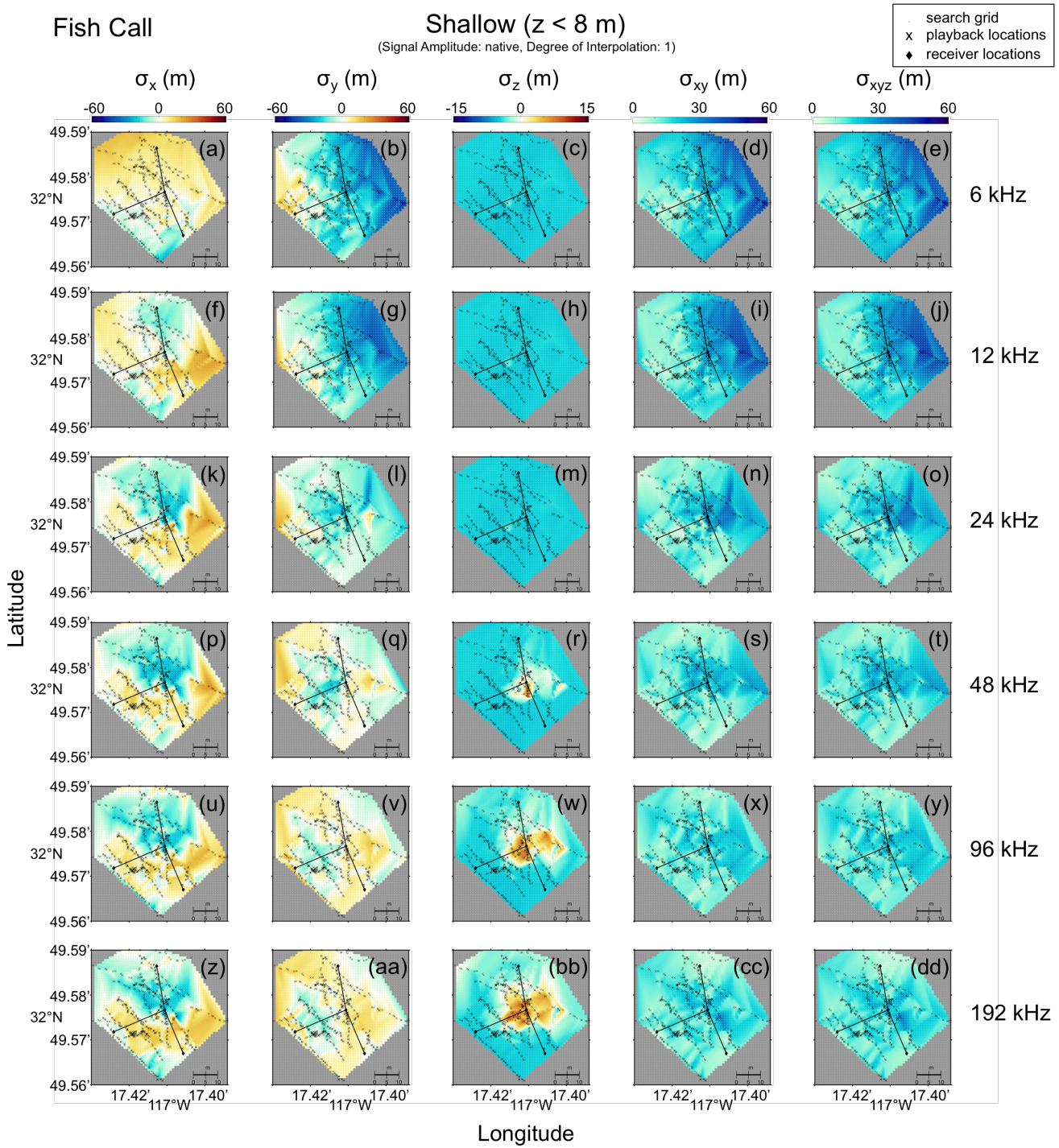
Method: TDOAs using waveform cross-correlation with plane wavefront

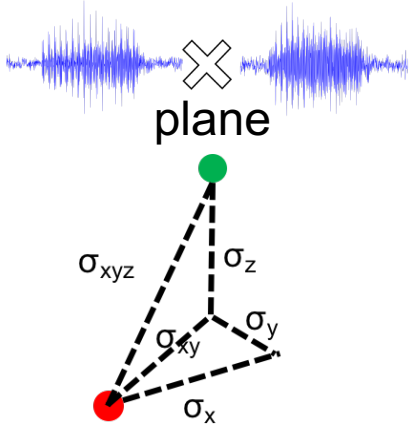




Parameter Selection

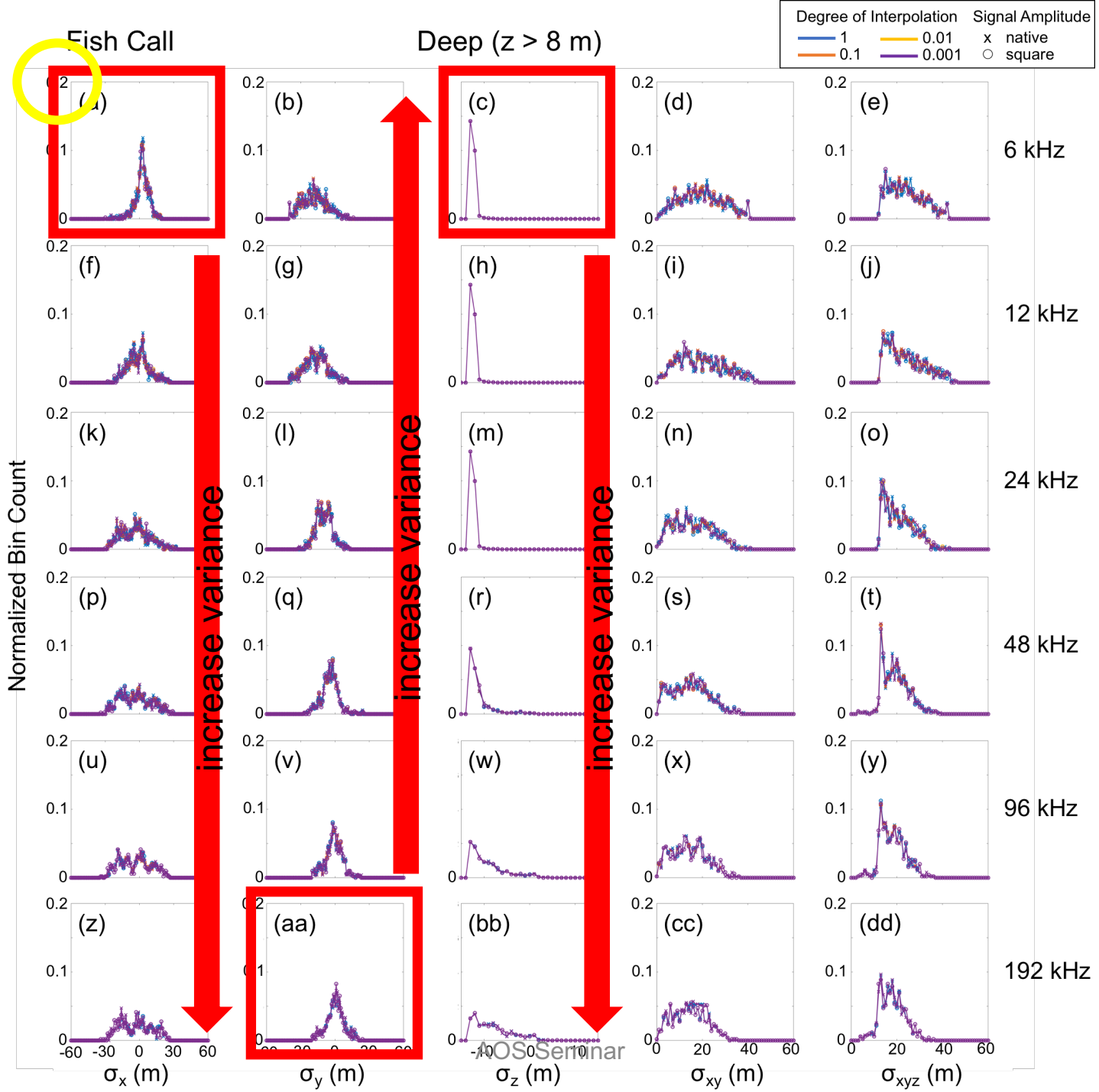
Method: TDOAs using waveform cross-correlation with plane wavefront

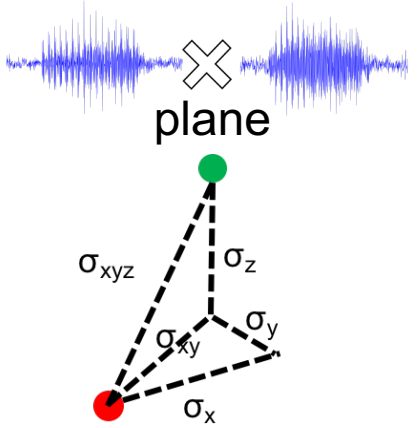




Parameter Selection

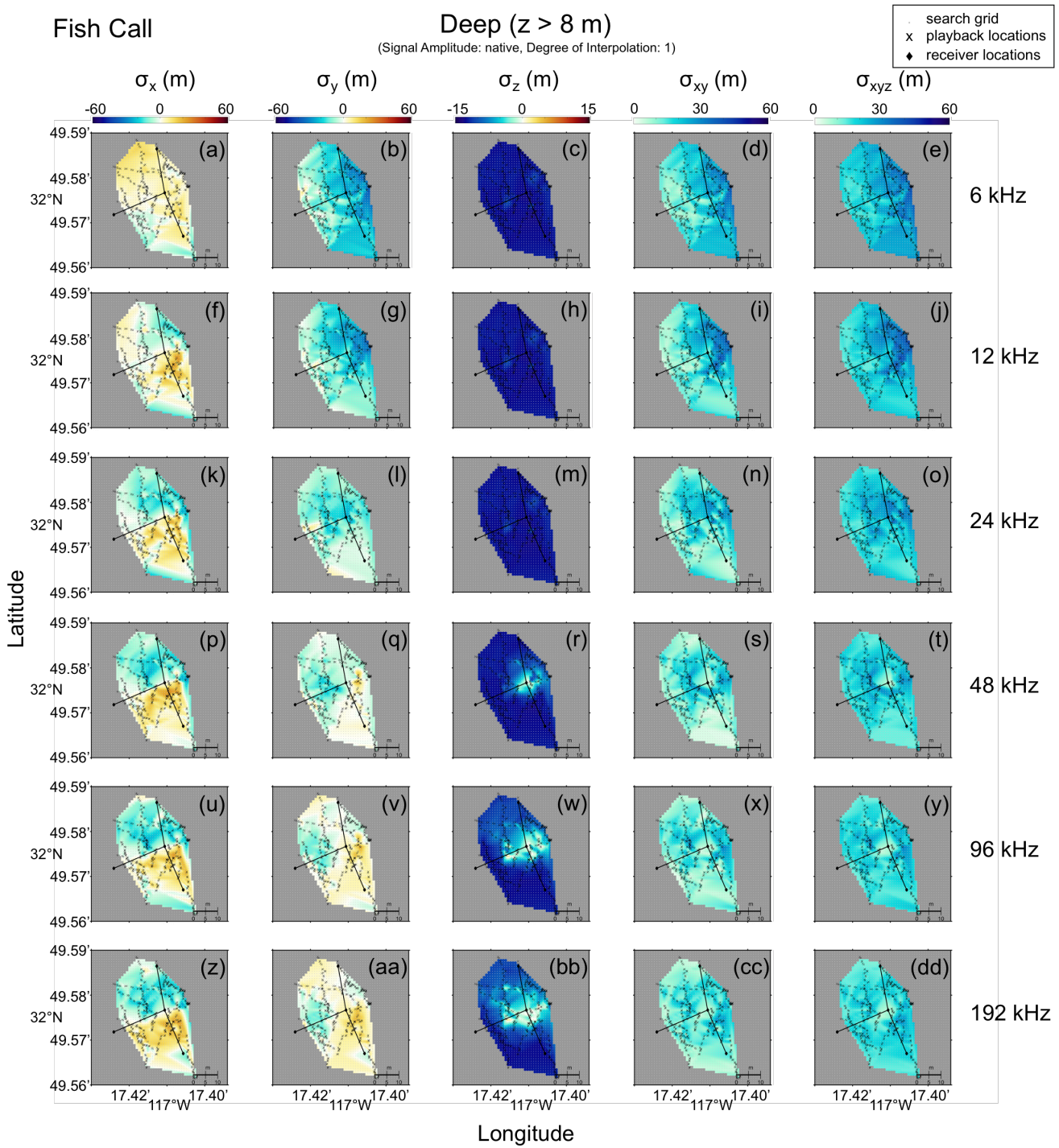
Method: TDOAs using waveform cross-correlation with plane wavefront

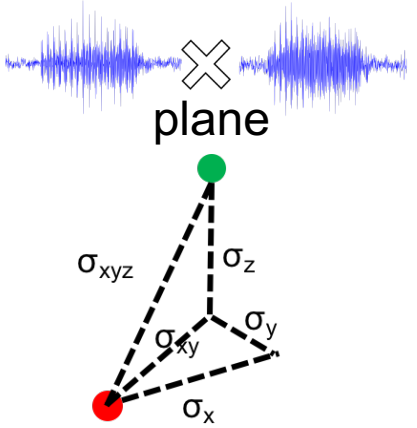


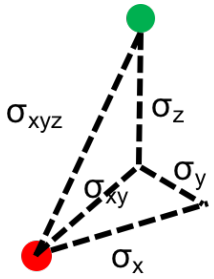


Parameter Selection

Method: TDOAs using waveform cross-correlation with plane wavefront







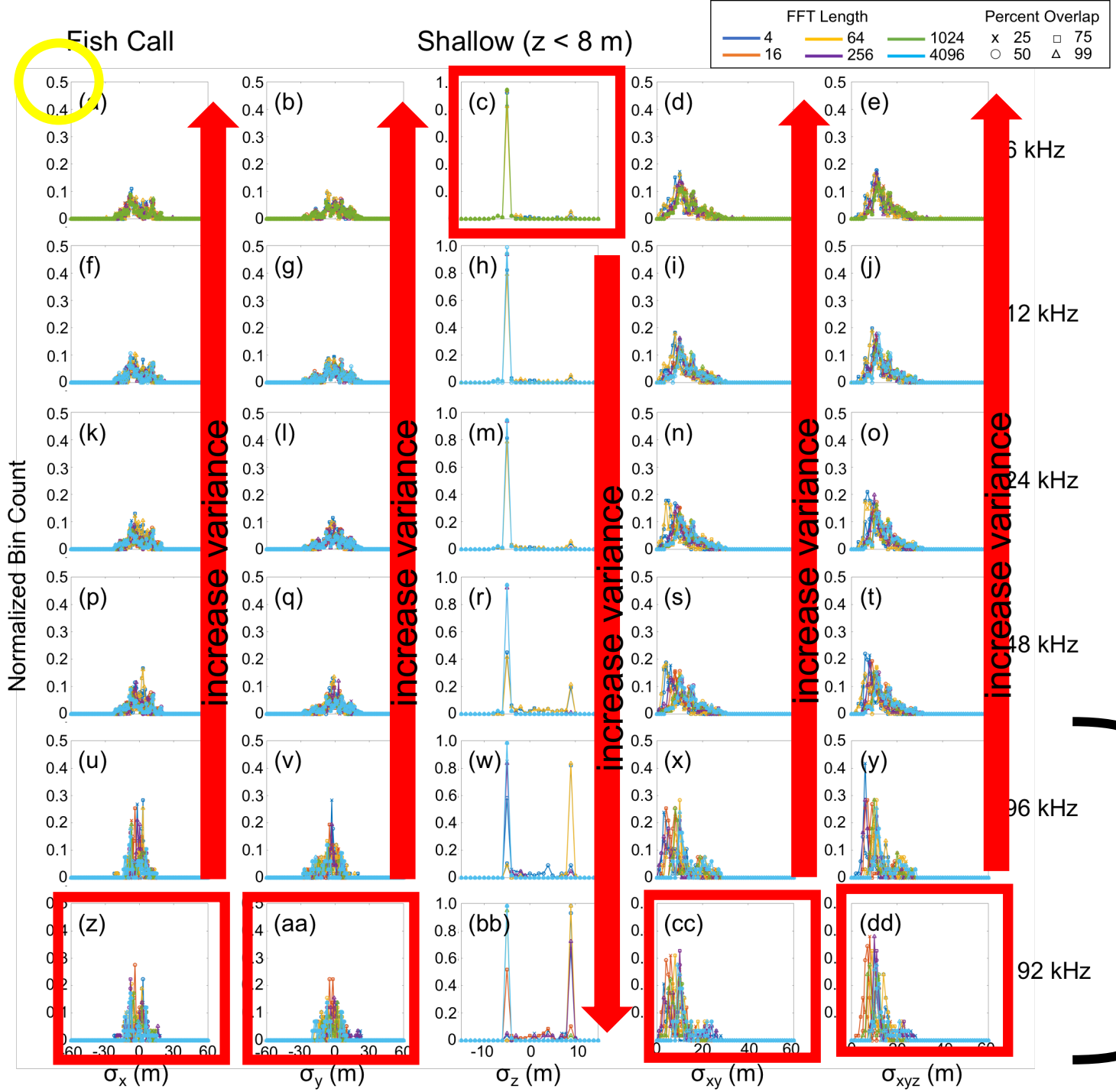
Parameter Selection

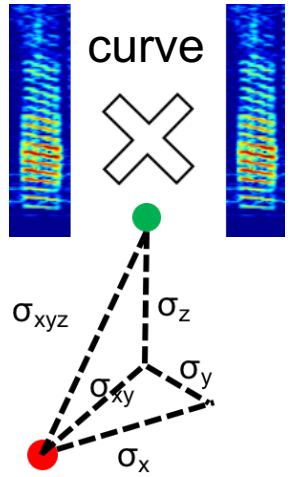
Method: TDOAs using waveform cross-correlation with plane wavefront

- propagation physics do not match plane-wavefront
- sampling frequency has variable effect on localization performance in each dimension
  - ↑ f_s : ↑ variance of σ_x and σ_z
  - ↑ f_s : ↓ variance of σ_y
  - little change in bias in each dimension (most in σ_y)
- degree of quadratic interpolation of the cross-correlation output and signal amplitude have little effect on localization performance for both shallow and deep sources
- localization performance is higher for deep sources (vs. shallow sources)
  - more direct path to receivers
  - but, fewer playbacks for deep sources

Parameter Selection

Method: TDOAs using spectrogram cross-correlation with curve wavefront

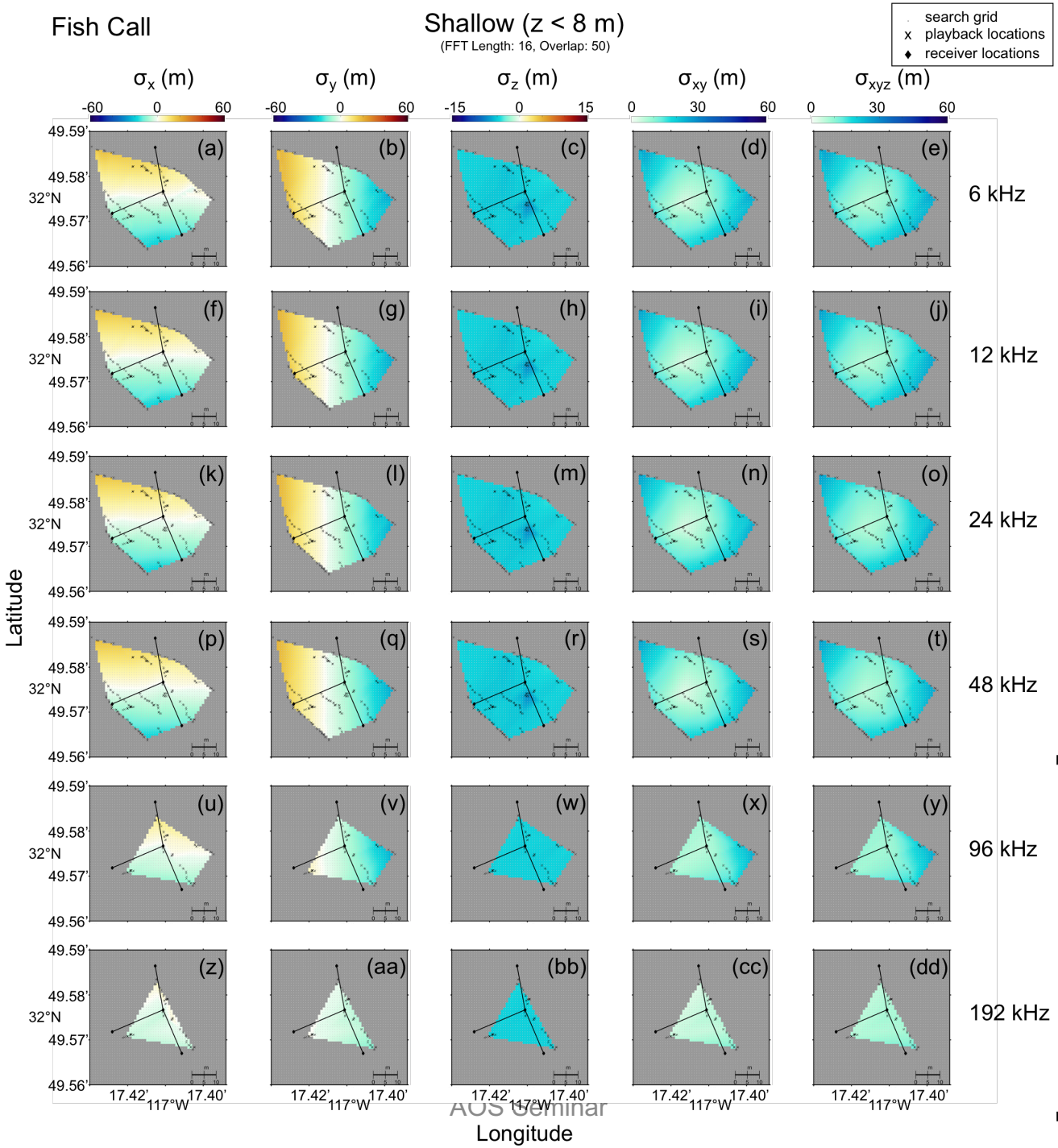


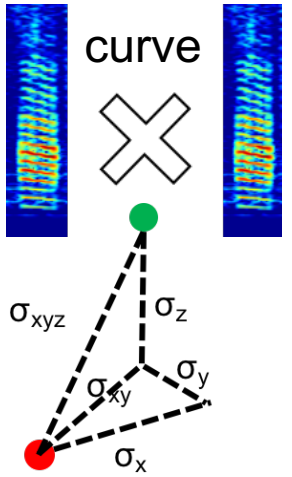


a lot fewer points

Parameter Selection

Method: TDOAs using spectrogram cross-correlation with curve wavefront

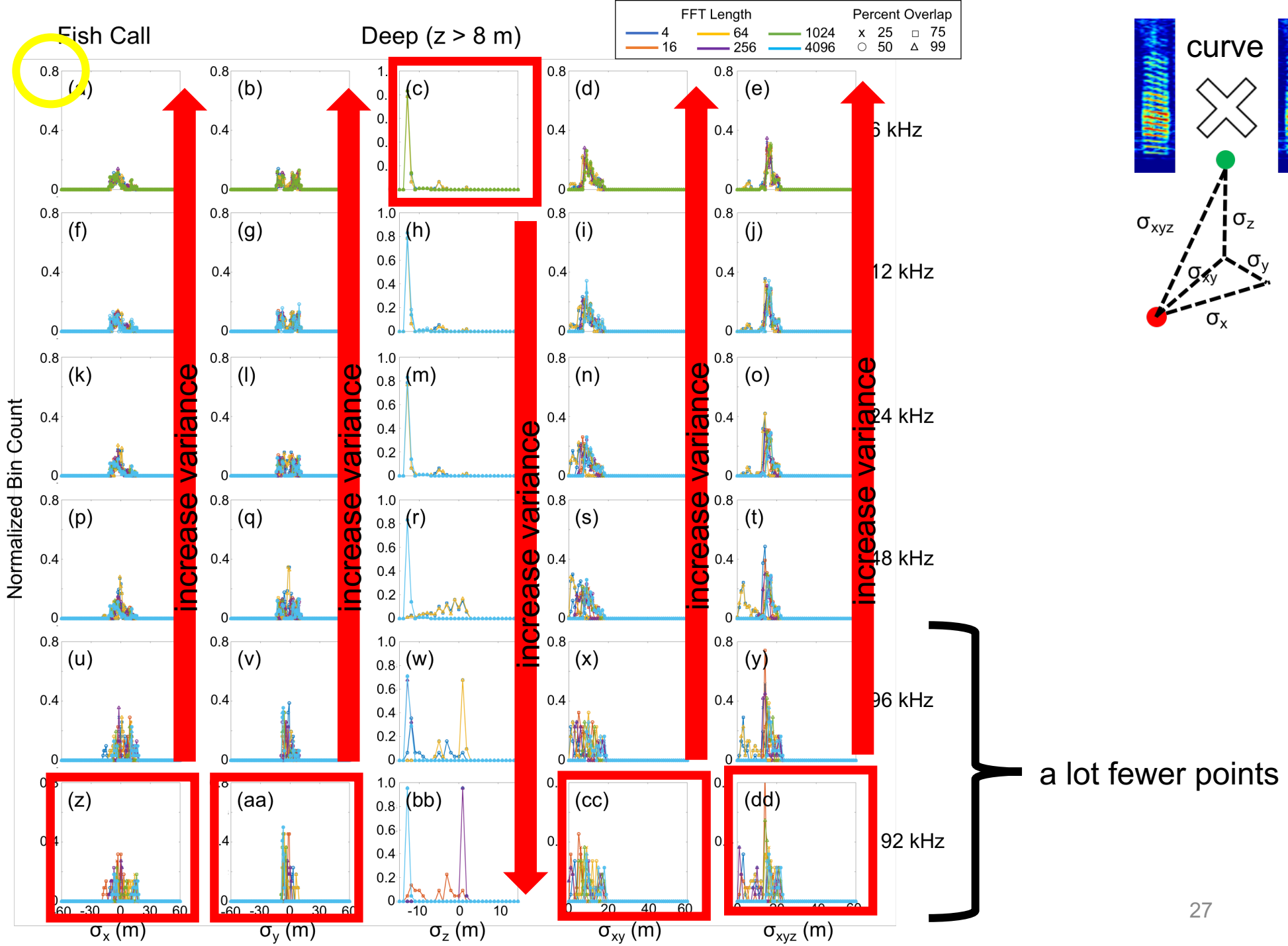




a lot fewer points

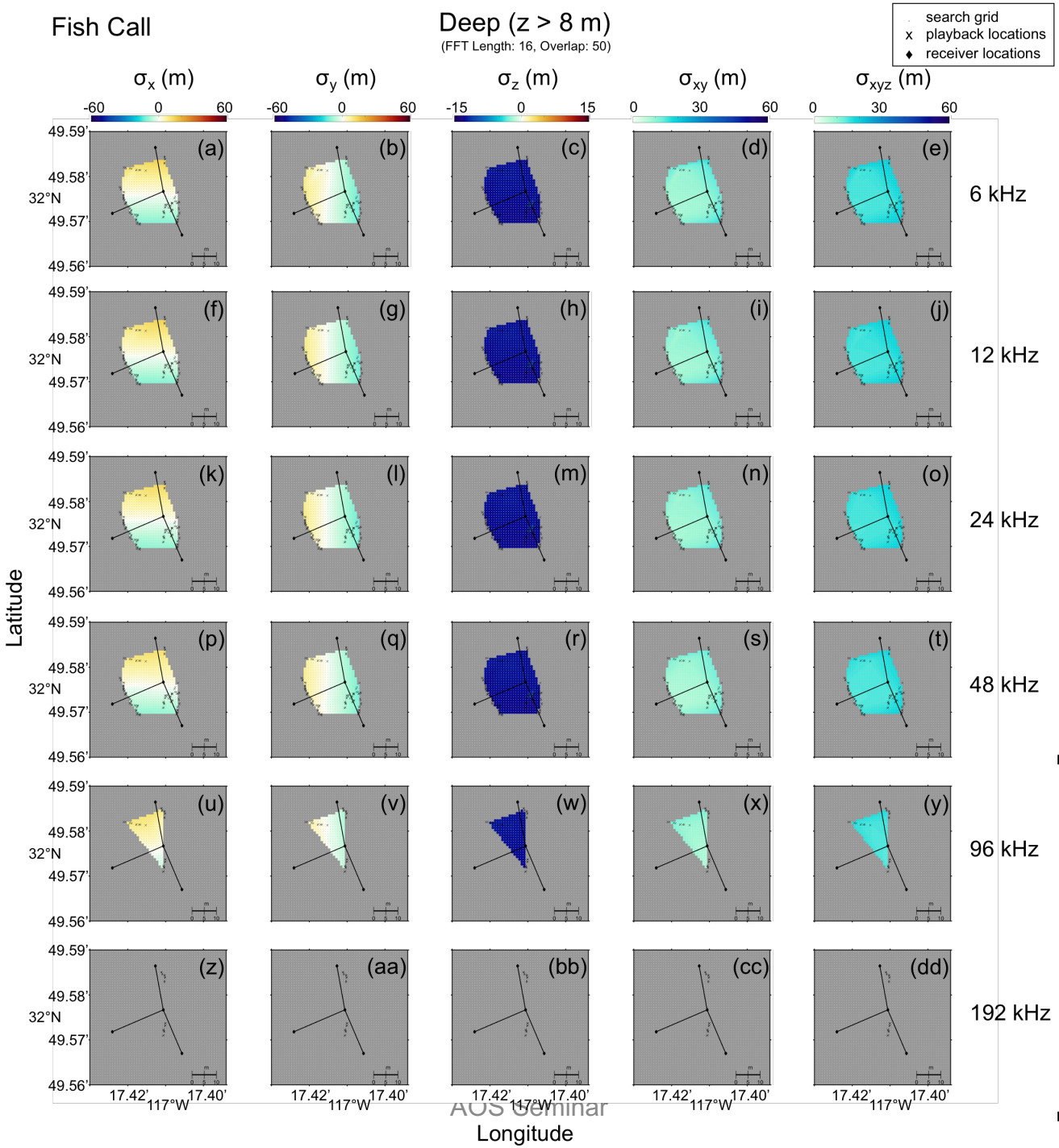
Parameter Selection

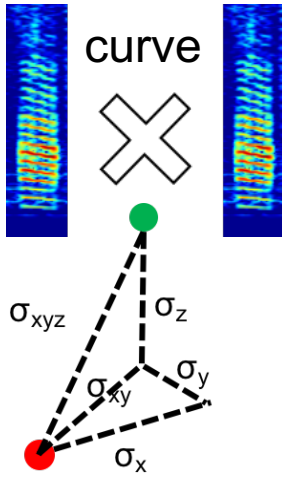
Method: TDOAs using spectrogram cross-correlation with curve wavefront



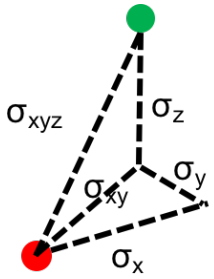
Parameter Selection

Method: TDOAs using spectrogram cross-correlation with curve wavefront



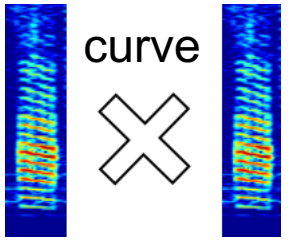


a lot fewer points



Parameter Selection

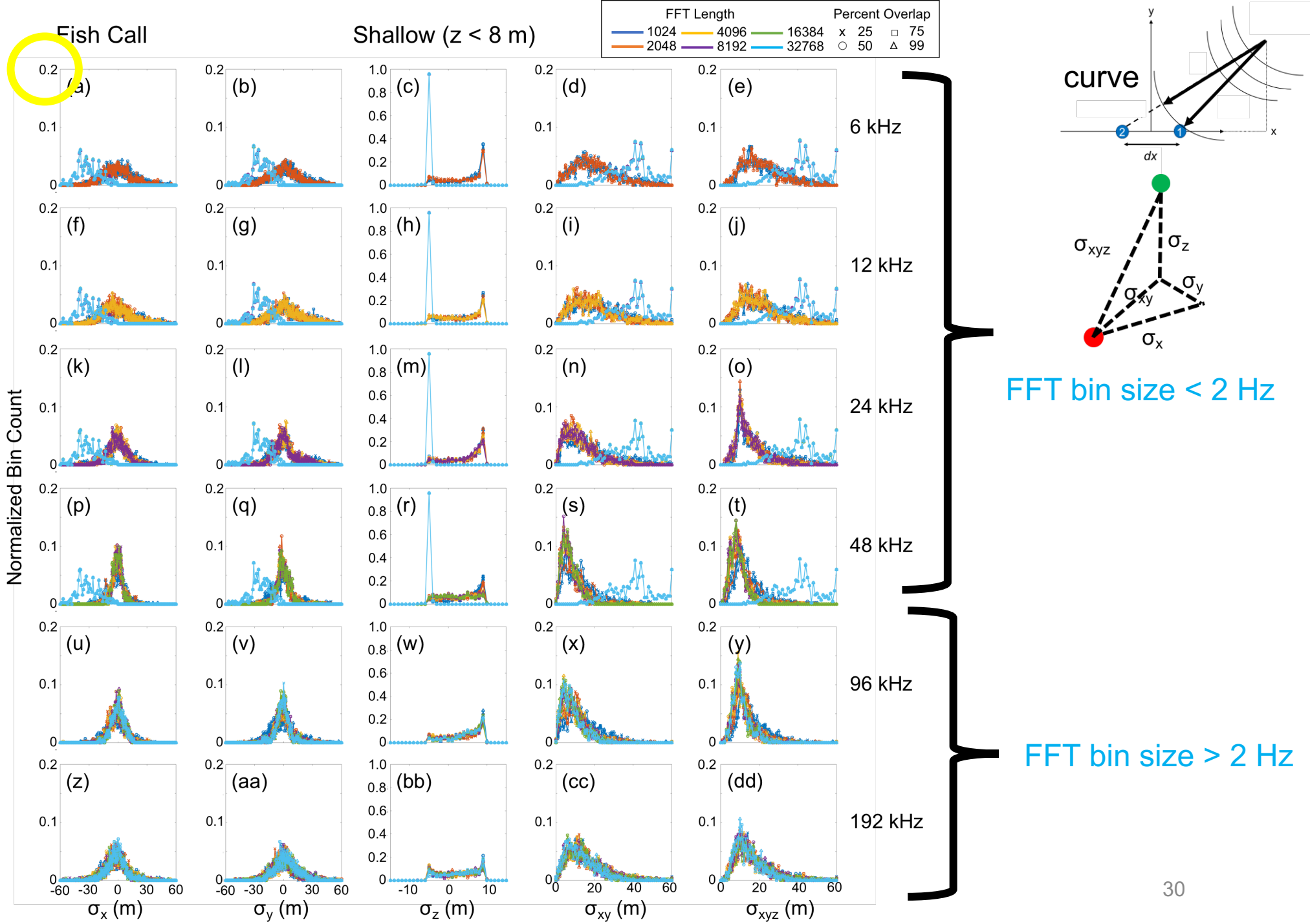
Method: TDOAs using spectrogram cross-correlation with curve wavefront



- increasing sampling frequency possibly improves localization performance
  - but at a huge computational cost (i.e., this is slowest method by far)
- too few points localized with highest sampling frequency to make strong conclusion

Parameter Selection

Method: curve-wavefront frequency-domain beamforming

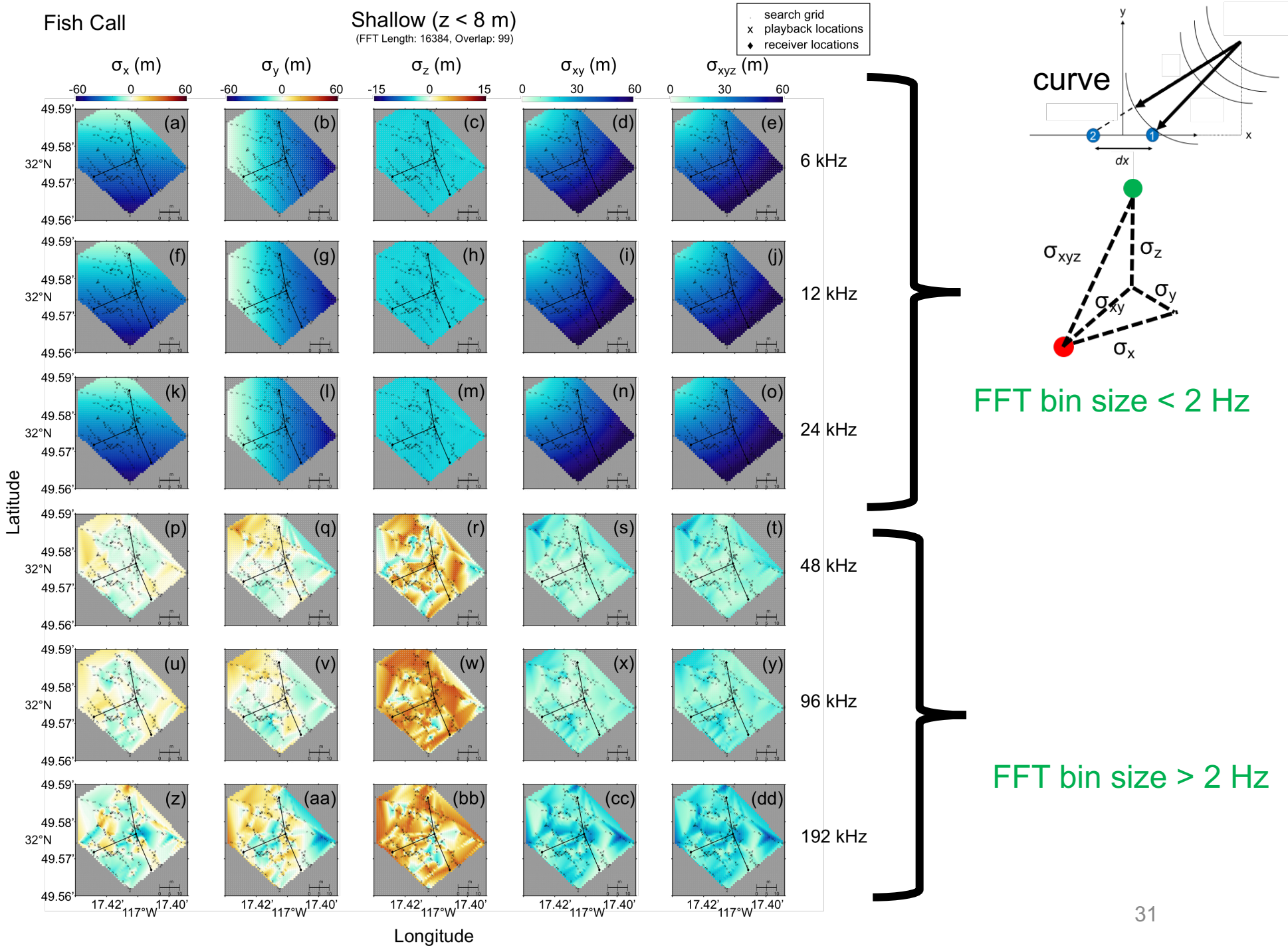


FFT bin size < 2 Hz

FFT bin size > 2 Hz

Parameter Selection

Method: curve-wavefront frequency-domain beamforming

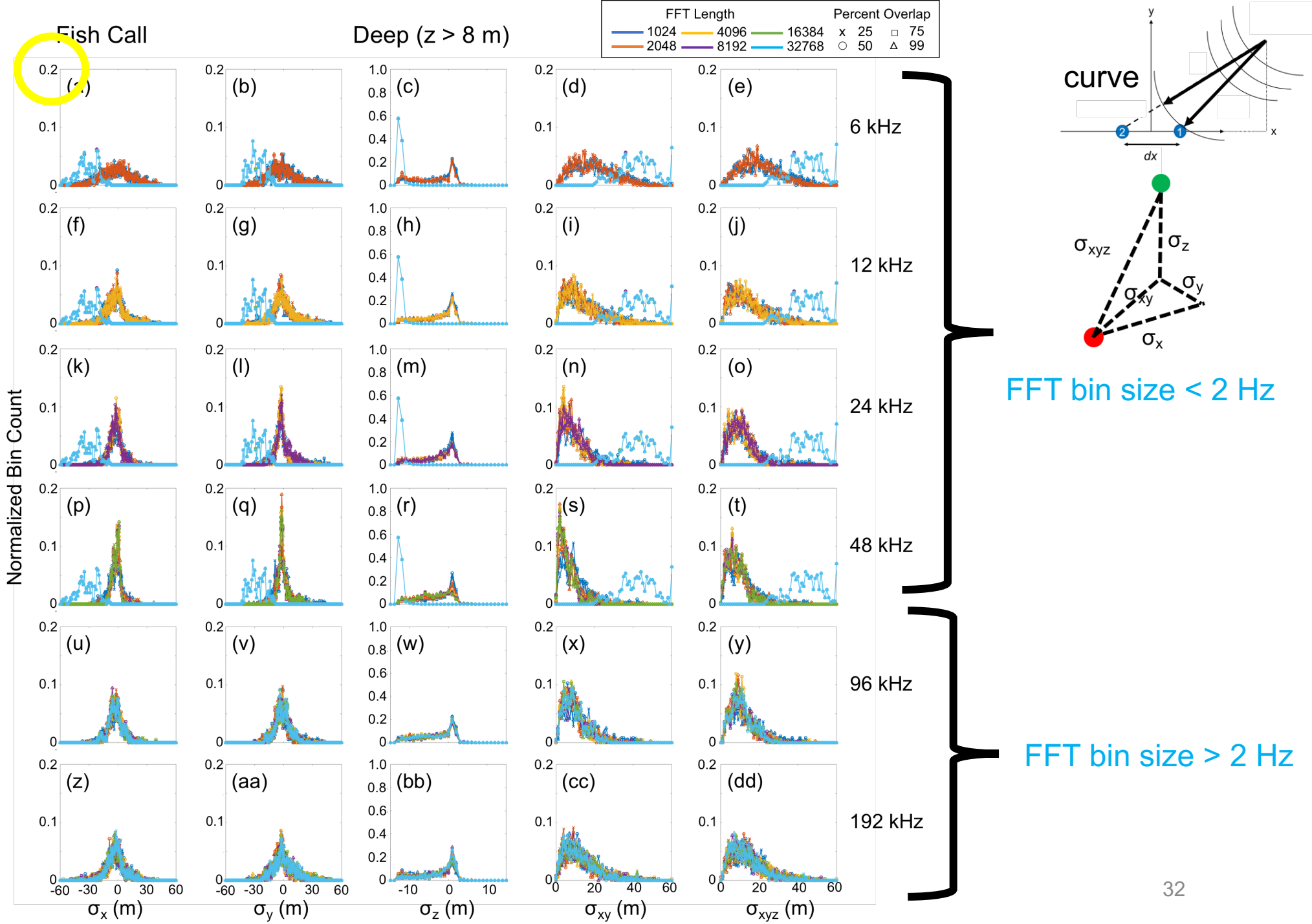


FFT bin size < 2 Hz

FFT bin size > 2 Hz

Parameter Selection

Method: curve-wavefront frequency-domain beamforming

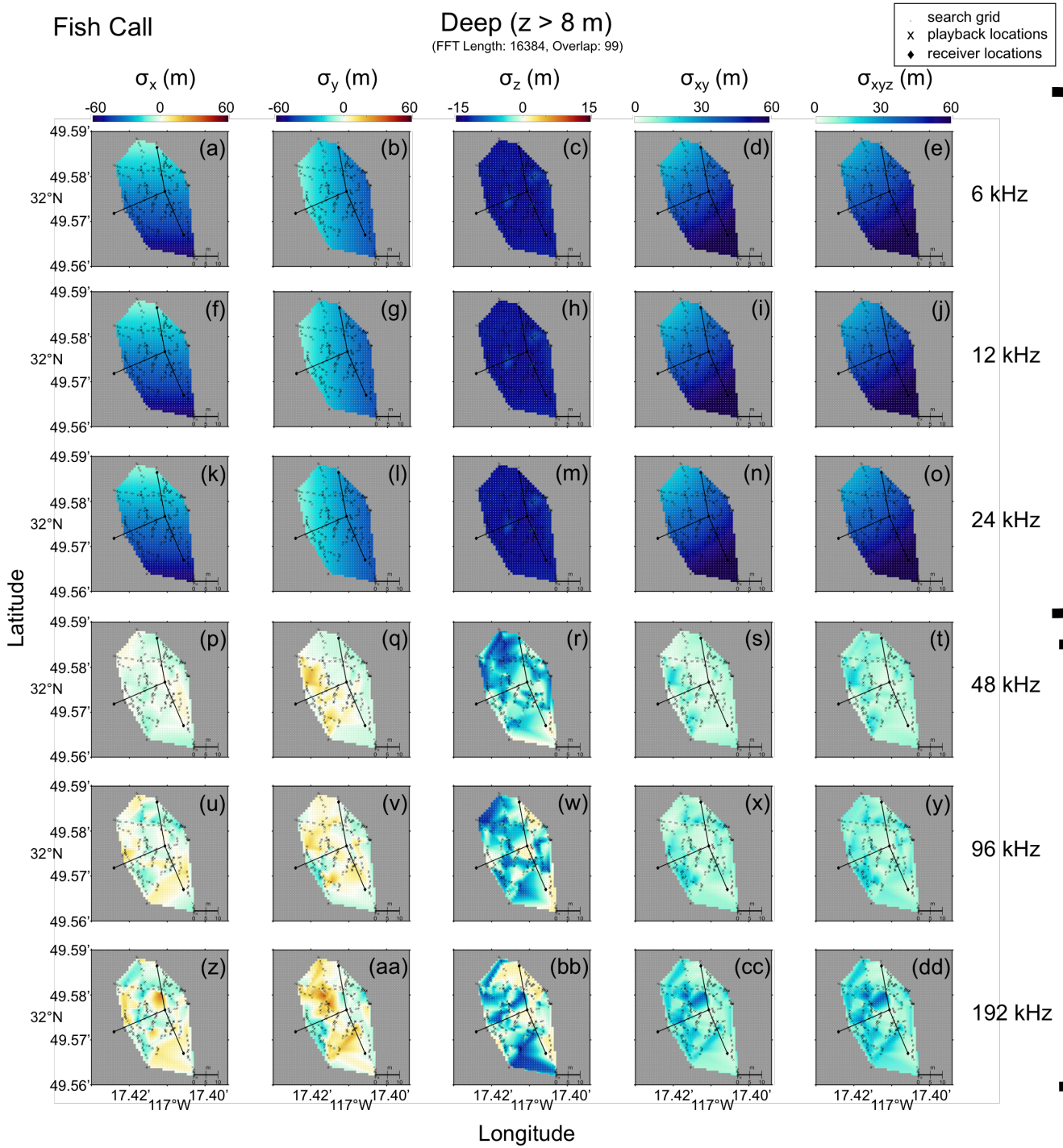


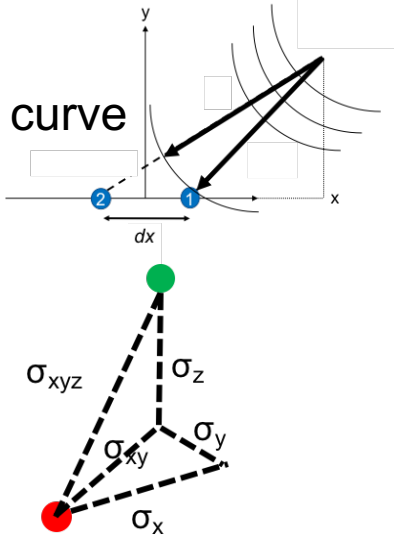
FFT bin size < 2 Hz

FFT bin size > 2 Hz

Parameter Selection

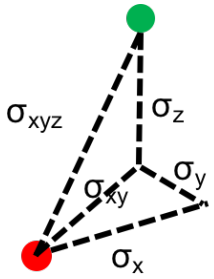
Method: curve-wavefront frequency-domain beamforming

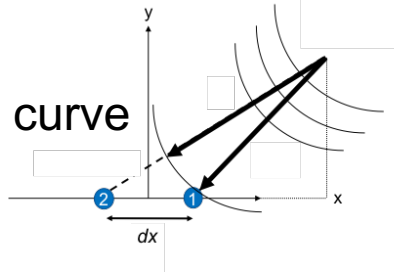




FFT bin size < 2 Hz

FFT bin size > 2 Hz





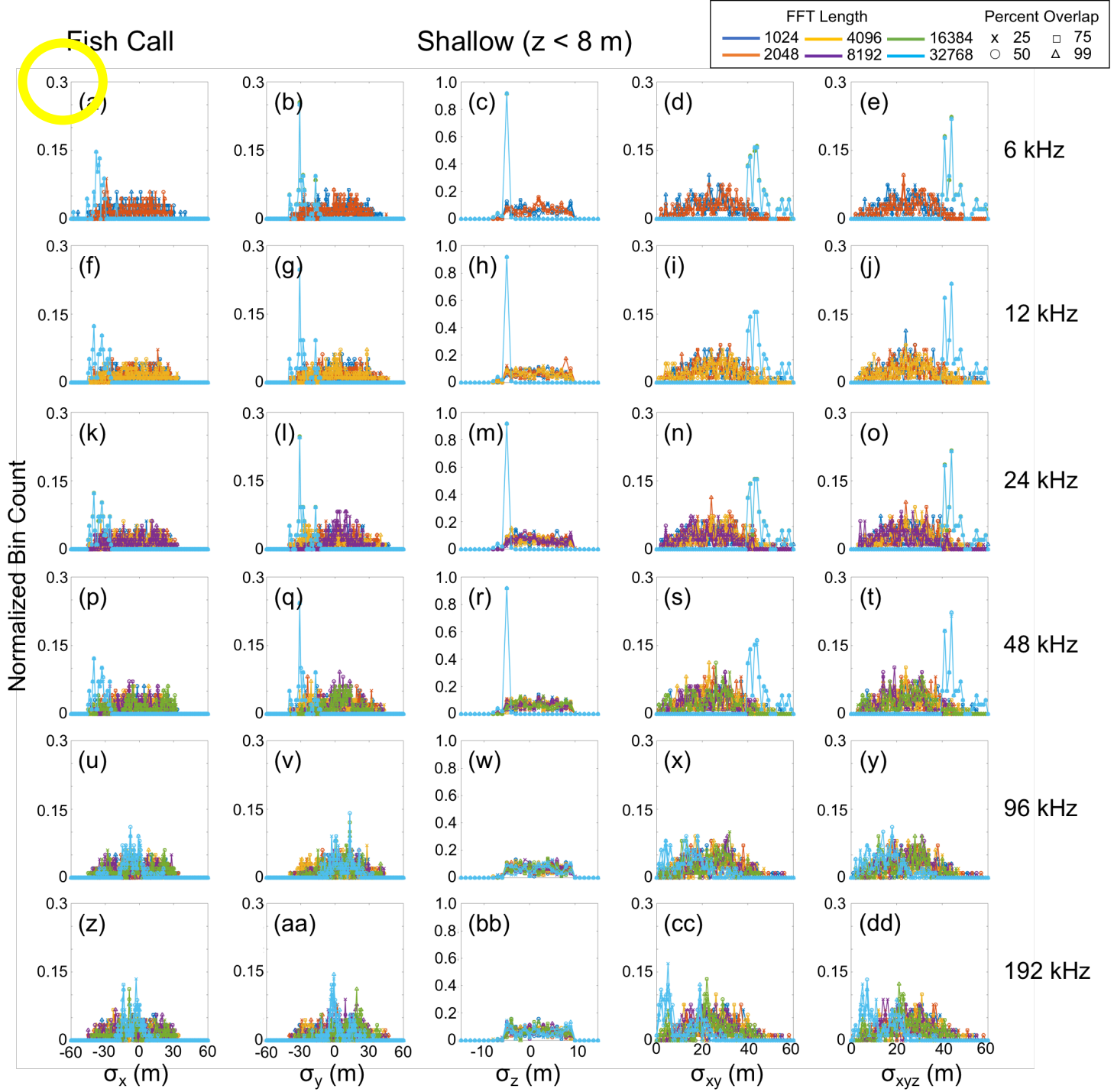
Parameter Selection

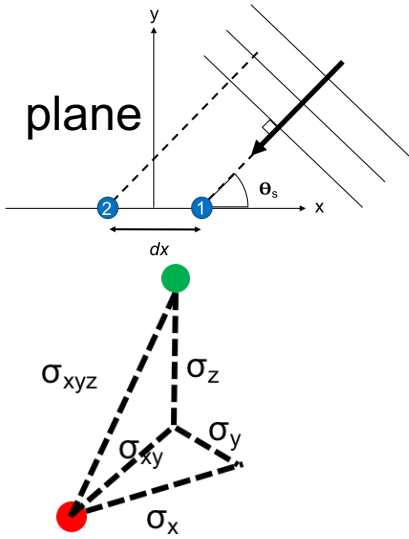
Method: curve-wavefront frequency-domain beamforming

- FFT bin size has greatest influence on localization performance (i.e., co-influence of sampling frequency and FFT length)
  - FFT bin size > 2 Hz: distribution with high variance and low bias
  - FFT bin size < 2 Hz: distribution with low variance and high bias
- distribution variance decreases with increasing sampling frequency (up to native sampling frequency)
- distribution shape changes for “groups” of FFT length
- effects of percent overlap are negligible

Parameter Selection

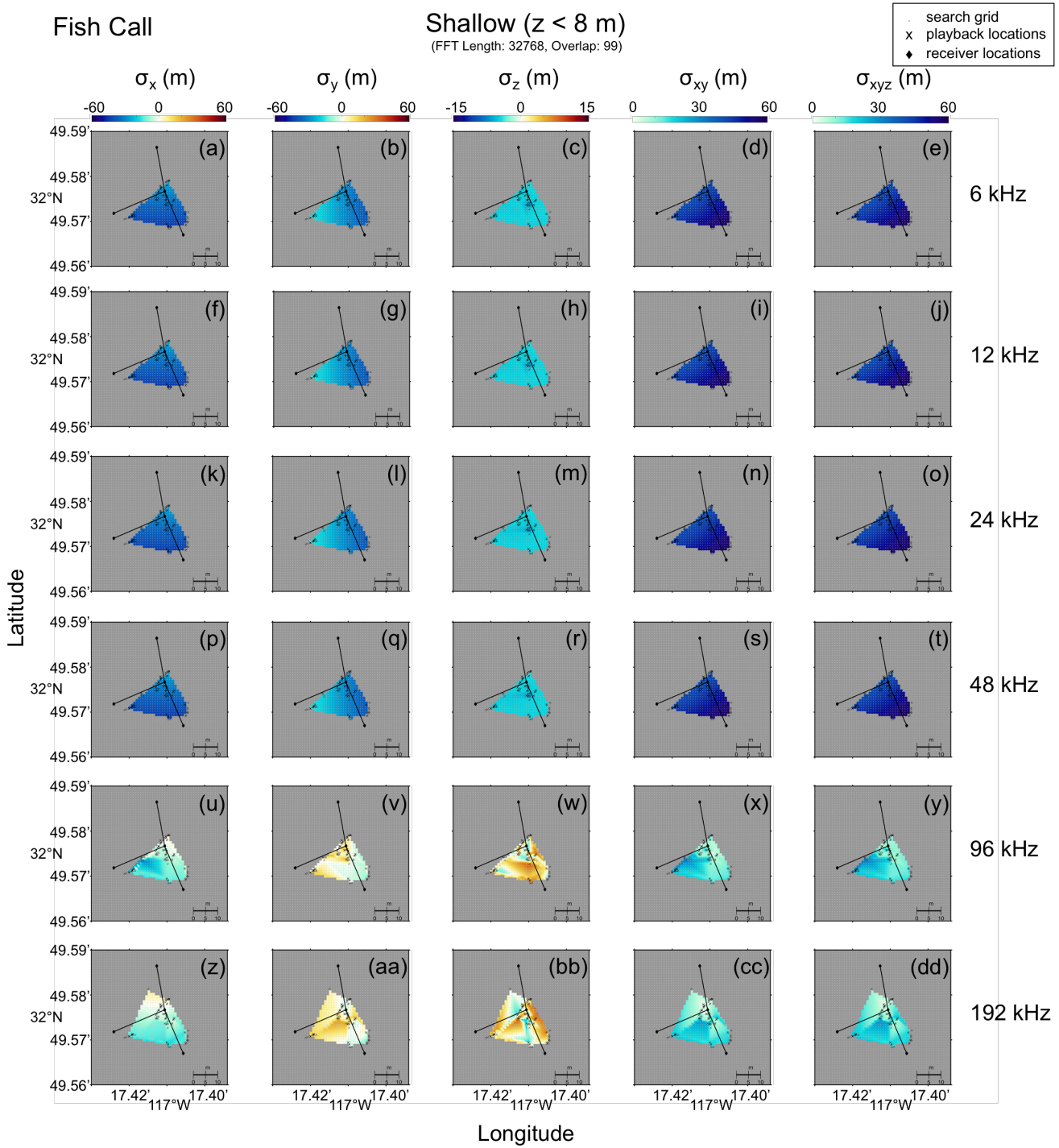
Method: plane-wavefront frequency-domain beamforming

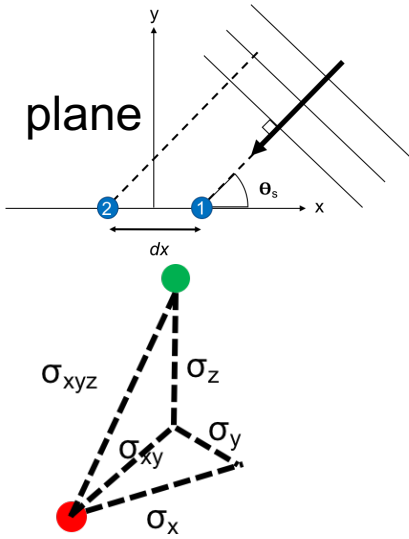




Parameter Selection

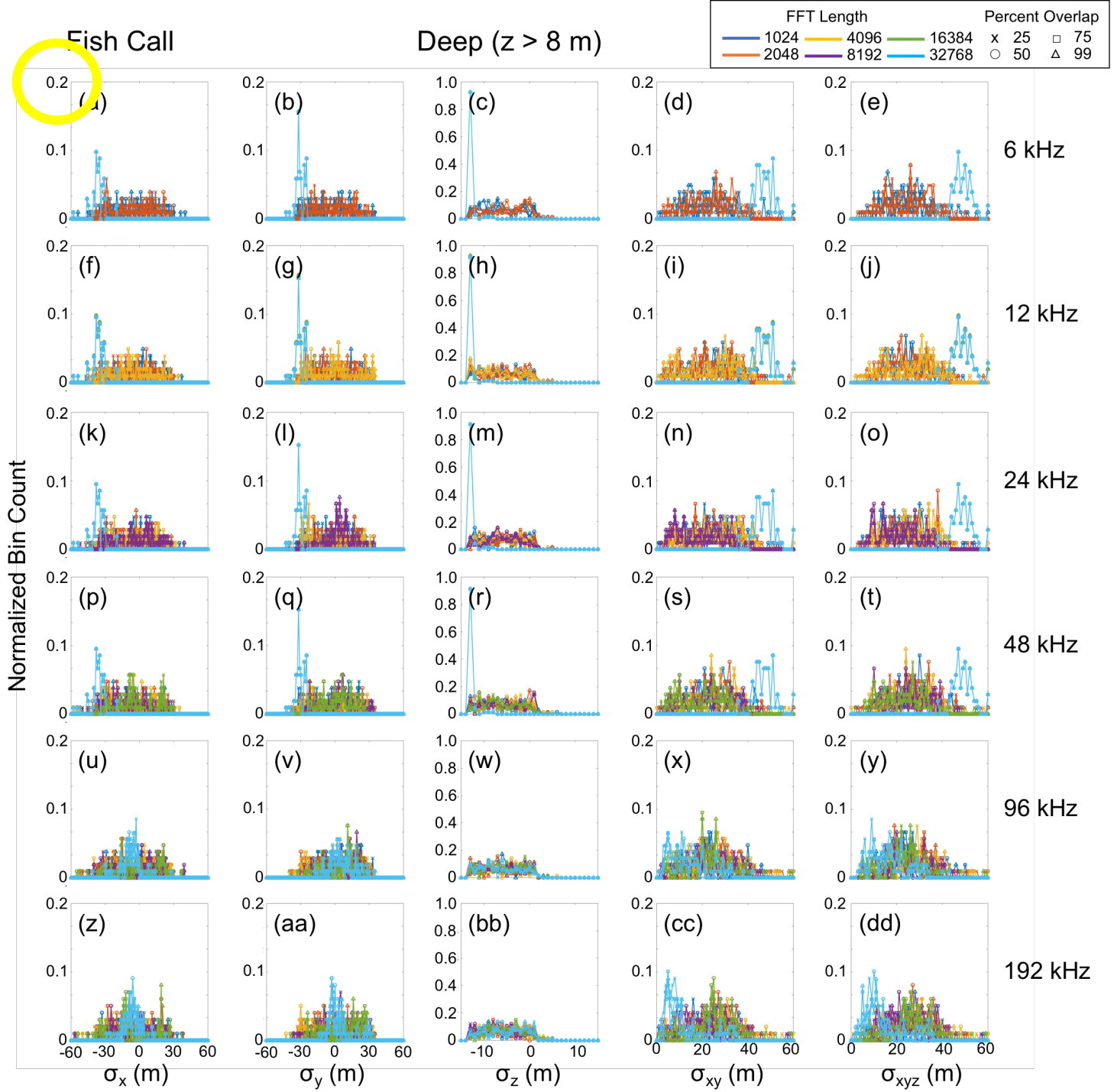
Method: plane-wavefront frequency-domain beamforming

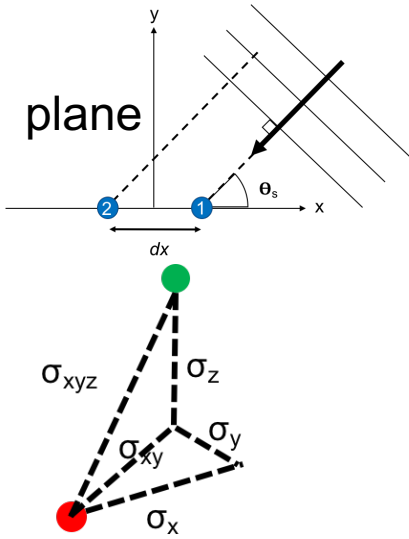




Parameter Selection

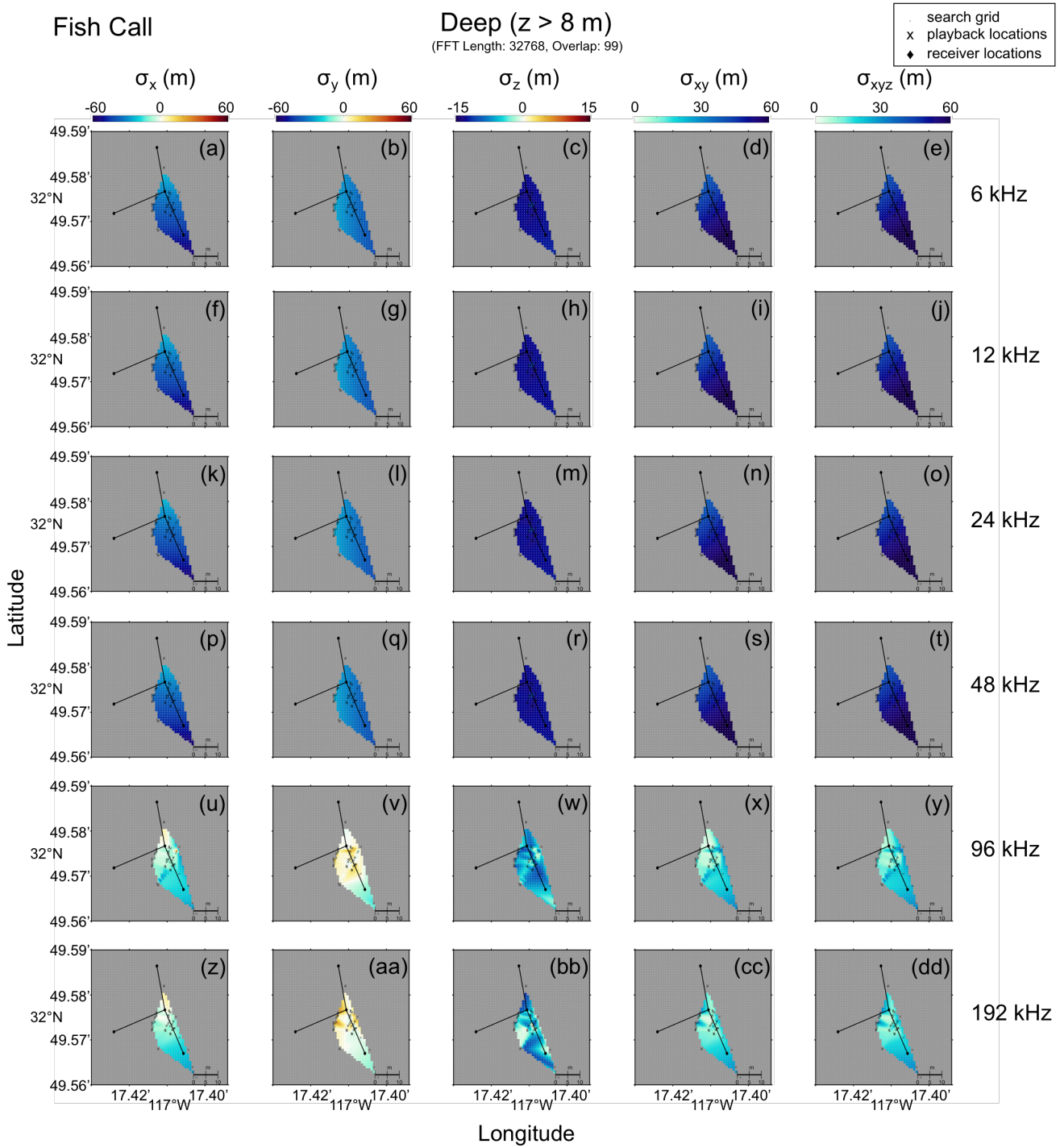
Method: plane-wavefront frequency-domain beamforming

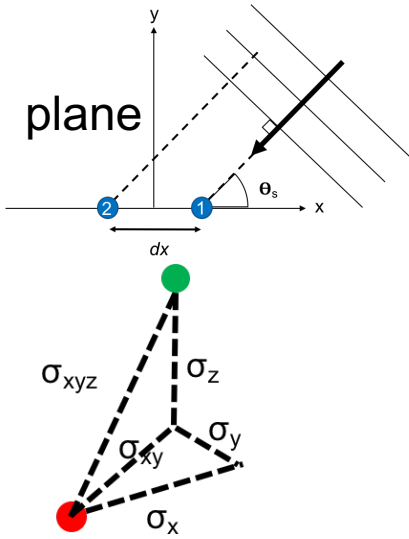


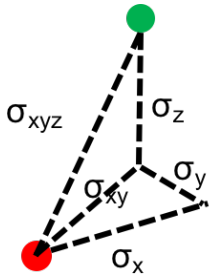


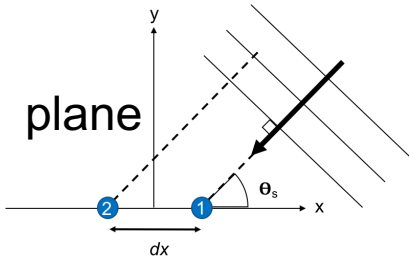
Parameter Selection

Method: plane-wavefront frequency-domain beamforming









Parameter Selection

Method: plane-wavefront frequency-domain beamforming

- propagation physics do not match plane-wavefront
- FFT bin size has greatest influence on localization performance (i.e., co-influence of sampling frequency and FFT length)
  - FFT bin size > 2 Hz: distribution with high variance and low bias
  - FFT bin size < 2 Hz: distribution with low variance and high bias
- effects of percent overlap are negligible
- increasing sampling frequency and FFT length leads to distribution similar to when correct propagation physics (i.e., curve-wavefront) are used

Conclusions and Next Steps

- method with best overall localization performance (so far…)

  TDOAs using waveform cross-correlation with curve-wavefront

- sampling frequency and Nfft and greatly influence localization performance
- no clear spatial pattern as to where each method performs best

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- finish computing remaining playback positions
- more in-depth comparison between methods
- quantify influence of each parameters
- localize individual fish using their naturally produced sounds with confidence intervals from error surfaces

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