Coherent Flow Power Doppler

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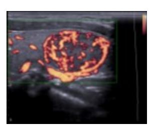
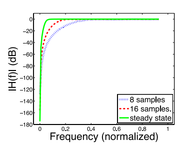
Power Doppler

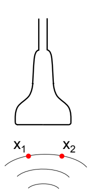
- Kind of a special motion detector.
- Noise sources:
  - Thermal (white) noise is associated with the high frequencies and builds up in the background of the image
  - Reverberation noise is low frequency and can pass through the filter if there is tissue/transducer motion.
- Challenges
  - Flow is dependent on filter performance
    - Steady state vs. Transient state
  - The difficult-to-image patient sees large amounts of the noise sources



http://www.medison.ru/ultrasound/gal581.htm



What is Spatial Coherence?



- Spatial coherence is a measure of the similarity of the ultrasound waves at any two points in the spatial field.
- Generally this means comparing the ultrasound signal originating from the same point, recorded at two different points on the array
- Can be compared via covariance, cross-correlation, etc.

$$R_{12}(x_1, x_2) = ?$$

Spatial Coherence

Spatial covariance can be theoretically predicted by using the van Cittert-Zernike (VCZ) theorem:

$$C(x,y)=\iint\left|D(X,Y)H(X,Y)\right|^2\exp\left\{-j\frac{2\pi}{\lambda z}(xX+yY)\right\}dXdY$$

Or more generally by:

$$R_{\psi\psi}(x)=\frac{1}{\lambda^4 z^4}A(x_1,x_2)A^*(x_1,x_2)\times \underbrace{\left[A(x_1,x_2)**A^*(x_1,x_2)**FT\left\{R_{\chi\chi}(X_1,X_2)\right\}\right]}_{\text{more general form of VCZ theorem}}+\underbrace{R_{NN}(x_1,x_2)}_{\text{from noise}}$$

Pinton et al. "Spatial Coherence in Human Tissue: Implications for Imaging and Measurement" UFFC, 2014.

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Spatial Coherence

Lag: The distance between two points

x_1 x_2 x_3 x_4
Δx Δx

The lag between x_1 and x_2 is equal to the lag between x_3 and x_4.

Statistically speaking, spatial coherence is stationary, meaning that

$$R_{xx}(x_1,x_2)=R_{xx}(\Delta x)=R_{xx}(x_3,x_4)$$

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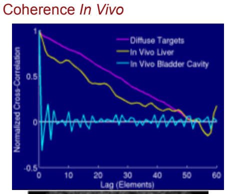
Spatial Coherence *In Vivo*



- Coherence of diffuse targets in phantom agree well with VCZ theory.
- Coherence of *in vivo* liver shows significant drop at first 1-2 lags.
- Coherence of bladder region indicates noise.
- A Delay-and-Sum beamformer shows a speckle pattern for all 3 of these cases.

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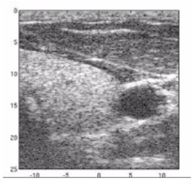
Spatial Coherence *In Vivo*



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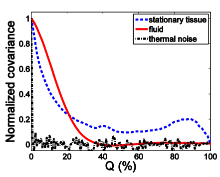
Spatial Coherence of *In Vivo* Blood



- Coherence in fluid (blood) shows similar characteristics as tissue.

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Coherence Beamforming

Describes the spatial coherence of the wave at every point in the field

- Image response to high coherence is bright
- Image response to low coherence is dark

Normalization matters!

- Normalized values removes influence of amplitude/energy on coherence image

Flow Imaging

- In Coherent Flow, we lose phase information, so we can't get directional information – thus we are restricted to a Power Doppler equivalent
- The Power in the flow is related to the power of the normalized cross-correlation

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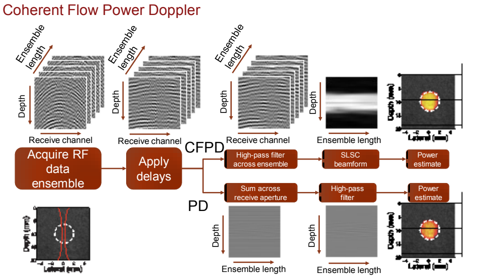
Coherent Flow Power Doppler



Li and Dahl, TUFFC 62(6):1022-1035, 2015.

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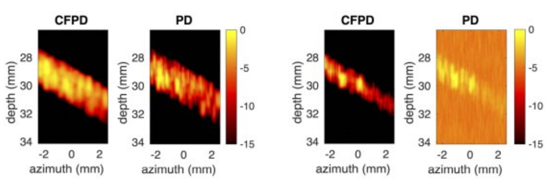
Coherent Flow Power Doppler



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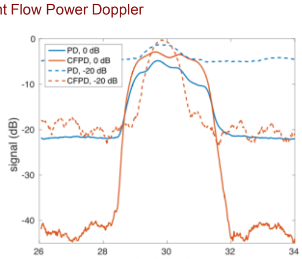
Coherent Flow Power Doppler



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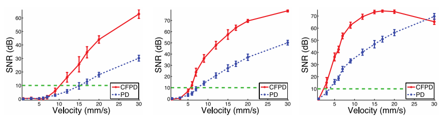
Quantitative Analysis of Performance vs. Velocity



0 dB SNR   10 dB SNR   20 dB SNR

SNR improvement: 7.5-12.5 dB
Detection threshold: 10 dB in SNR (green line)
Limit of detection (LOD) in velocity:

30% slower flow than the LOD of PD

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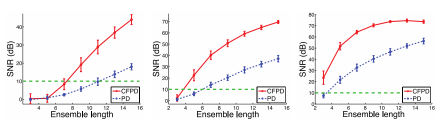
Simulation Results: Quantitative Analysis



0 dB SNR   10 dB SNR   20 dB SNR

Velocity: 20 mm/s
SNR improvement: 7.5-12.5 dB
Produce Doppler images with smaller ensemble sizes so that frame rate can be increased and flash artifact decreased

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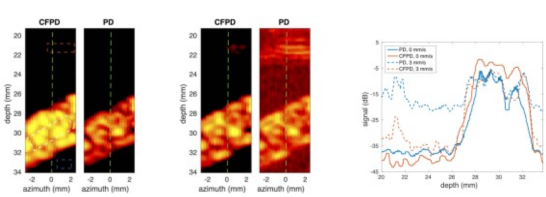
Coherent Flow Power Doppler Performance



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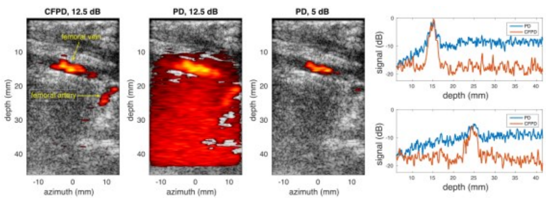
Coherent Flow Power Doppler Examples



Li et al. Visualization of small-diameter vessels by reduction of incoherent reverberation with coherent flow power Doppler. TUFFC, 2016.

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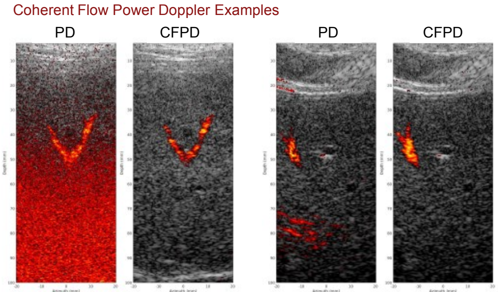
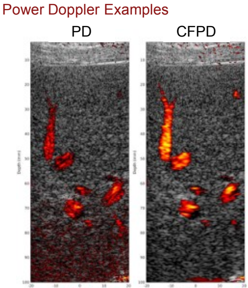
Coherent Flow Power Doppler Examples



Coherent Flow Power Doppler Examples



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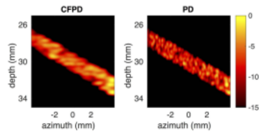
Adapting CFPD to Angular Coherence



- CFPD (and coherence beamforming) can be applied to synthetic focusing techniques, such as plane wave synthetic transmit focusing (aka coherent compounding).
- In synthetic focusing techniques, we can take advantage of acoustic reciprocity to compute coherence in the transmission domain rather than in the reception domain. Combined with "transmit aperture downsampling," this can be used to increase framerate (i.e. HFR or ultrafast imaging)
- In the angular domain (as used by PWSTF), there are no physical spatial lags, and therefore an equivalent theory must be used to associate the angular lags to the spatial lags.
- The theory turns out to be rather simple. Using acoustic reciprocity, the angular spatial coherence is just a scaled version of the autocorrelation of the receiving aperture function.

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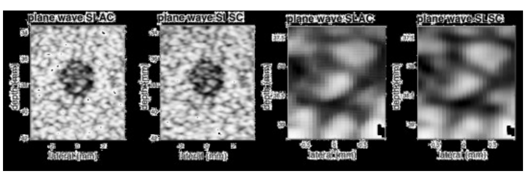
Adapting CFPD to Angular Coherence

- Applying this angular coherence theory (and acoustic reciprocity), an equivalent form of the short lag spatial coherence (SLSC) beamformer can be implemented in the transmission domain with angled plane waves.
- This form is called the short-lag angular coherence, or SLAC, beamformer:



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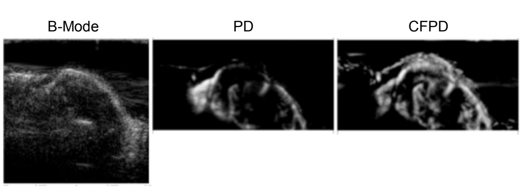
Adapting CFPD to Angular Coherence

- Applying SLAC to ultrafast Doppler can produce very interesting images.
- Shown here is the application of SLAC combined with CFPD in the mouse brain (through the skull) using contrast agent.



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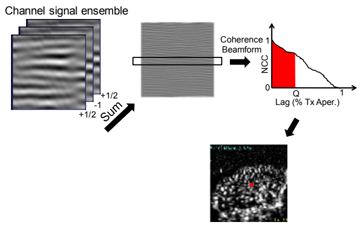
Coherent Contrast Pulse Sequencing



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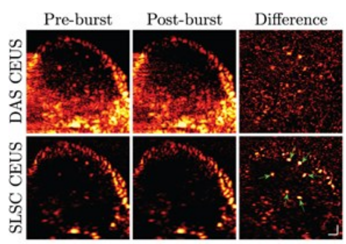
CPS Examples



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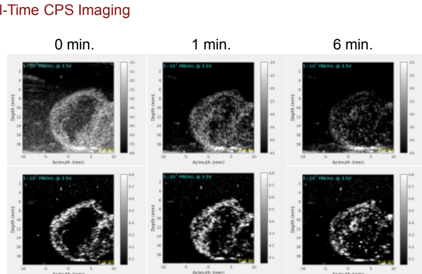
Real-Time CPS Imaging



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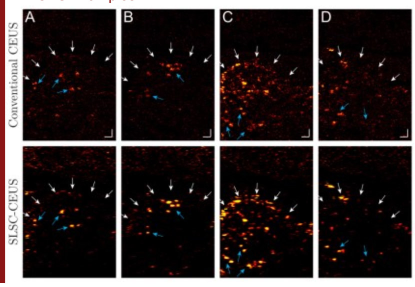
CPS Examples



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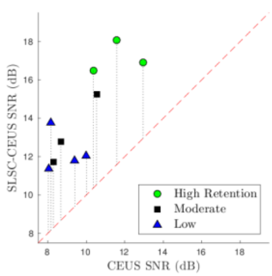
CPS Examples



- Average improvement in SNR
  - 65%
  - 4.3 dB

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Summary

- Reverberation and thermal noise are incoherent noise sources in the spatial (aperture) domain.
- Beamforming based on the spatial coherence can differentiate and suppress noise sources in flow imaging.
- CFPD can achieve 7.5 to 15 dB higher SNR than conventional PD, which can be used to increase frame rate, detect slower flow, or improve image quality.
- Coherence beamforming is compatible with most imaging techniques to further improve sensitivity (e.g. synthetic focusing, high-frame rate imaging, or CEUS imaging).
- Adapted versions of CEUS imaging (molecular imaging) show on average 4.3 dB greater sensitivity.

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