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Signal Acquisition Modeling and Processing Lab

Towards Sub-Nyquist Tissue Doppler Imaging

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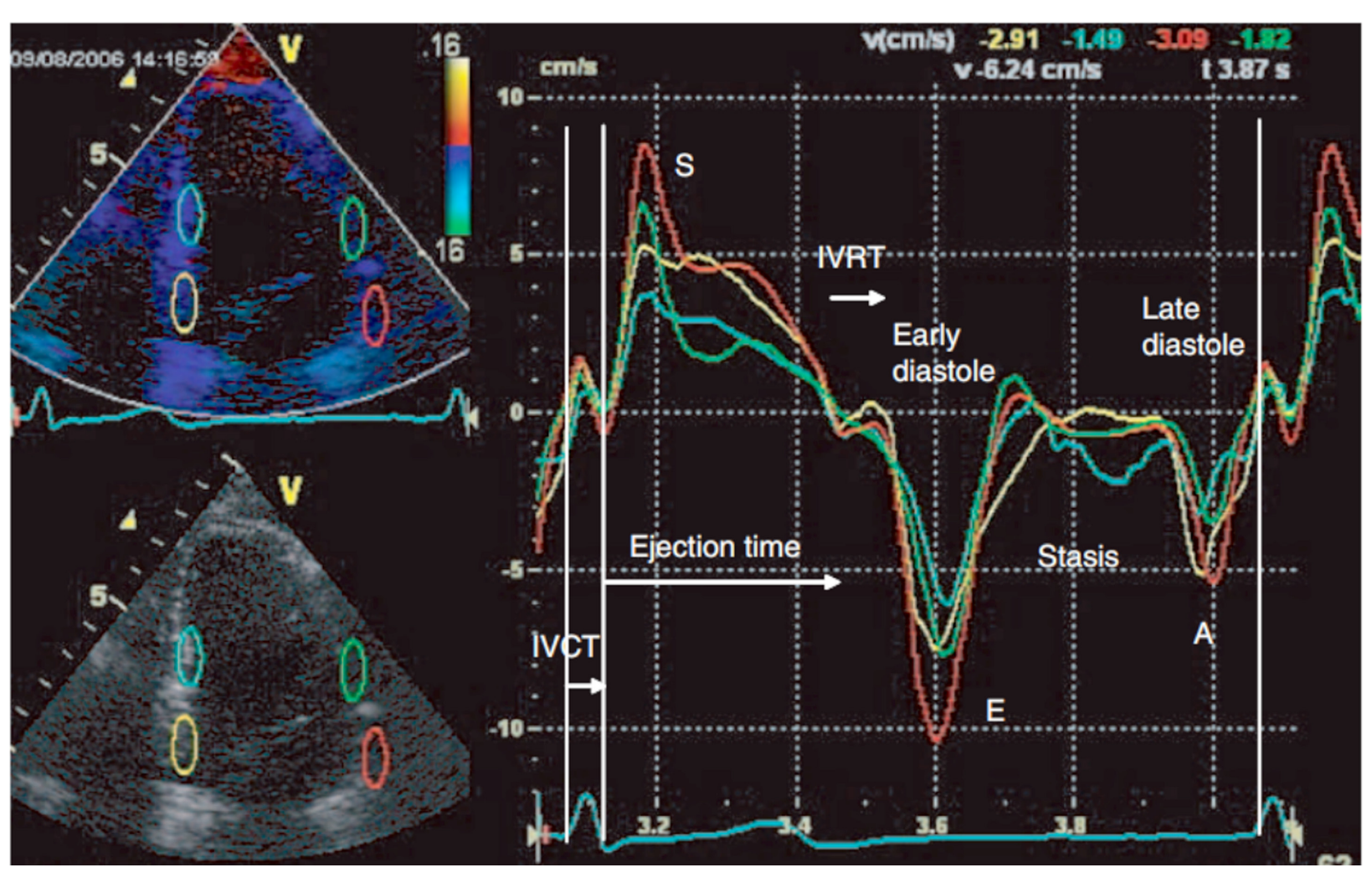
Tissue Doppler Imaging

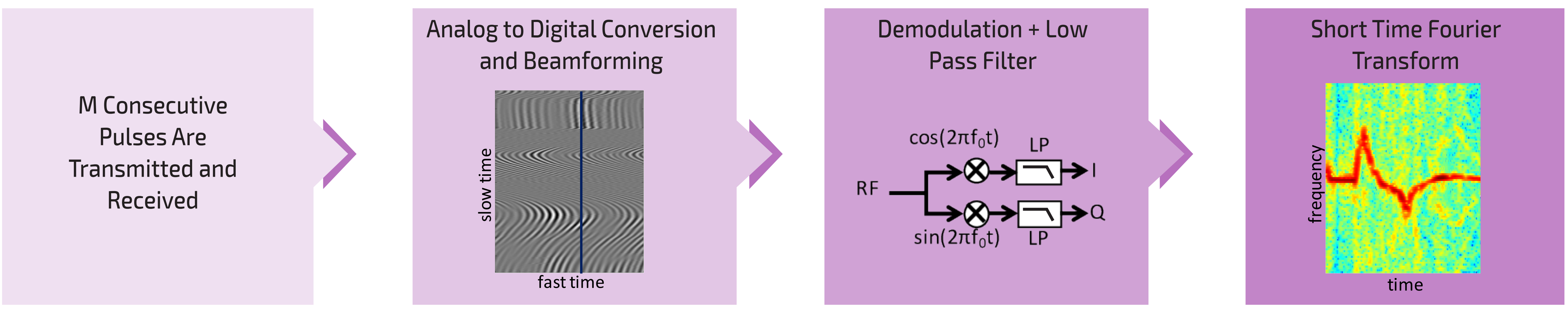
- Tissue Doppler imaging (TDI) facilitates quantification of LV function by estimating the myocardial velocity profile
- Currently: few measurement points through the LV [1]



Motivation

- Tradeoff between spectral and spatial resolution
- The received A-ling signals (fast time) are sampled at frequencies higher than the Nyquist rate

Current Technology



M Consecutive Pulses Are Transmitted and Received → Analog to Digital Conversion and Beamforming → Demodulation + Low Pass Filter → Short Time Fourier Transform

Methods

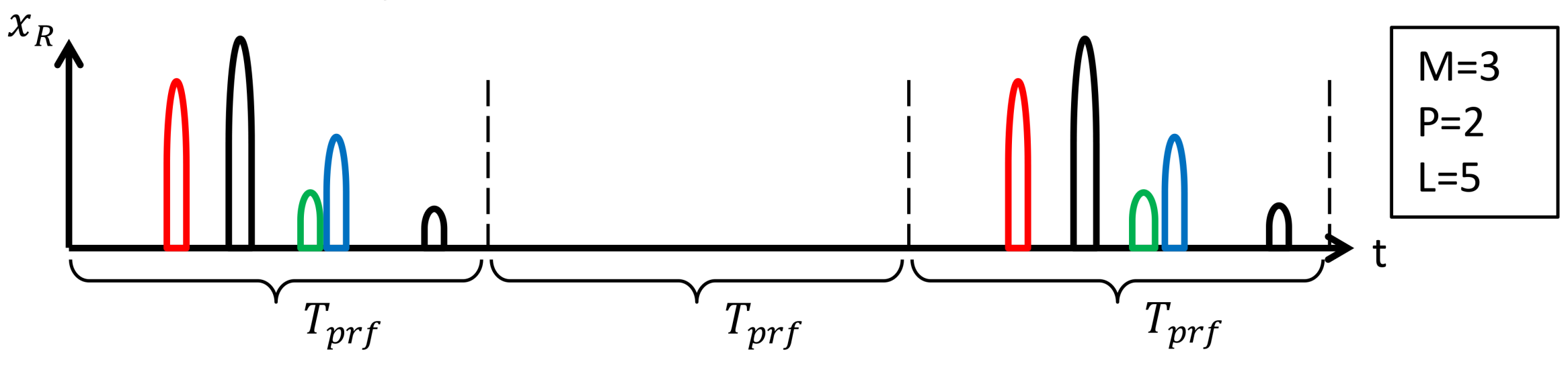
Non-Uniformly Spaced Pulses

- Non-Uniformly Spaced Stream of Pulses is transmitted:

$$x_T(t)=\sum_{p=0}^{P-1} h\left(t-m_pT_{prf}\right)\sin\left(2\pi f_0\left(t-m_pT_{prf}\right)\right).$$

- The received signal from L dominant scatterers is defined by the 3L degrees of freedom (DOF): $\{\bar{a}_l,\tau_l,\nu_l\}_{l=1}^{L}$
- The received A-line reflected from L scatterers:

$$x_p\left(t+m_pT_{prf}\right)=\sum_{l=1}^{L}\bar{a}_l\cdot h(t-\tau_l)\cdot\exp\left(-j\nu_lT_{prf}m_p\right).$$

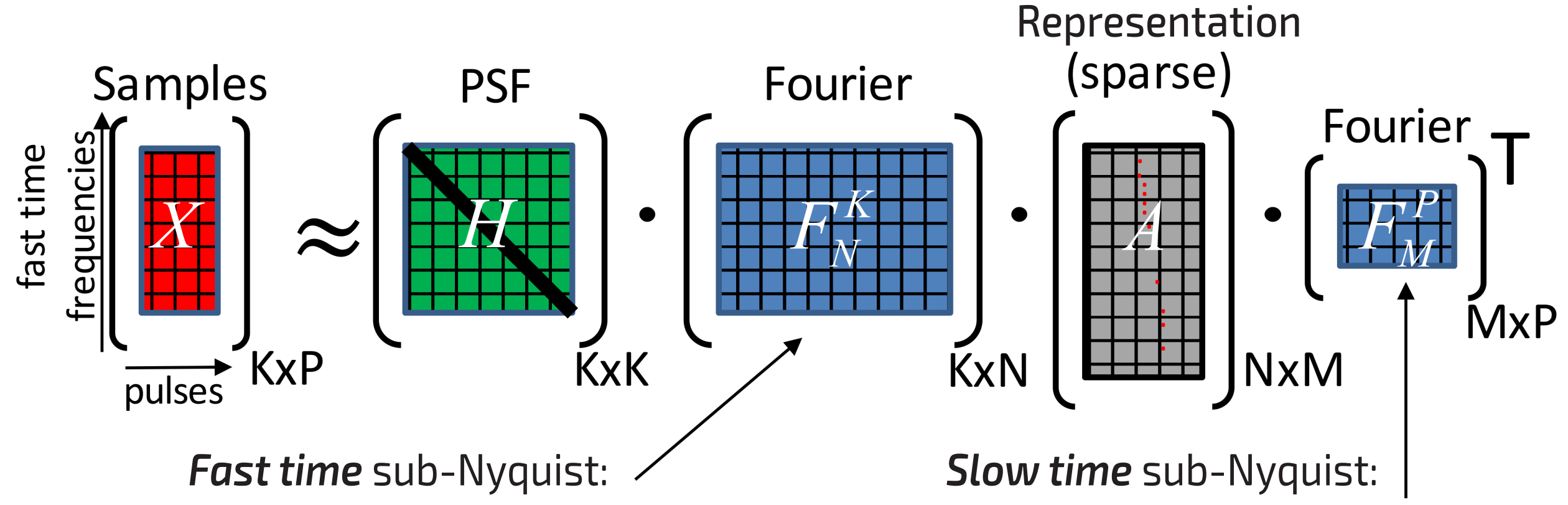


- The Fourier series representation of a single A-line is [2]:

$$X_p[k]=\frac{1}{T_{prf}}\boxed{H[k]}\sum_{l=0}^{L-1}\boxed{\bar{a}_l}\cdot\exp\left(-j2\pi k\boxed{\tau_l}/T_{prf}\right)\cdot\exp\left(-j\boxed{\nu_l}T_{prf}m_p\right).$$

Sampling rate reduction via CS

- The system of equations :



Fast time sub-Nyquist: F_N^K contains K out of the N rows of the DFT matrix

Slow time sub-Nyquist: F_M^P contains P out of the M rows of the DFT matrix

Under-determined system of equations

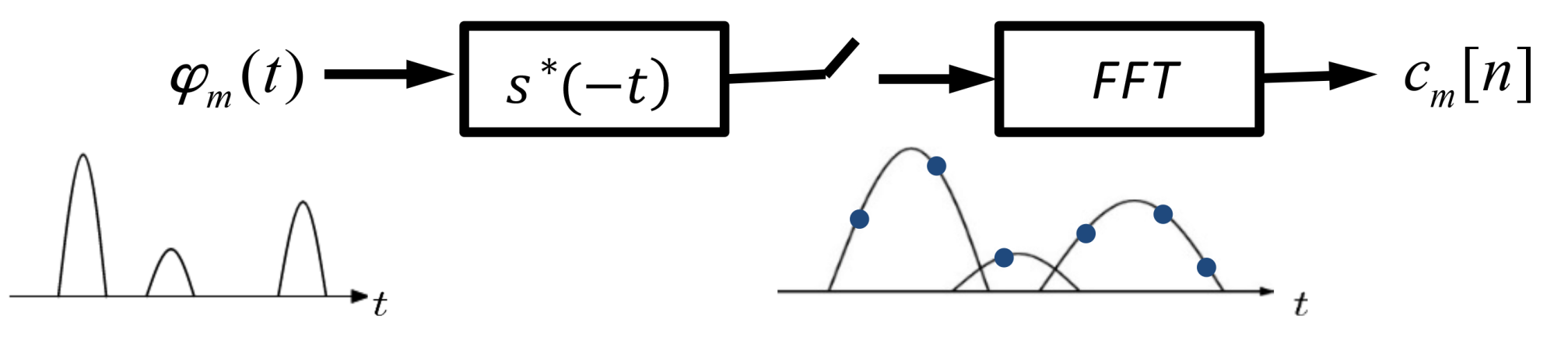
- **The sparse representation matrix** A is estimated from the measurements by solving the l1 minimization problem:

$$\min_{A}\left\{\frac{1}{2}\left\|Y-F_N^KA\left(F_M^P\right)^T\right\|_F^2+\lambda\|A\|_1\right\},\qquad Y=XH^{-1}$$

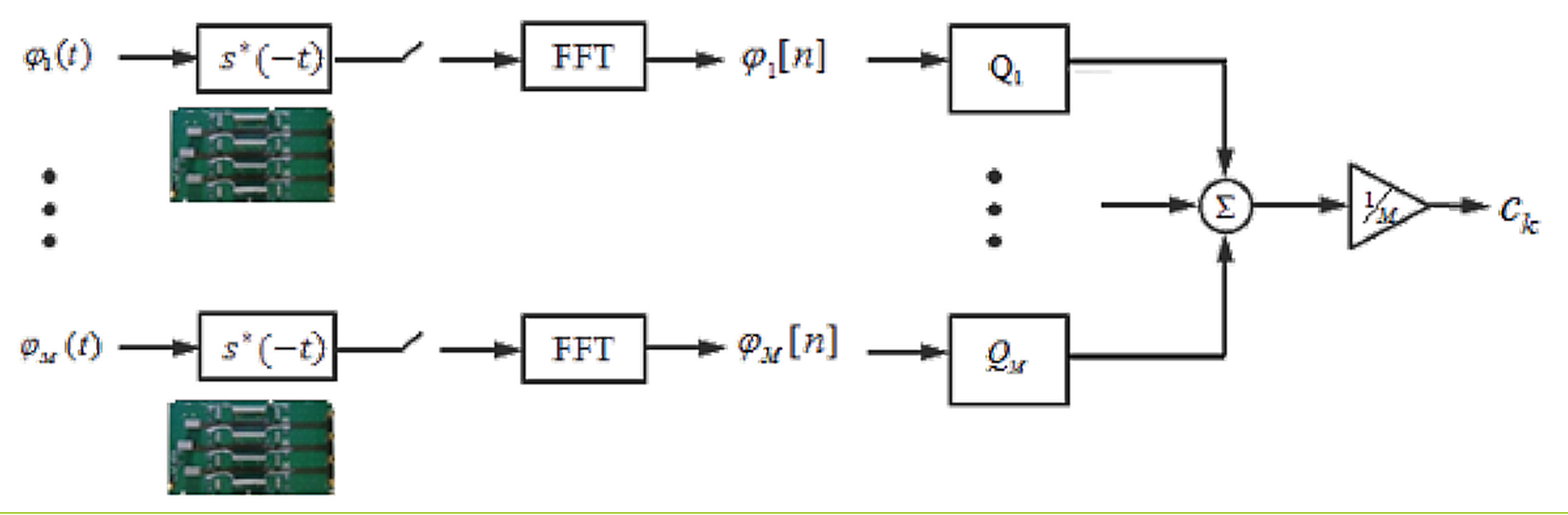
Estimating the Fourier Coefficients

- Compression+Sampling = **Xampling** [3]

Fourier coefficients can be estimated following pre-filtering

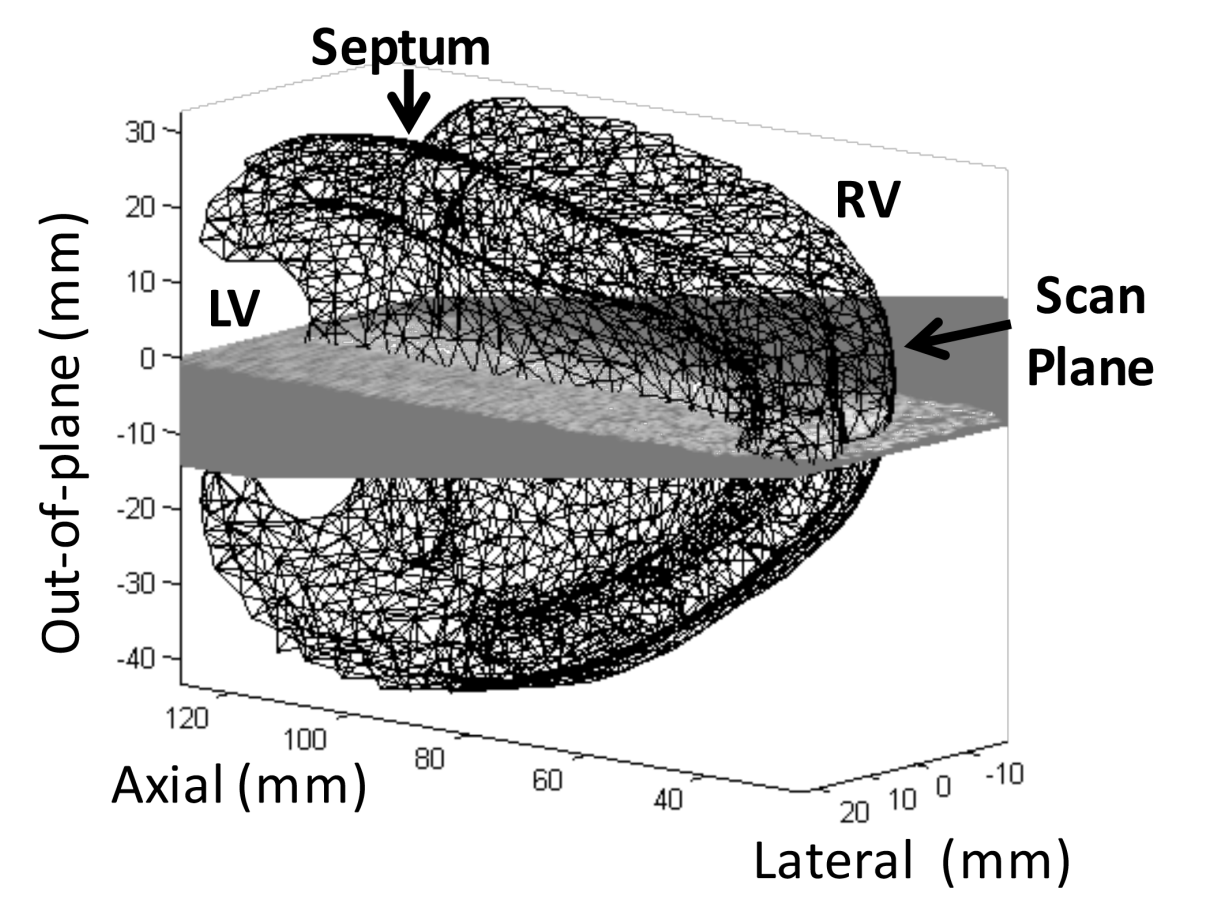


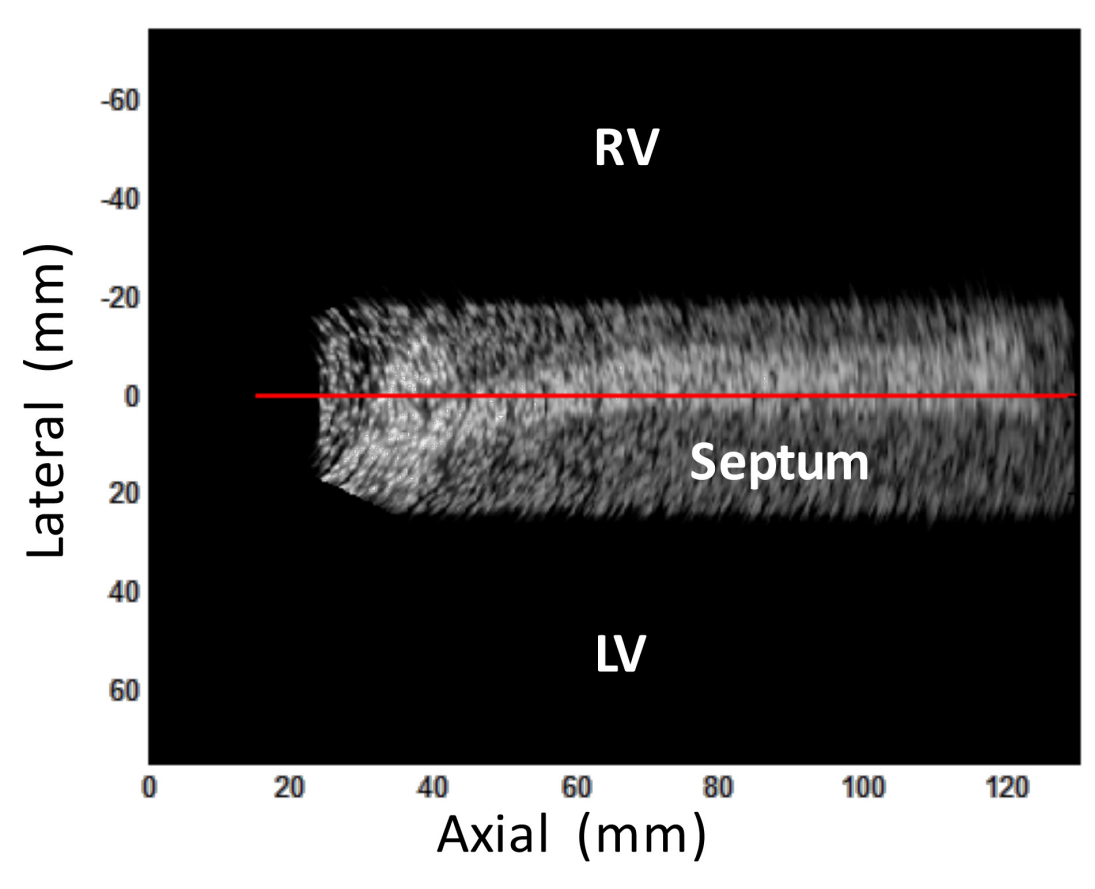
- Multi element transducer:
Compressed Beamforming - beamforming in the Fourier Domain on low rate samples [4]



Validation

- Using synthetic echocardiographic sequences[5]
- Geometries extracted from 3D ultrasound scans





- A demo version was implemented on a Verasonics Vantage 256™ system

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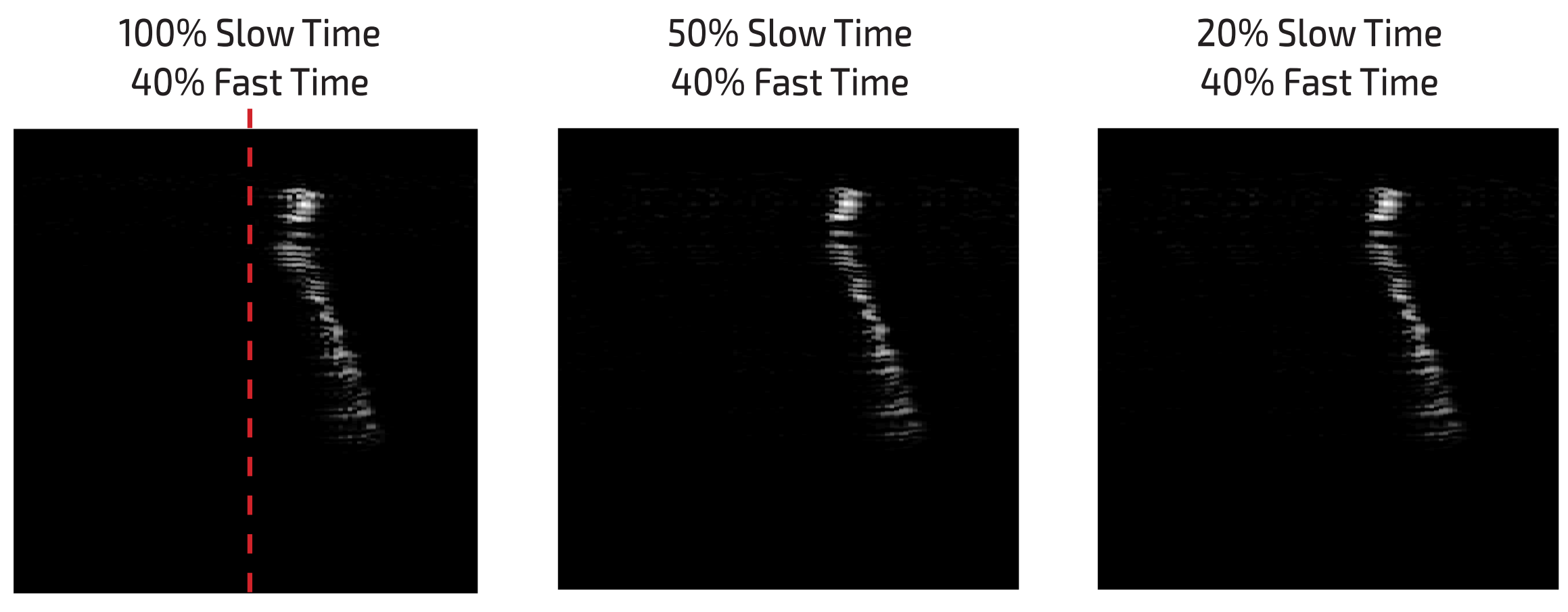
The leader in Research Ultrasound™

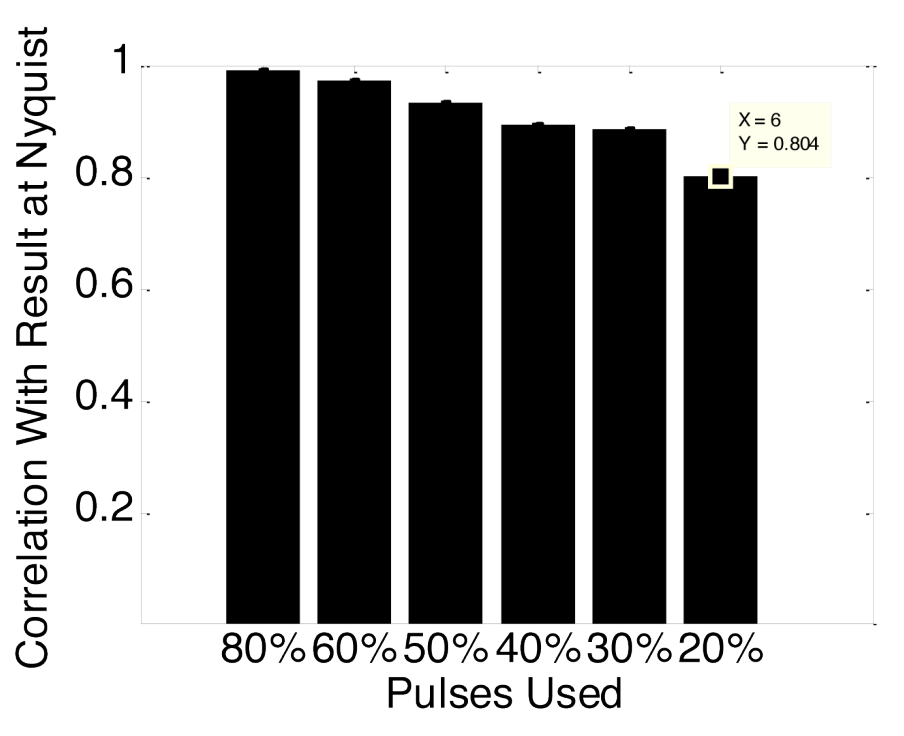
Results

Depth-Doppler Maps - Quantification

- The representation matrices present the velocities at different depths:

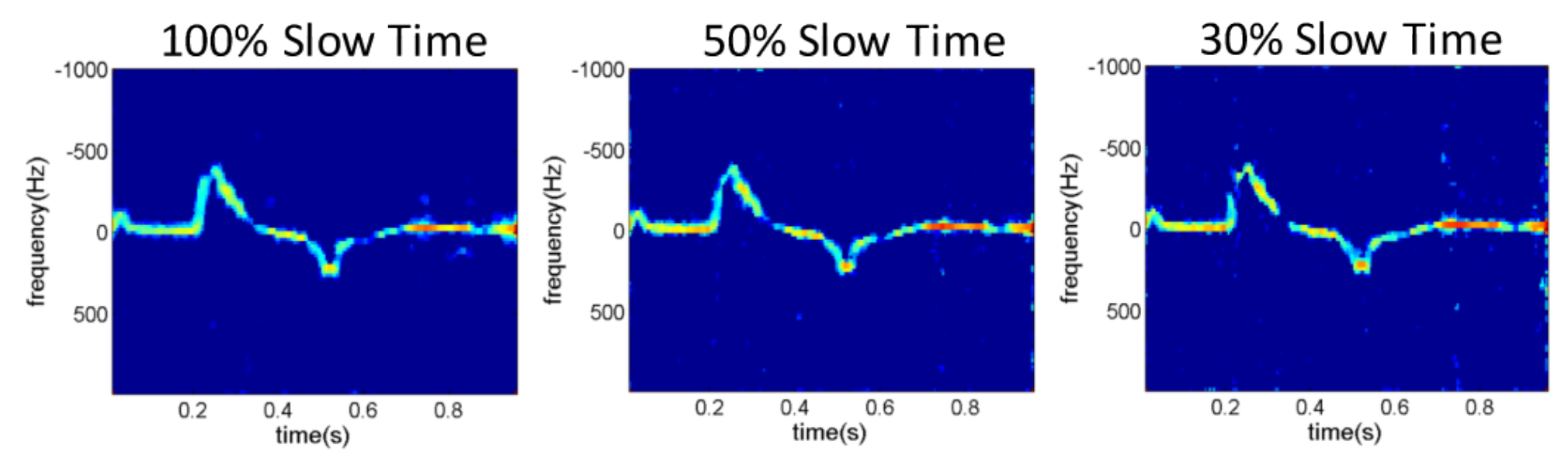


- With 20% of the pulses the map's correlation coef. R > 0.8



TDI Plots

- Spectral estimations from specific depths can be concatenated to produce spectral Doppler images



Depth = 6.2 cm; 40% fast time

Conclusion

- The proposed signal model was supported by our results
- TDI signals can be reconstructed from sub Nyquist samples:
  - Only subset of the fast time frequencies are used
  - Non-uniformly space stream of pulses transmitted
- Time gaps between pulses can be used for scanning in different directions
- Current performance is satisfactory, and can still be improved
- Future research directions includes:
  - Extension to vector Doppler
  - Extension to color Doppler
  - Optimization of the reconstruction algorithm and the selection of transmitted pulses

References

1. T. H. Marwick, C. Yu, J. P. Sun, Myocardial Imaging: Tissue Doppler and Speckle Tracking," 2007.
2. D. Cohen, A. Dikopoltsev and Y. C. Eldar, "Extensions of Sub-Nyquist Radar: Reduced Time-on-Target and Cognitive Radar," 2015.
3. M. Mishali, Y. C. Eldar, O. Dounaevsky, and E. Shoshan, "Xampling: Analog to digital at sub-Nyquist rates," 2011.
4. T. Chernyakova, Y.C. Eldar, "Fourier Domain Beamforming: The Path to Compressed Ultrasound Imaging," 2014.
5. M. Alessandrini et al. , "A Pipeline for the Generation of Realistic 3D Synthetic Echocardiographic Sequences: Methodology and Open-Access Database," 2015.

Thanks!

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