Analysis of Active Sonar Waveform Design by Echolocating Mammals

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UNCLASSIFIED

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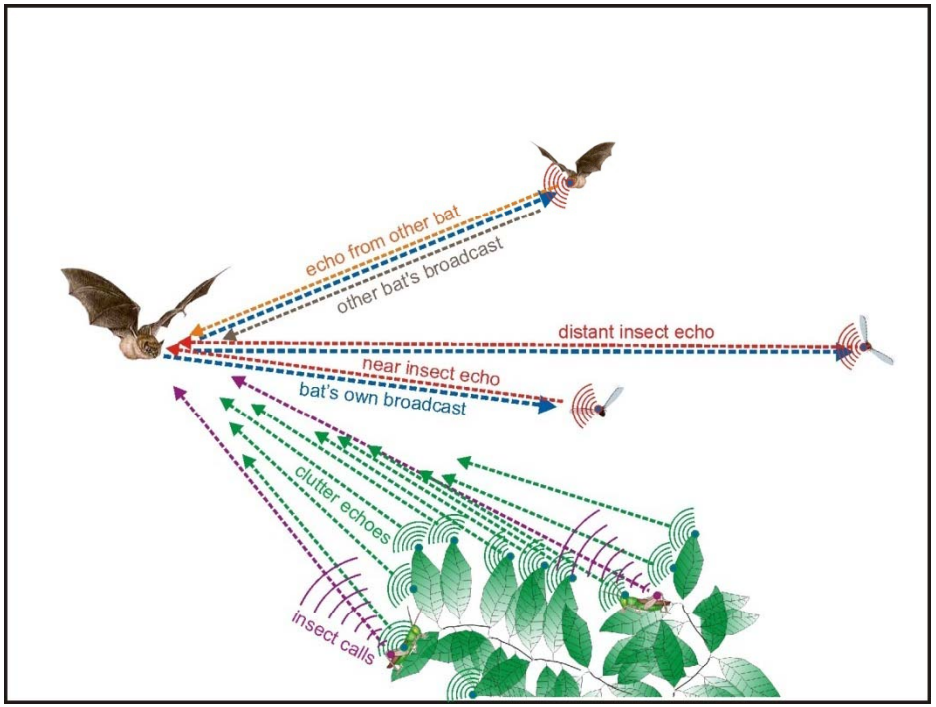
Research Motivation

What can we learn?
-Real-time sensing with multi-component, non-linear modulated signals

Bats have been shown to adapt their pulse design to the task and environment
- Wide range of pulse types depending upon bat species (CF/FM/CF-FM)
- Jamming avoidance response
- Strobe groups are prevalent in pulse sequences

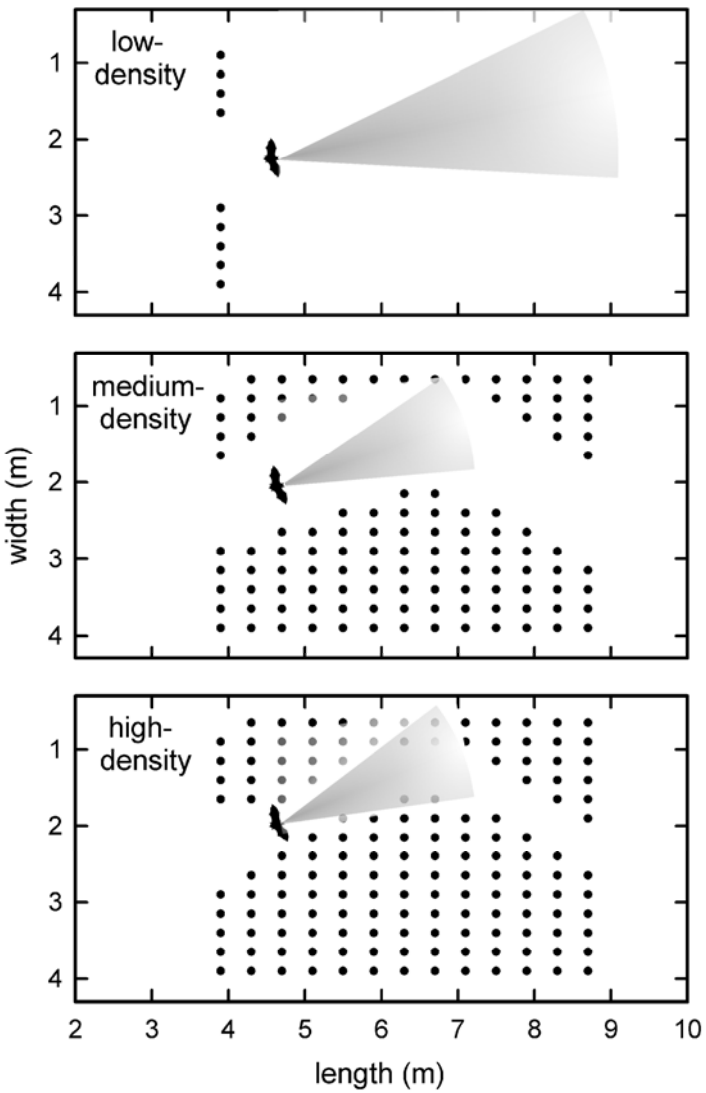
Compelling evidence that they achieve superior performance
- Hyper-resolution in dense natural clutter
- Immunity to pulse-echo ambiguity between strobe groups and other bats

The natural clutter experienced by bats is comparable to undersea environmental clutter



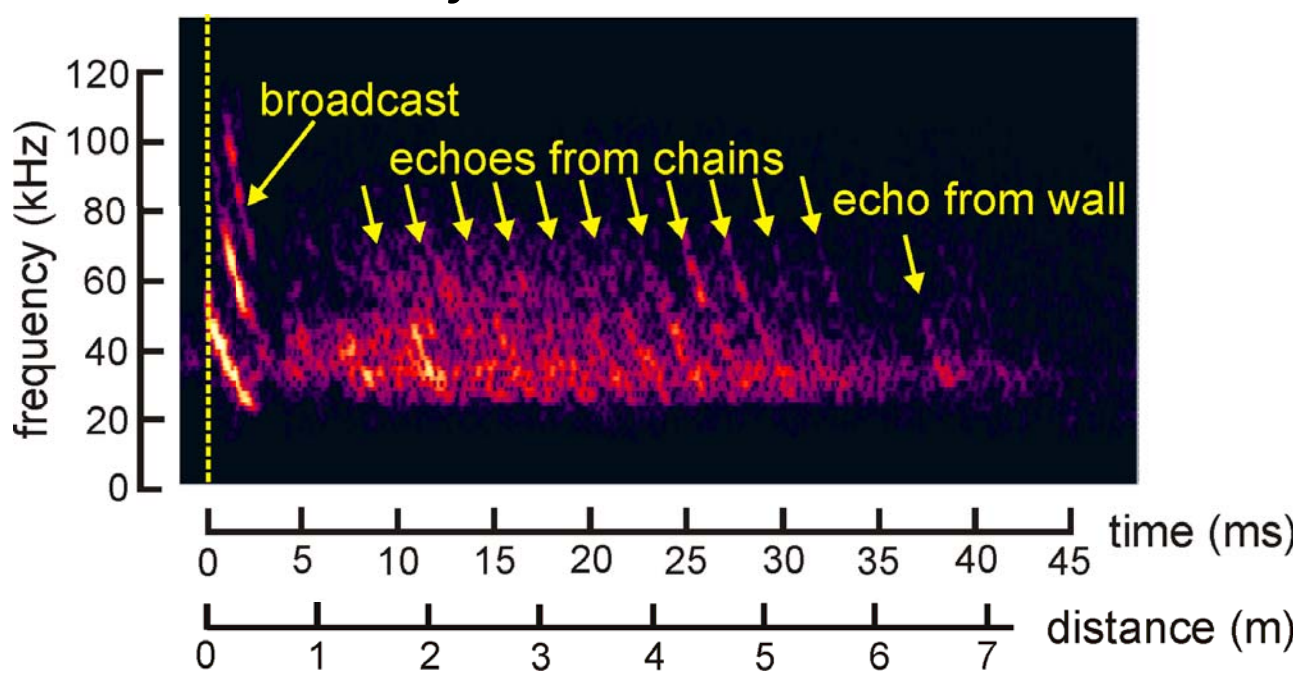
Understanding the adaptive pulse design of echolocating mammals is an understudied problem that requires advanced signal processing techniques

Simulated Clutter Experiments

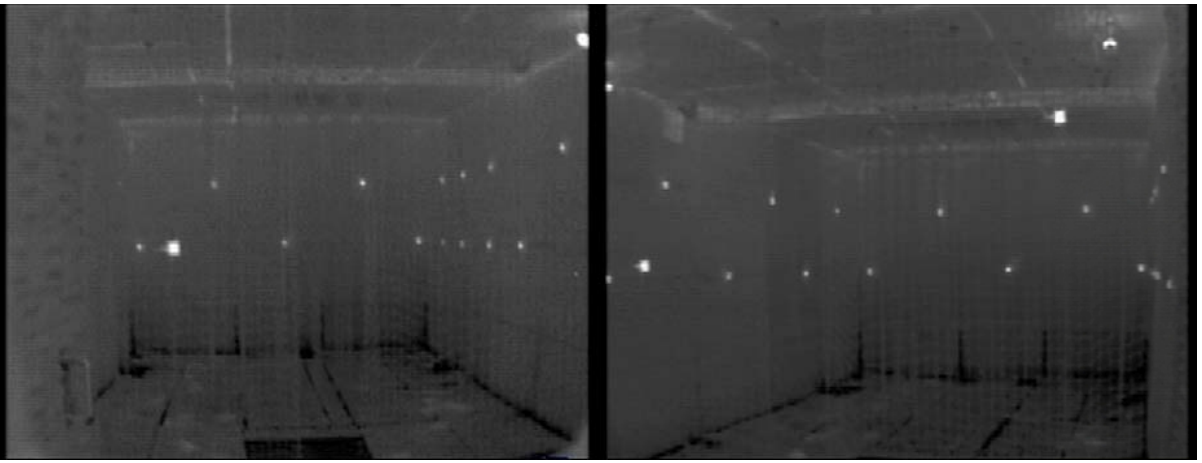


The bats navigate a semi-anechoic flight room under a wide range of controlled clutter experiments

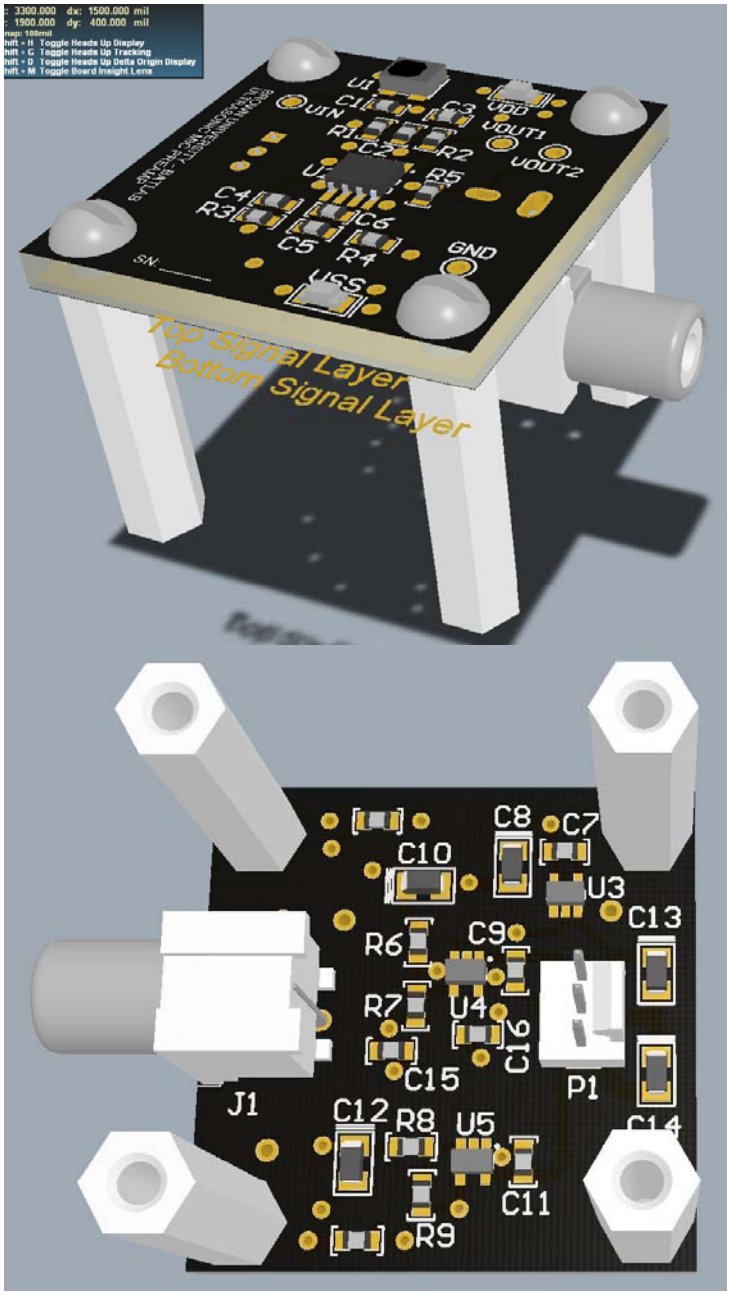
Single broadcast and echoes returned to the bat from chain obstacles



Data Collection



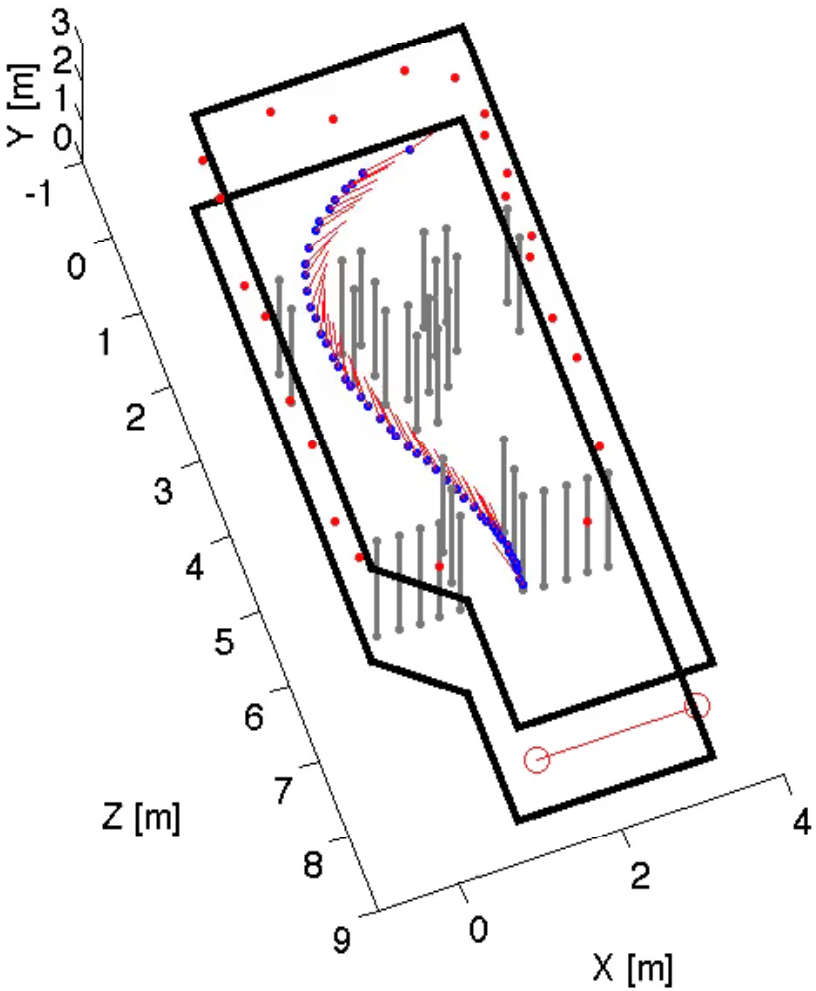
Stereoscopic infrared cameras record the bats flying through a sparse chain array to demonstrate obstacle avoidance in clutter

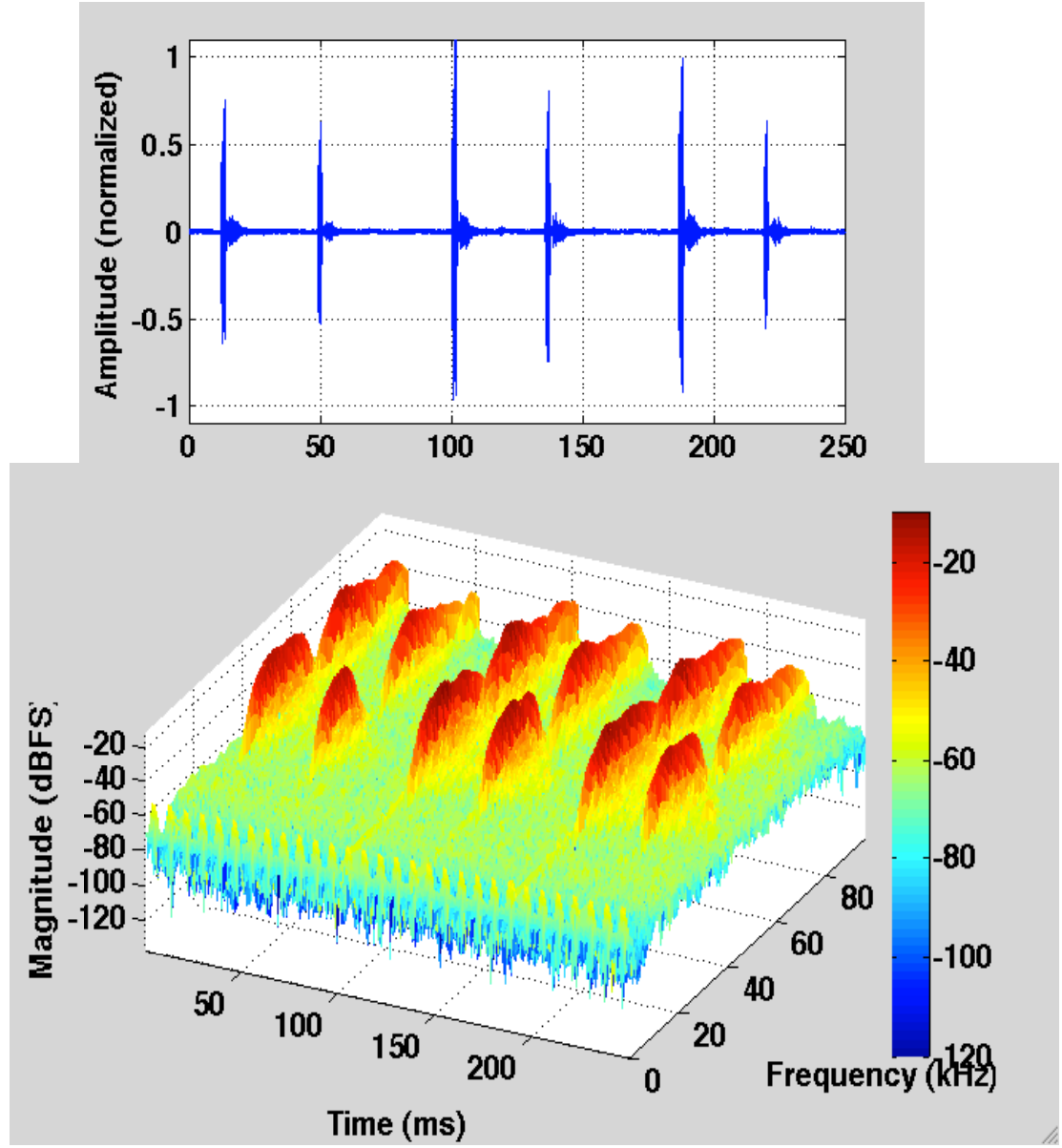


Custom built circuit boards contain a surface mount MEMS ultrasonic microphone and preamp filter

Data Collection

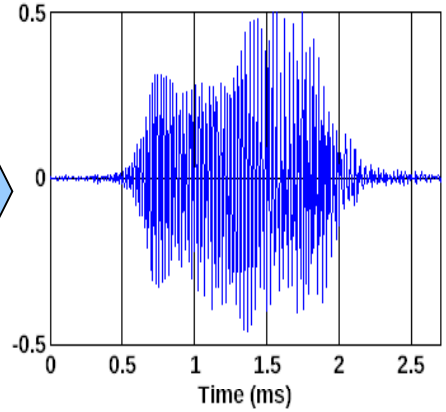
Post processed estimates of flight path and head aim for each echolocation pulse

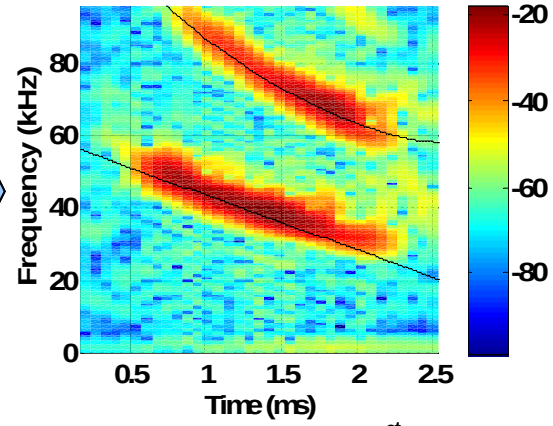


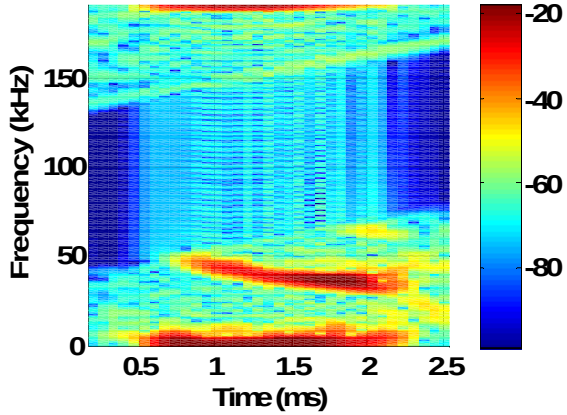


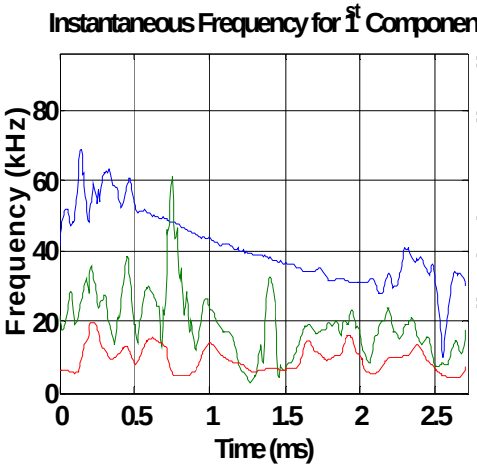
Time series and spectrogram of 6 pulses recorded during flight

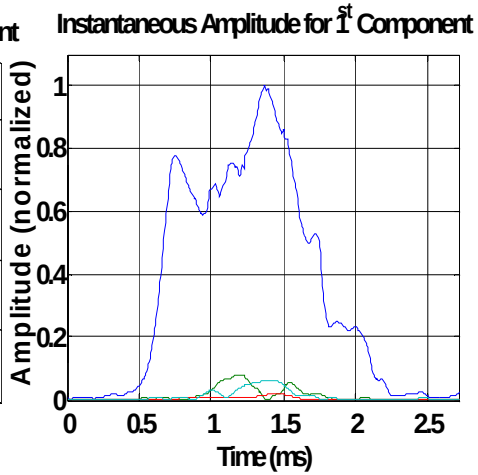
Processing

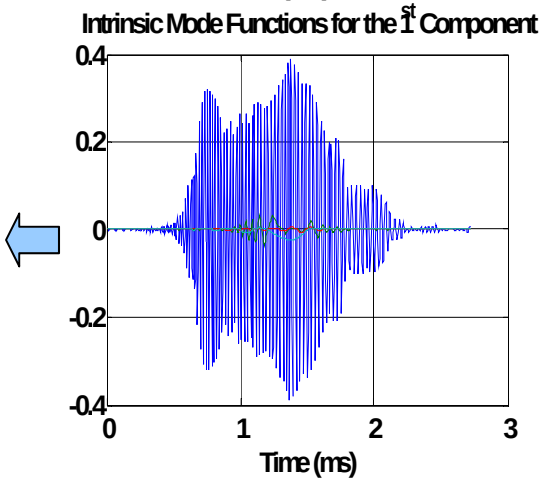

0.5
0
-0.5
0 0.5 1 1.5 2 2.5
Time (ms)

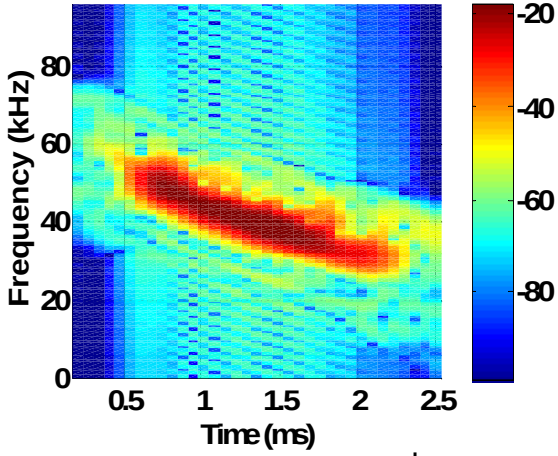

Frequency (kHz)
0 20 40 60 80
0.5 1 1.5 2 2.5
Time (ms)
-20 -40 -60 -80

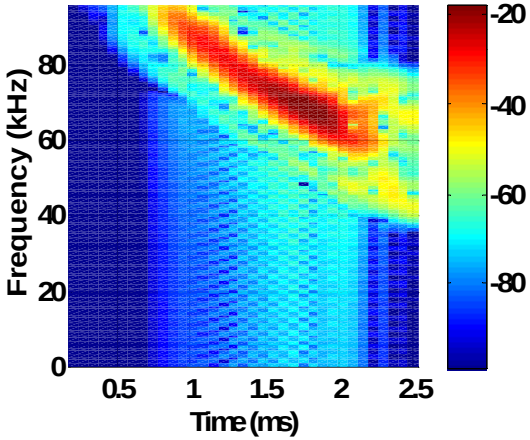

Frequency (kHz)
0 50 100 150
0.5 1 1.5 2 2.5
Time (ms)
-20 -40 -60 -80

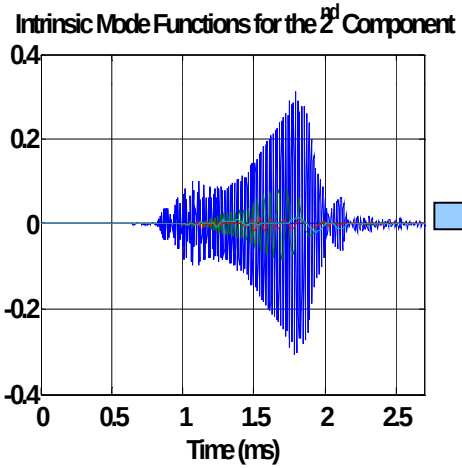

Instantaneous Frequency for 1st Component
Frequency (kHz)
0 20 40 60 80
0 0.5 1 1.5 2 2.5
Time (ms)

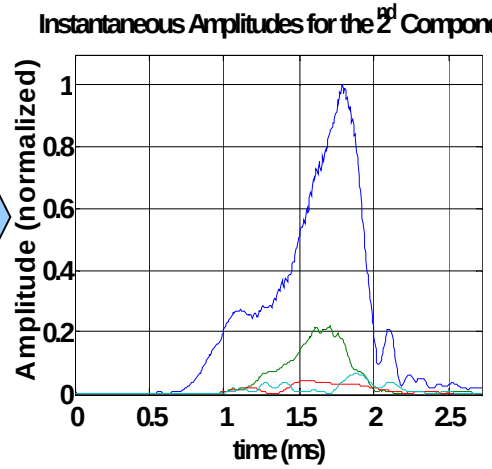

Instantaneous Amplitude for 1st Component
Amplitude (normalized)
0 0.2 0.4 0.6 0.8 1
0 0.5 1 1.5 2 2.5
Time (ms)

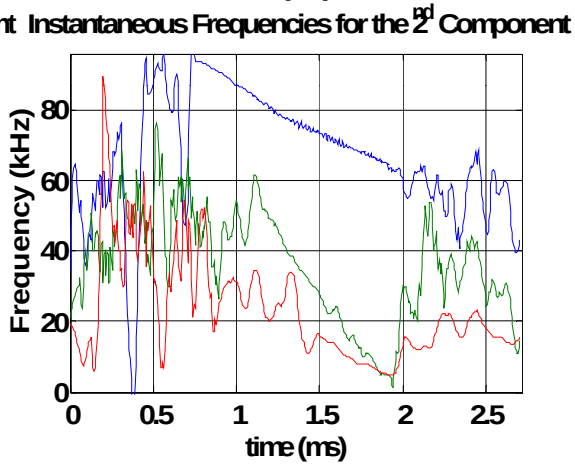

Intrinsic Mode Functions for the 1st Component
0.4 0.2 0 -0.2 -0.4
0 1 2 3
Time (ms)


Frequency (kHz)
0 20 40 60 80
0.5 1 1.5 2 2.5
Time (ms)
-20 -40 -60 -80


Frequency (kHz)
0 20 40 60 80
0.5 1 1.5 2 2.5
Time (ms)
-20 -40 -60 -80

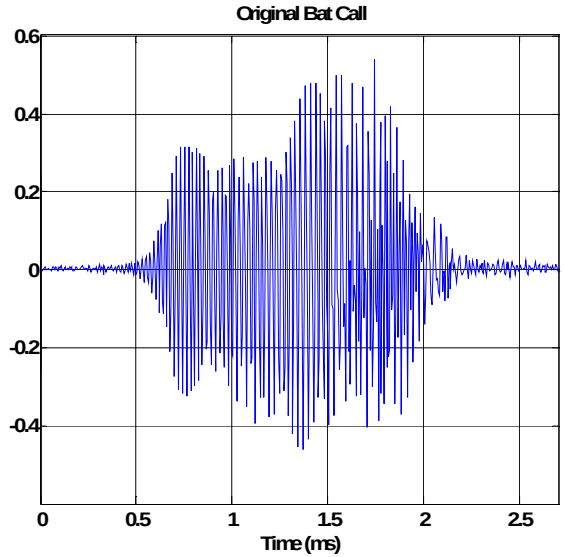

Intrinsic Mode Functions for the 2nd Component
0.4 0.2 0 -0.2 -0.4
0 0.5 1 1.5 2 2.5
Time (ms)

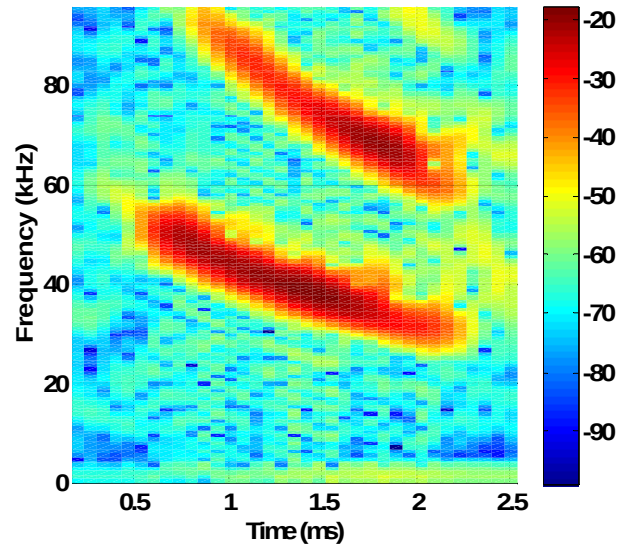

Instantaneous Amplitudes for the 2nd Component
Amplitude (normalized)
0 0.2 0.4 0.6 0.8 1
0 0.5 1 1.5 2 2.5
time (ms)

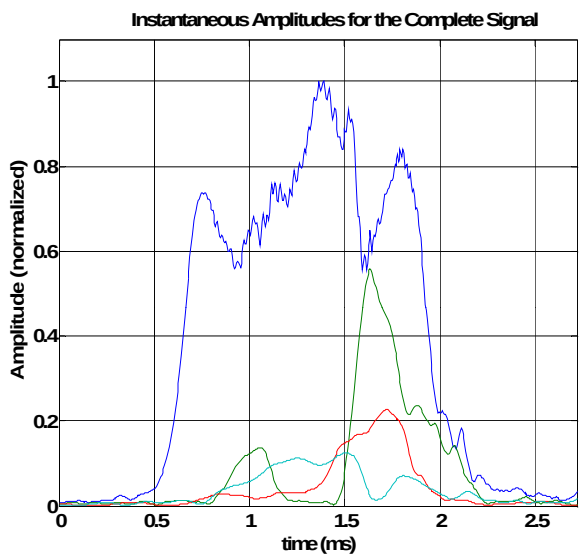

Instantaneous Frequencies for the 2nd Component
Frequency (kHz)
0 20 40 60 80
0 0.5 1 1.5 2 2.5
time (ms)

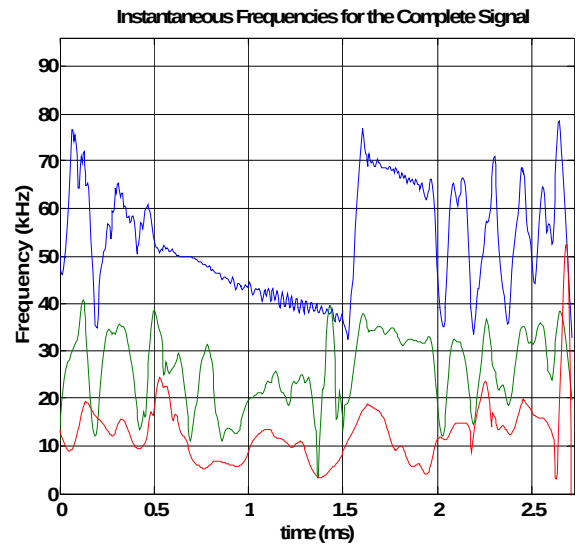
Why Separate Components?

- Empirical mode decomposition performs poorly on multicomponent signals
- Tends to follow the strongest energy at any instant in time
- Multicomponent signals with overlapping components in time shield one another

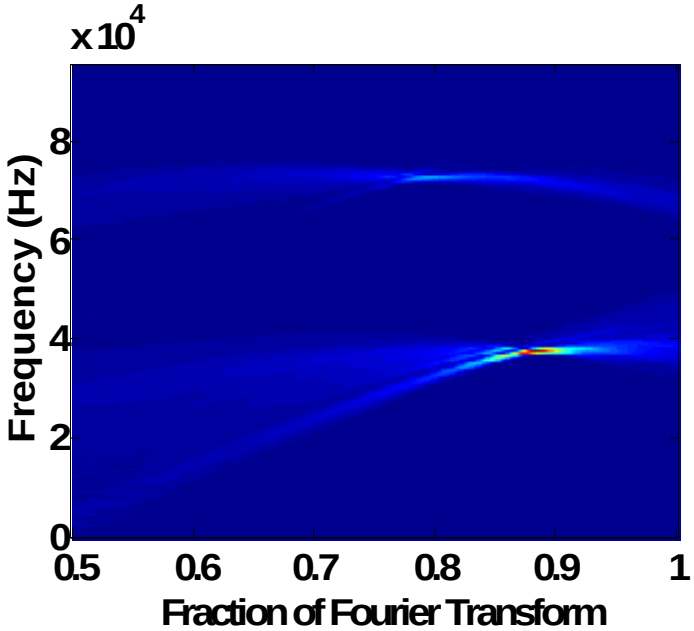


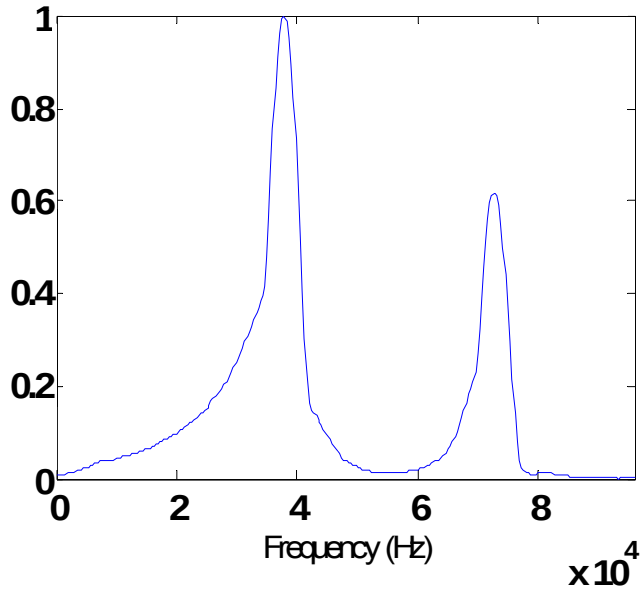


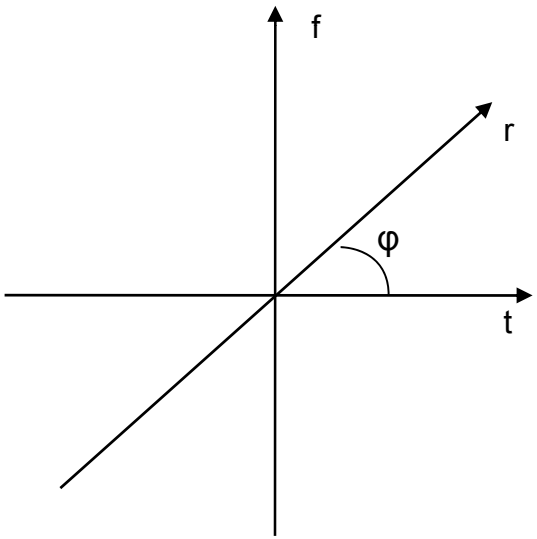




Use Fractional FT to Determine Overlap





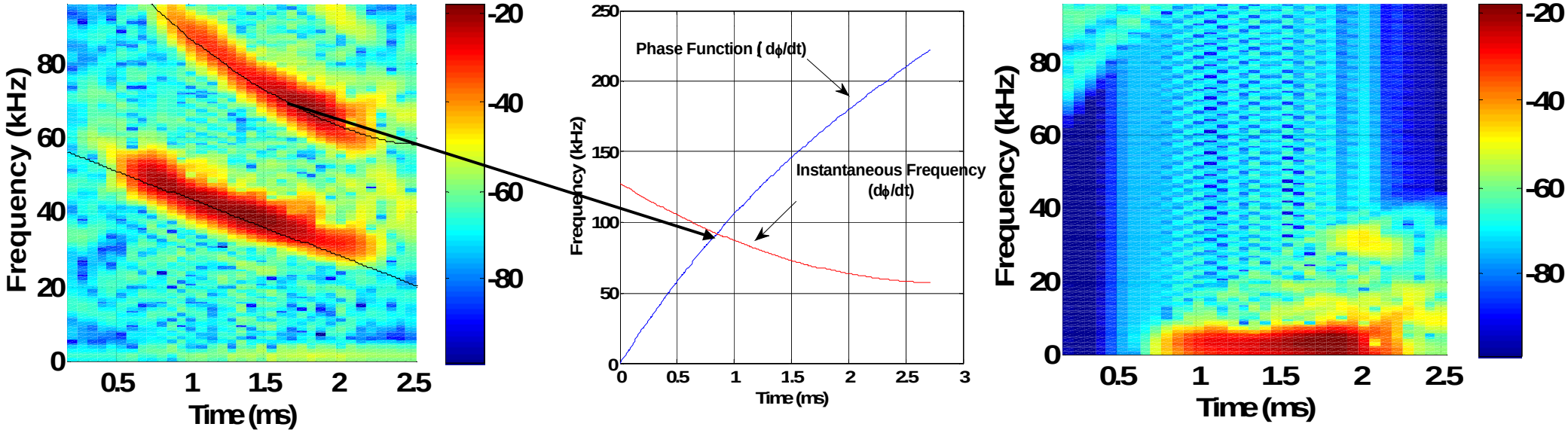


- Fractional Fourier transform is a rotation of the signal s(t) in the counterclockwise direction of the time-frequency plane.
- In the above, the signal is piece-wise rotated from π/4 through π/2, or half of the full rotation to the full rotation of signal through the time-frequency plane, as time and frequency form an orthogonal pair on the time-frequency plane.
- Figure 1 is generally regarded as a collection of column-wise Radon-Wigner transforms (RWT)
  - equivalent to the squared-modulus of the Fractional Fourier Transform.
- Figure 2 is the row-wise summation of the RWT and is used to determine the overlap between the two components of the echolocation call.

Empirical Mode Decomposition

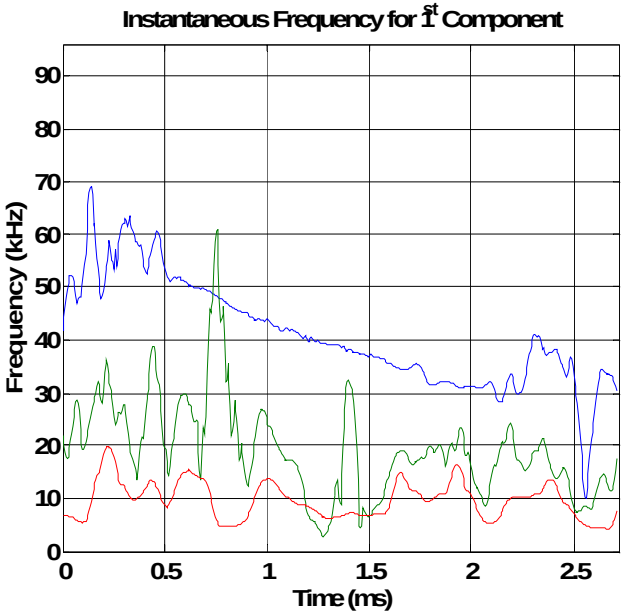
- Identify all maxima and minima from time series
- Fit cubic spline to upper and lower extrema
- Find the mean waveform associated with the upper and lower splines
- Subtract the mean waveform from the original time series and repeat
- IMF if certain conditions are met
- IMFs are based on and derived from the data
  - Complete and almost orthogonal
  - Based on scale for mode definition (time)
- Basis to represent nonlinear and non-stationary time series
  - Complete
    - Precision of expansion
  - Orthogonal
    - Positive energy and avoids leakage
  - Local
    - No time scale for non-stationary data
    - Events are handled by the time of occurrence (amplitude and frequency are functions of time)
  - Adaptive
    - Underlying physics
      - Nonlinearity accounts for harmonic distortion in Fourier analysis

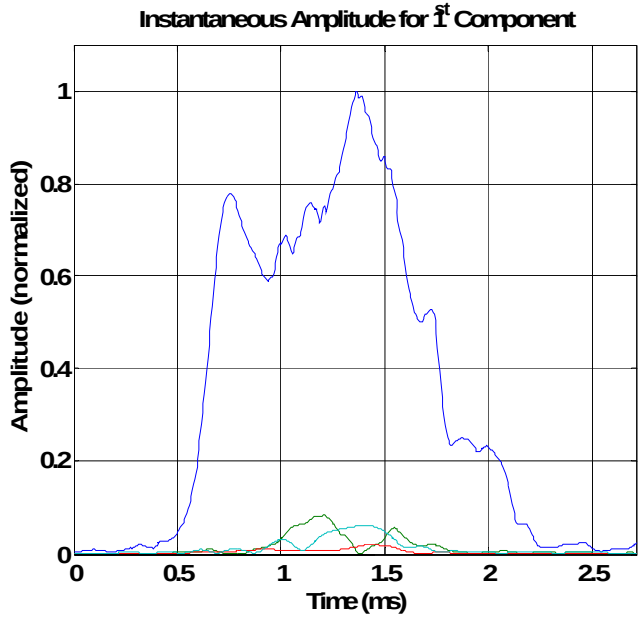
Demodulate/Remodulate with Phase Function

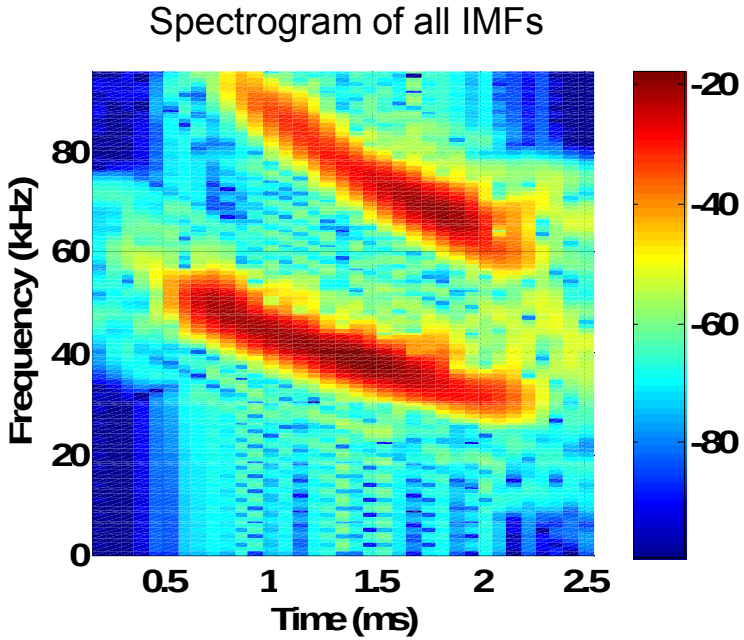


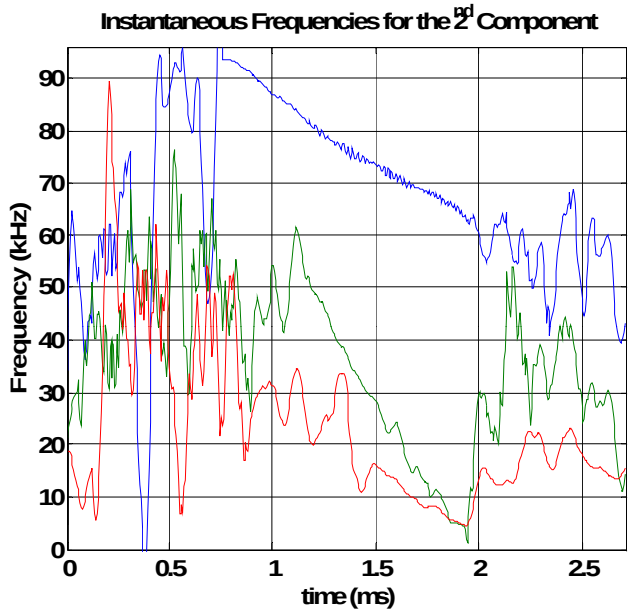
- Fit polynomial to the each of the components
  - Polynomial order determined based on series of parameters – monotonicity, derivative, and length of IF versus IA of the 1st intrinsic mode function.
- Instantaneous frequency (IF) is extracted through a derivative of the unwrapped phase function.
  - Data is forced to be analytic through Hilbert transform and central difference applied using the conjugate
- Since the IF represents the unwrapped phase, simply integrate to retrieve the unwrapped phase function.
- Multiply the analytic signal by $e^{-j\omega\varphi(t)}$ to demodulate and $e^{j\omega\varphi(t)}$ to remodulate
- Low pass filter at the nominal bandwidth to isolate component

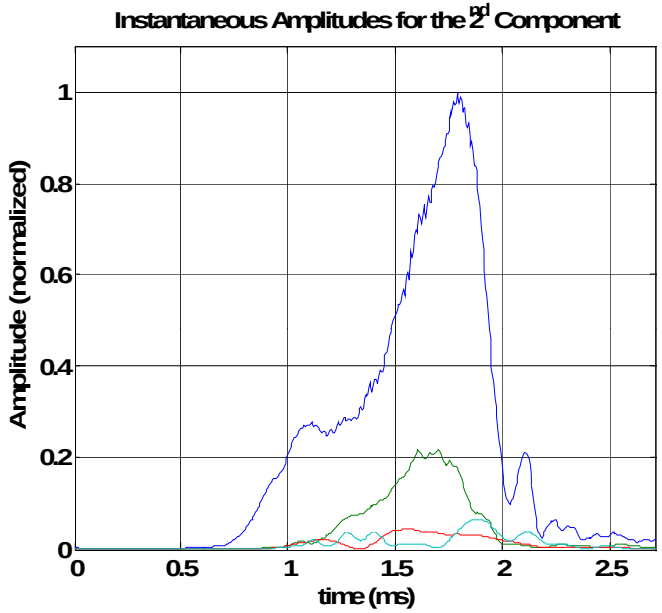
Reconstruction

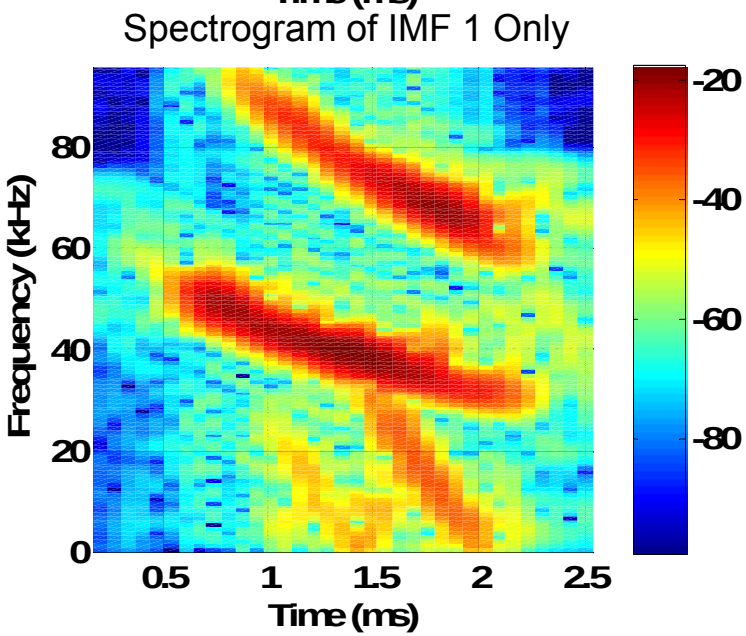




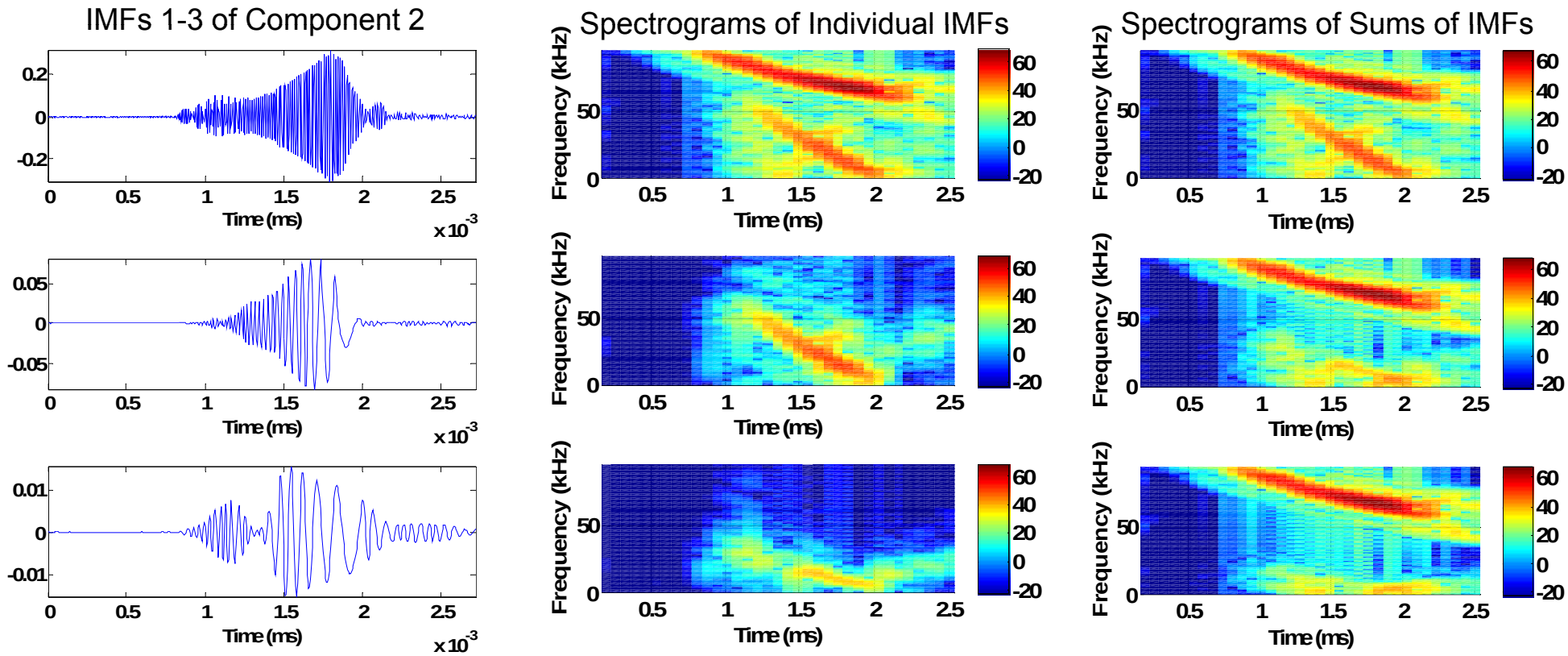








Analysis



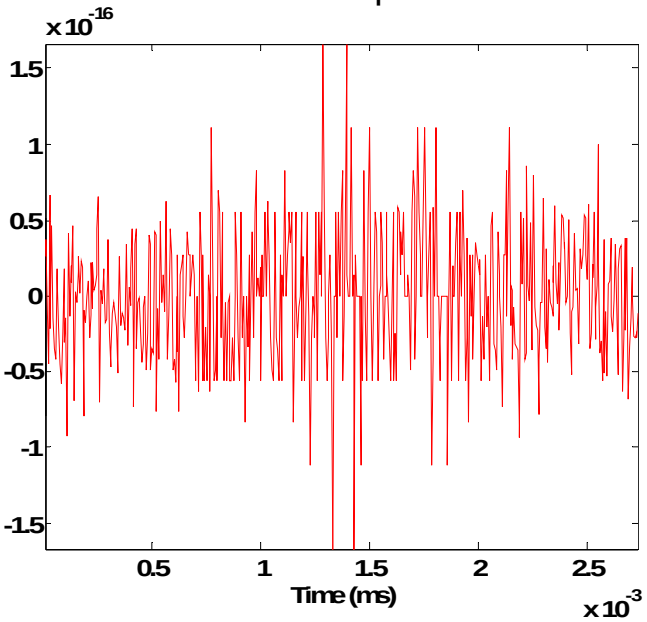
- Signals appear physically realizable
- Summation of the IMFs is complete – error between sum of IMFs and data is approaching machine error.
- Unclear if the bat is generating these components or if they are artifacts of the processing.
  - Will address this in follow on research by sending back an echo to the bat that is strictly the first IMF.

Summary and Conclusions

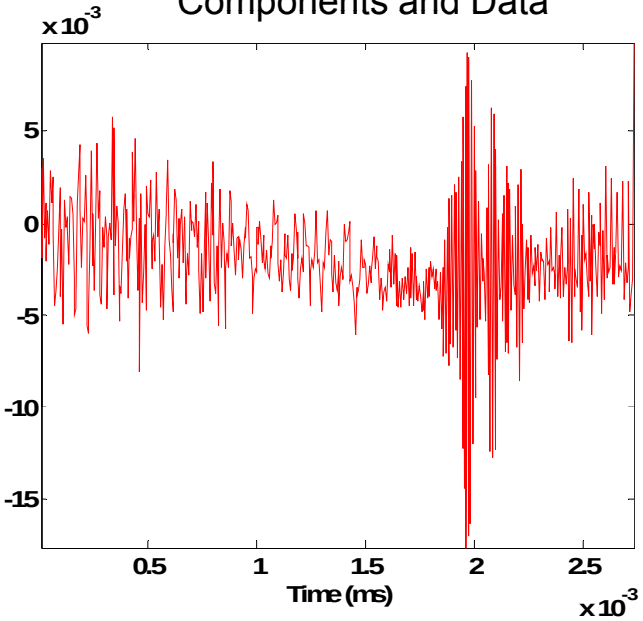
- Method provides a new set of tools for investigating adaptive sonar waveform analysis and design by echolocating animals
- Process is reversible
  - Can completely describe a synthetic bioacoustic signal for communications with layers of components
- Could aid in classification for bioacoustics as well as anthropogenic acoustics
  - Biomass migration
- Bioacoustic signal reconstruction allows for
  - Efficient and clandestine way to encode information by ships and UUVs
  - Accurate reconstruction of animal echolocation tasks in simulation
- Future work involves mining the Brown dataset and exploring cetacean and whale signals

Back-Up

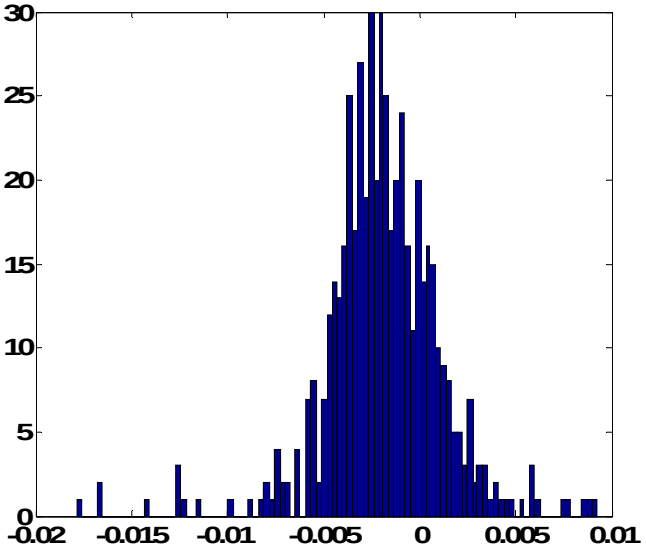
Error between Decomposition and Data

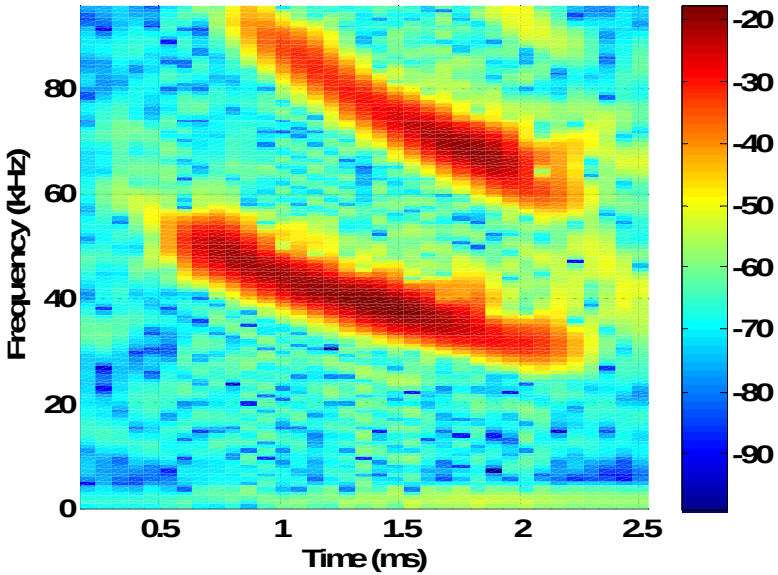


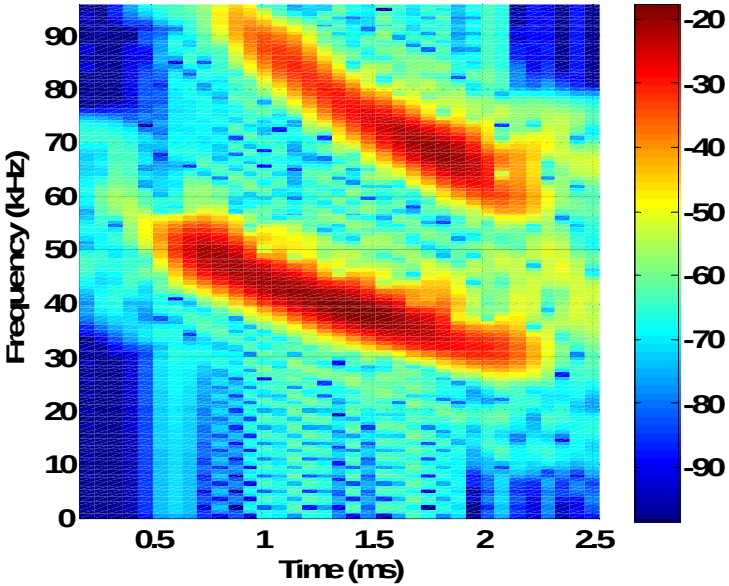
Error between IMFs of Isolated Components and Data



Error between IMFs of Isolated Components and Data







Applications

- Process is reversible
  - Can completely describe a synthetic bioacoustic signal for communications with layers of components.
  - Represtents an efficient and clandestine way to encode information.
- Insight into marine mammal bioacoustics may allow for “better” sonar design.
- While the dynamics are not entirely comparable between bat bioacoustics and marine mammal bioacoustics, the methodology provides a new set of tools to investigate.
- Could aid in classification for bioacoustics as well as anthropogenic acoustics.