Open Source Wide Band Software Defined Acoustic Modem

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Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR)
Opportunity Announcement HR001120S0019-06
Virtual Proposers' Day

April 2020

Opening Comments

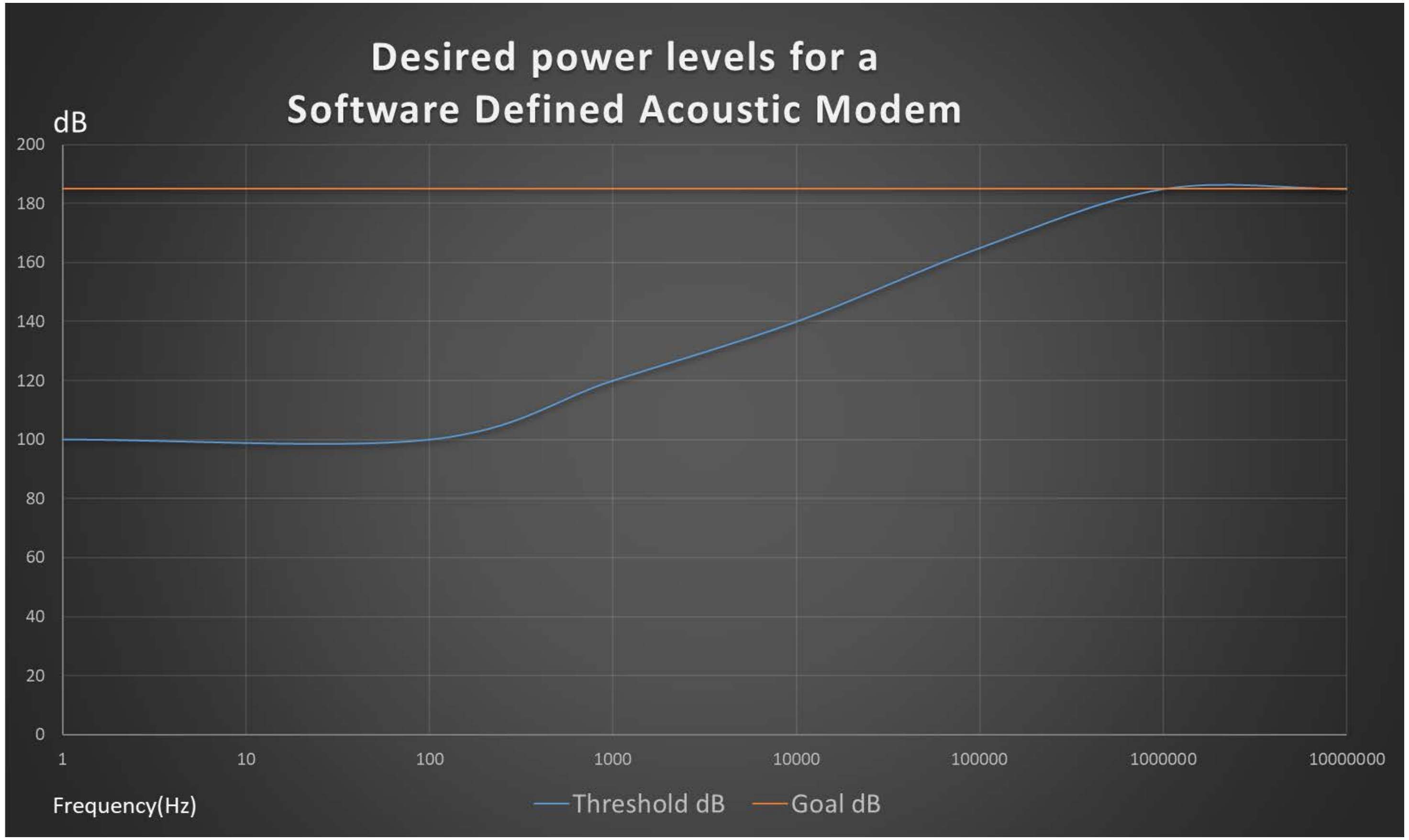
- The Proposers' Day briefing is intended to provide an orientation to DARPA HR001120S0019-06
- In the event of any conflict, real or perceived, between Proposers' Day materials and the solicitation, the solicitation shall prevail
- Material presented in this Proposers' Day (e.g., artwork, invited presentations) should not be interpreted as dictating or preferring a particular system design or solution approach
- The solicitation is written to outline an ambitious vision and guiding metrics, but permit tremendous latitude in technical solutions

What are we trying to do?

- This SBIR would develop a highly modular and wide band software defined acoustic communication system for incorporation into predefined unmanned underwater vehicle (UUV) payload volumes to provide a reliable alternative to legacy acoustic modems.

- An open architecture environment that allows for any communication band, bandwidth, protocol, and symbol/constellation setting, essentially a GNU-like open source do-it-yourself workspace

- The hardware should be able to support any particular communications protocol or scheme the user desires.



How is it done today? Who does it?

- Communications in the undersea environment span a vast range of needs including high bandwidths at short distances to low bandwidth at long distances and everything in between.

- Missions may include long distance communication between nodes or passing of large data such as images between undersea units.

- Commercialization trends for the oil and gas industry as well as undersea scientific exploration continue to grow; however, needs for improved undersea communications from the currently limited options of wide band acoustic communications systems persist.

- There are a limited number of providers of legacy acoustic modems.

What are the limitations of the present approaches?

- The current state of practice for UUV communications often involves highly constrained, static communication protocol, and keying methods based on closed commercial standards. Solutions have led to near vendor lock on UUV acoustic communication systems.

- To date, most acoustic communication – and to that end, most undersea electromagnetic and optical communication – have been mostly band limited

- Most acoustic communication systems, even if they have variable center frequencies over a relatively wide band, do not allow for flexible bandwidth management (e.g. center frequency may vary over 10 KHz but the bandwidth is often hard coded to 4 KHz)

- Today’s protocols are typically hard coded

What is new about our approach?
Why do we think we can be successful at this time?

- Performers would be tasked to conduct research and development for innovative wide band, highly dynamic acoustic communications systems capable of enabling low cost, open-source architecture fielding in UUVs or similar undersea nodes.
- Employment of the resulting system would enable advances in affordable underwater command and control by ensuring that dynamic undersea communication is not impeded by environmental noise, fixed frequency ranges of operation, or non-open standards.
- This SBIR will design, develop, test, and field an acoustic software defined communications system with open-source architecture software.
- Solutions will include definitions for communication methods and protocols as well as the widest possible bandwidth (e.g. 1 Hz to 10 MHz) for demonstration to enable underwater command and control.
- Both narrow and spread spectrum acoustic communications will be supported such that the result is capable of integration by the end user into an expendable UUV or similar low cost undersea node.
- Spread spectrum solutions that minimize disturbances to or noise from environmental acoustic sources while communicating are encouraged but not required.
- The modem should demonstrate the support of an open architecture Integrated Design Environment (e.g. user community for Raspberry Pi, user community for GNU Radio level access to programming).

If we succeed, what difference do we think it will make?

- Delivery of a highly programmable acoustic communications capability should allow for lower power output, significant reduction in cost, and development of capabilities beyond the current state of practice.

- The intention of this SBIR is to demonstrate the widest possible acoustic communications capacity and optimization at a sufficiently low price point to allow one or more expendable UUVs to coordinate during a nominal multi-UUV exercise.

- The experimentation conducted as part of this SBIR should yield integrated measurements of performance throughout both littoral and deep sea ocean environments.

- Solutions should support an open architecture for flexible user defined programming of communication protocols.

- See Navy's Excerpts from Dr. Cameron Matthews Briefing at the Acoustical Society of America (ASA) Proceedings May 2019 also provided in this Virtual Proposers' Day

How long do we think it will take? What are our mid-term and final exams?

- The Phase I portion of the SBIR is 6 months duration including mid-term milestone reports. The final exam of Phase I would be a report summarizing the approach; prototype architectures and algorithms; quantification of accuracy; quantification of robustness to errors; and major deviations from legacy acoustic modems and communication definitions; critical design metrics for Phase II including acoustic bandwidth, power, and open-source architecture

- Phase II would consist of a maximum 12 month period of performance. Exams include reports, bench test design, simulation results, in-water test plan, final in-water demonstrator design, in-water testing in conjunction with a Government test agent, and a final report.

How much will it cost?

- Please see the solicitation for cost information.

www.darpa.mil

Ad Hoc Biological Acoustic Communications Design Considerations for a Software Defined Modem

Dr. Cameron Matthews
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Intent

Many animals in the sea utilize acoustic communication for a number of reasons

Man uses acoustic communications in the sea as a means of communicating between divers, robots, submerged and surface platforms

Animals have spent their entire evolutionary period refining their methods for communication

Acoustic modems have for the overwhelming period of their existence been defined in terms of bandwidth and protocol by their analog circuitry – however, advances in Digital Signal Processing (DSP) technology allow for the development of more dynamic, software defined modems

This brief presents a grouping of various communication strategies by sea life and state of the art industry products, which in turn informs a framework for designing software defined modems for optimization of the arbitrary acoustic environment

A notional design based on one particular species (Pelates Quadrilineatus) is presented to as an example of how a system could be implemented that mitigates the negative effects of anthropogenic noise associated with acoustic communication

Biological Acoustic Communication

Many species communicate acoustically, including many teleost species

The commercial market boasts a number of companies worldwide that do acoustic undersea communications, including Teledyne-Benthos, Woods Hole Oceanographic Institute, Evologics and others

These systems employ Multiple Frequency Shift Keying (MFSK), Phase Shift Keying (PSK) and other standard communication protocols to facilitate data transfer

Anthropogenic noise has been shown [1] to have negative effects on many species, including cetaceans, pinnipeds and teleosts as well as digital acoustic communications

With the advent of Software Defined Radio (SDR) type applications for Software Defined Modem applications, with increased bandwidth, adaptability and responsiveness to dynamic environments, biologically inspired design represents a potential path for decreasing anthropogenic impacts with active communication systems

1. Guangxu, Liu, Noise in the Sea and its Impact on Marine Organisms, *Int. J. Environ. Res. Public Health* **2015**, *12*, 12304-12323; doi:10.3390/ijerph121012304

Example Digital Acoustic Communication system: Teledyne Benthos 900 series of commercial acoustic modems

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Features of the 900 series:

A hypothetical revision via SW defined components:

	Features of the 900 series	A hypothetical revision via SW defined components
POWER	**378 W*Hr internal batteries (can also be powered by external source)**	likely power savings in digitization and reduction of analog components
FREQUENCY OPTIONS	Low frequency (LF): 9-14 kHz Mid frequency (MF): 16-21 kHz Band C frequency: 22-27 kHz	user defined bands that are a function of the ceramics and the digital signal processing (not the analog hardware)
TRANSDUCER	Omni directional (180 degree beam) Low Frequency (LF) Directional (70 degree beam) Medium Frequency (MF) Directional (60 degree beam)	a wider band at a cost to the power requirement
BAUD RATE	140-15,360 bps	more flexibility via wider band, but still constrained by the operating environment
BIT ERROR RATE	Better than 10-7 with high SNR	more flexibility via user defined protocols, but still constrained by the operating environment
PROCESSING	Data redundancy, 1/2 rate convolutional coding mulitpath guard period selection MFSK and PSK modulation schemes	Open architecture would be desirable to support user defined processing in both the Tx/Rx modes
DISTANCES / RANGES	2-6 km common, greater distances possible 20+ km available using repeater functionality	This will always be defined primarily by the operating environment, but the flexibility of the SW definitions allows for dynamic sampling and revisions across a wider band of communication paths

The Ocean Environment and Acoustic Communication

Why else (besides not harming biologics) would we need SW defined modems?

- ***Better bandwidth management***
- ***Better control over protocols***
- ***Lets us evolve with a dynamic environment***

Why use biologics as a model?

- ***Biologics know their environment and are adapted to it***
- ***Lets a SW defined modem take advantage of fish talk***
- ***Even if the fish is talking in a way that is not optimal for the acoustic communication, this informs the acoustic communications model still – talk some other way than the fish***

This paper considers what could be done with a modem that

1. ***Widened the typical COTS operating bands from hard-coded, nominally 5 KHz to SW defined wide band (e.g. 30-60 KHz)***
2. ***Accepts power constraints as a benefit to biologics by reducing power and effective range***

Time Series Toolbox (TStoolbox) applications: defining anthropogenic and teleost feature characteristics

Using the Tstoolbox (no longer open source supported [2]), we present a general architecture for classification of

1. ***Aperiodic, Non-linear communication***
    - *Typical of textbook standard chaotic waveform generation for communication systems [3]*
2. ***Periodic, Non-linear communication***
    - *Typical of more complex animal communication systems [4]*
3. ***Periodic Linear communication***
    - *Typical of MFSK, PSK and CW acoustic communication systems, as well as many teleosts*

4. t

2. Merkwirth et al, OpenTSTOOL, Drittes Physikalisches Institut, version 1.2 (2009) tstool@phhysik3.gwdg.de
3. Michaels, Signal Processing Techniques for Non-Stationary Chaotic Spread Waveforms, DASP Workshop 2011 *https://daspworkshop.org/uploads/DASP11Proceedings/Michaels_Alan.pdf*
4. McKibben, Bass, Non-linear Acoustic Complexity in a Fish Two Voice System, Proceedings of the Royal Society B: Biological Sciences · May 2011

Time Series Toolbox (TStoolbox) applications: defining anthropogenic and teleost feature characteristics continued

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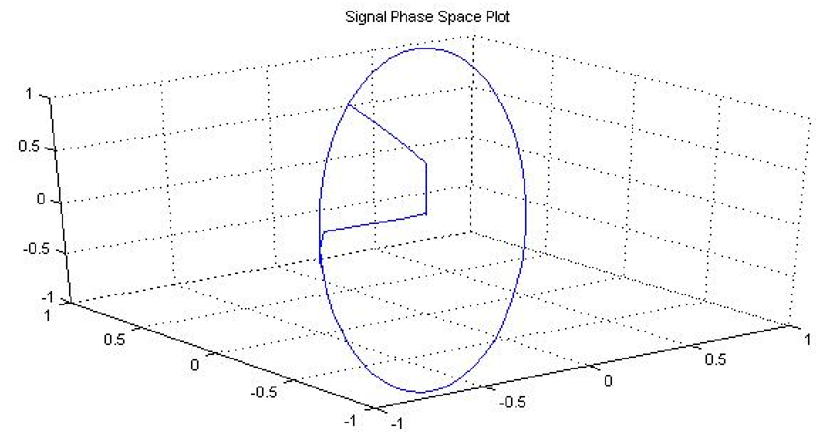
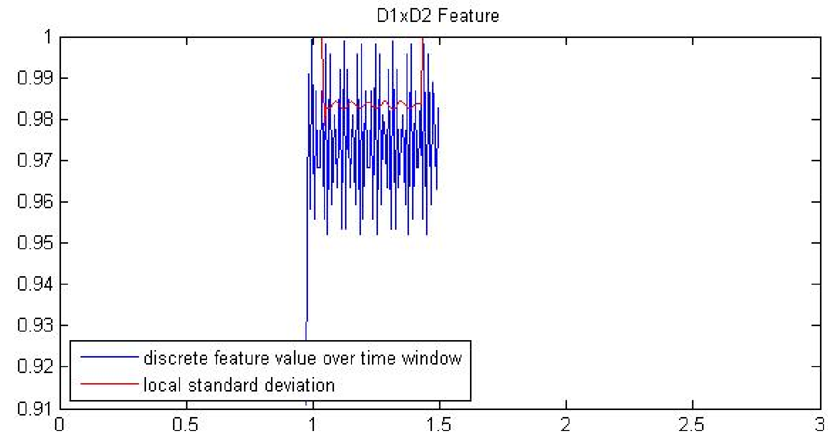
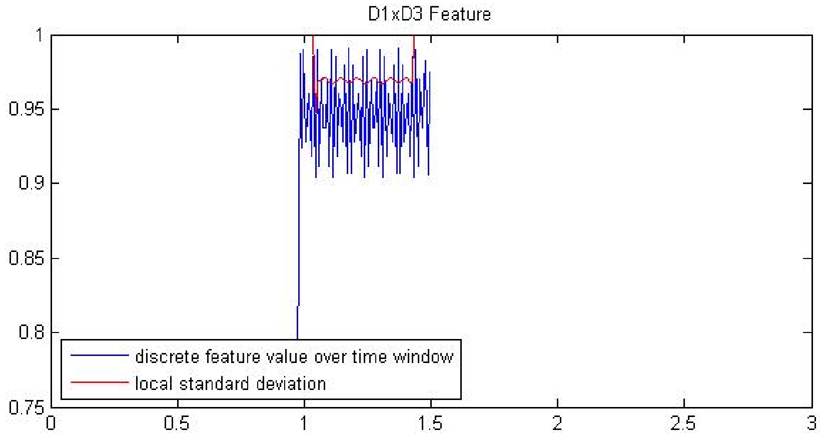
For Aperiodic Non-linear, Periodic Non-linear, and Periodic Linear communications, we create a 3-feature set based on the phase space elements as described in [4] as follows:

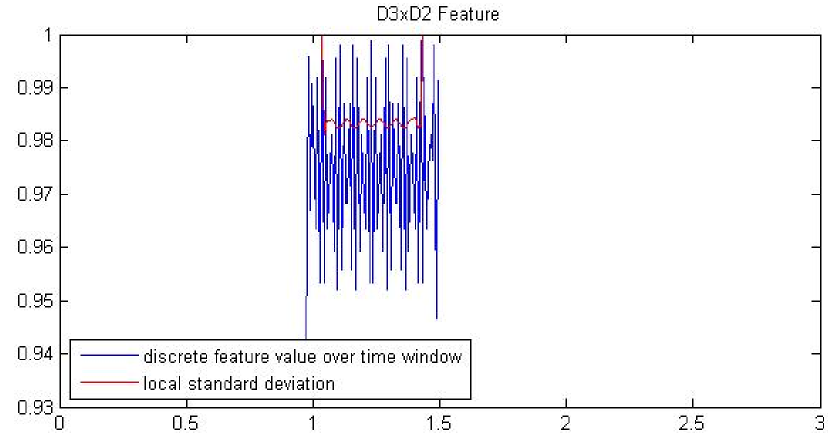
1. ***Create short time plots (e.g. 4-D) of the 3-D curves defined in the Tstoolbox phase space***
2. ***Develop cross-correlated signal peaks for the 1st, 2nd and 3rd order curves of the phase space associated with the***
3. ***Take statistical measures to better isolate what are effectively transient shifts in an information bearing data packet (e.g. teleost vocalization, protocol defined data packet)***
4. *t*

Time-dependent feature set: 100 Hz Sine Wave



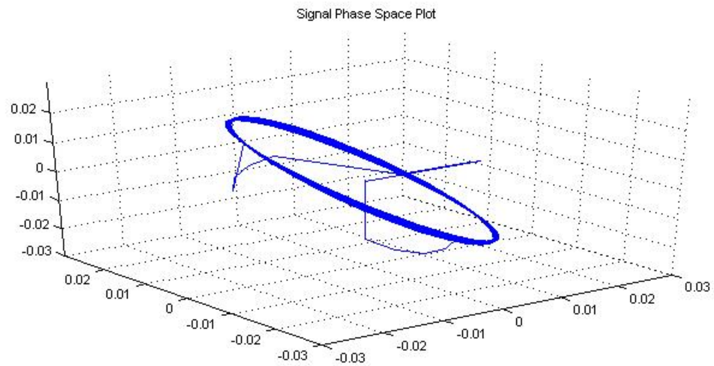


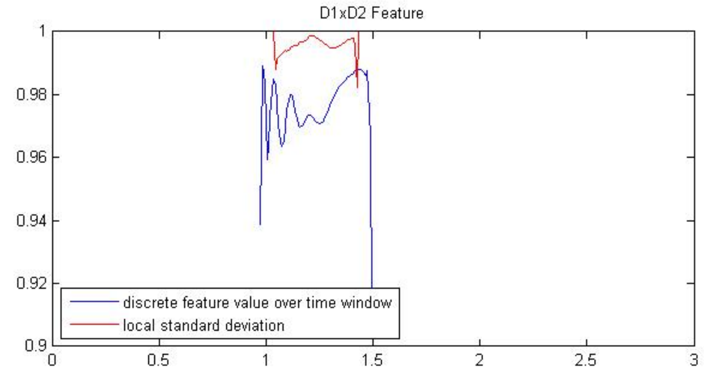


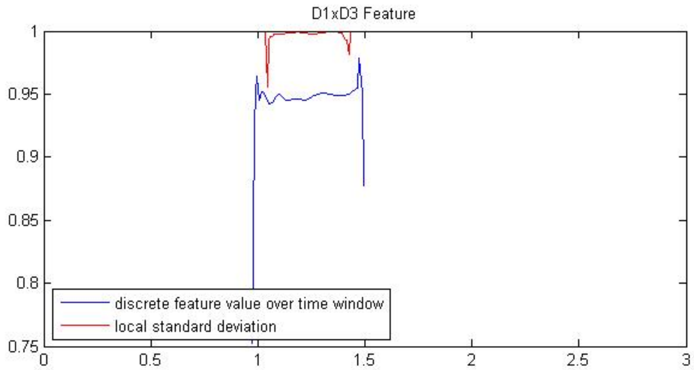


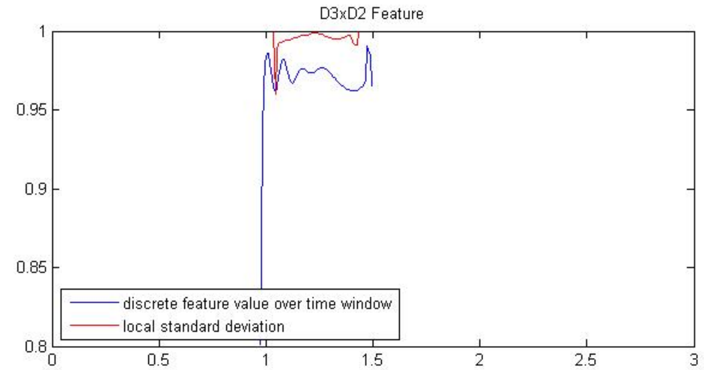
Signal Parameters (Fs = 10000): 90% overlap, 1/64 Fs precision (signal introduced at 0.62s)

Time-dependent feature set: 100 Hz 5Hz/s Sine Wave sweep



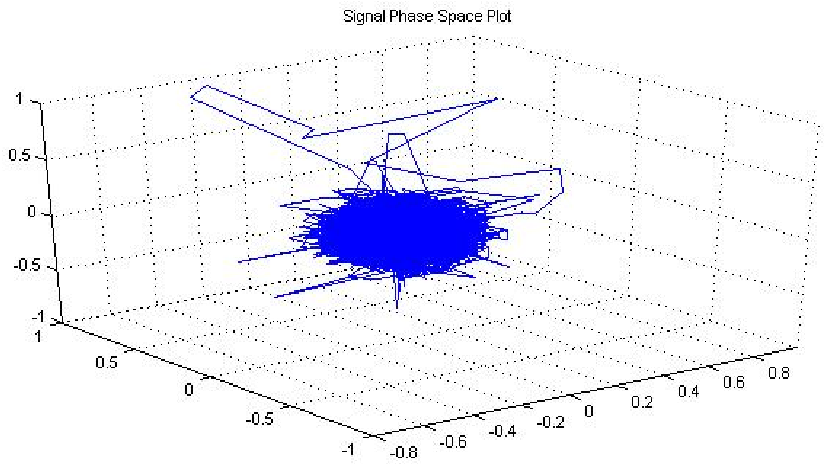


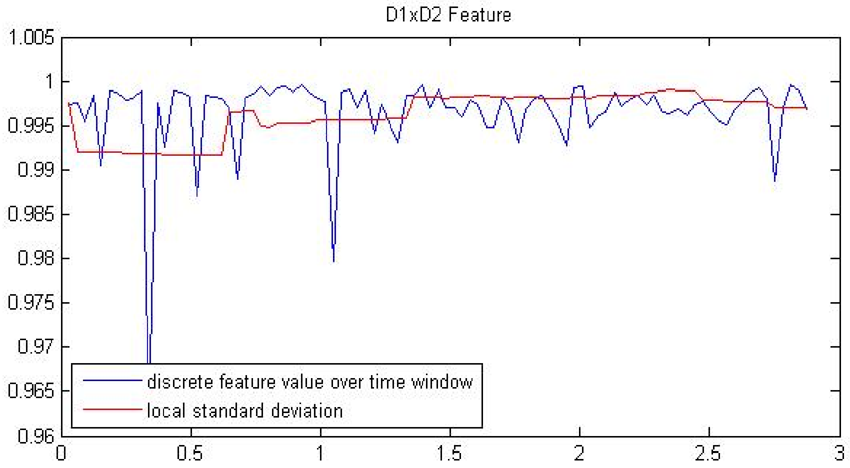


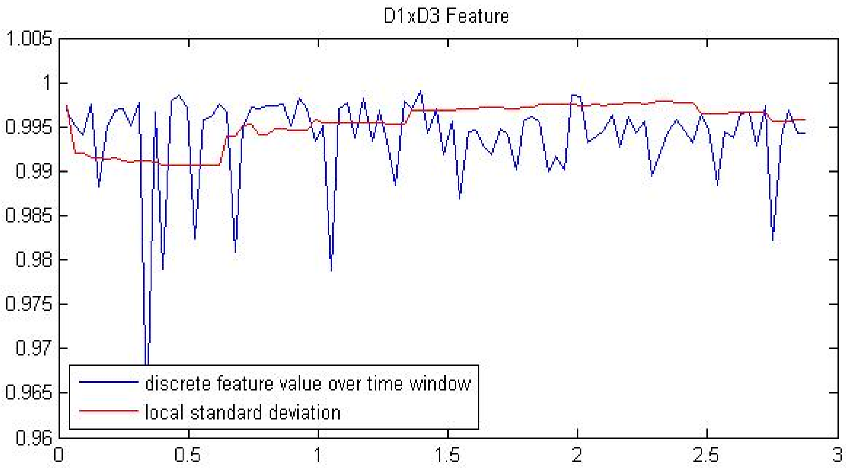


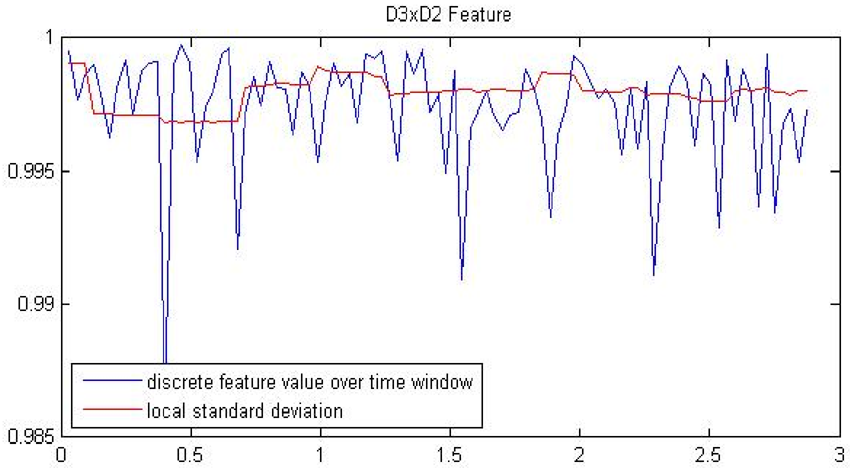
Signal Parameters (Fs = 10000): 90% overlap, 1/64 Fs precision (signal introduced at 0.62s)

Time-dependent feature set: Standard Chaotic Waveform



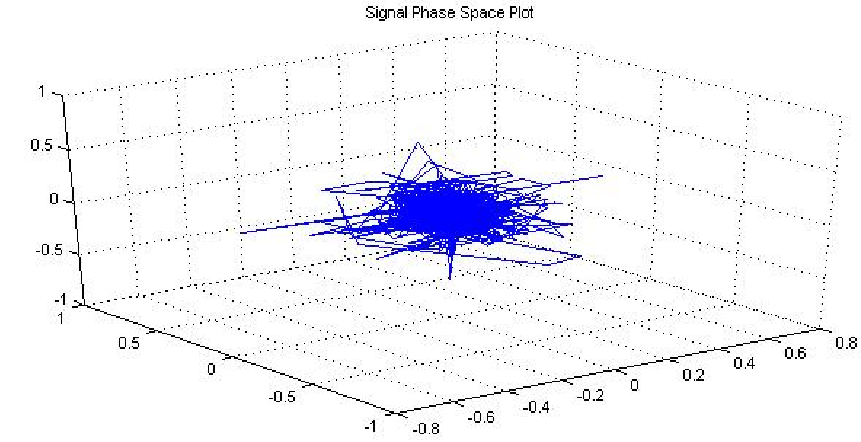


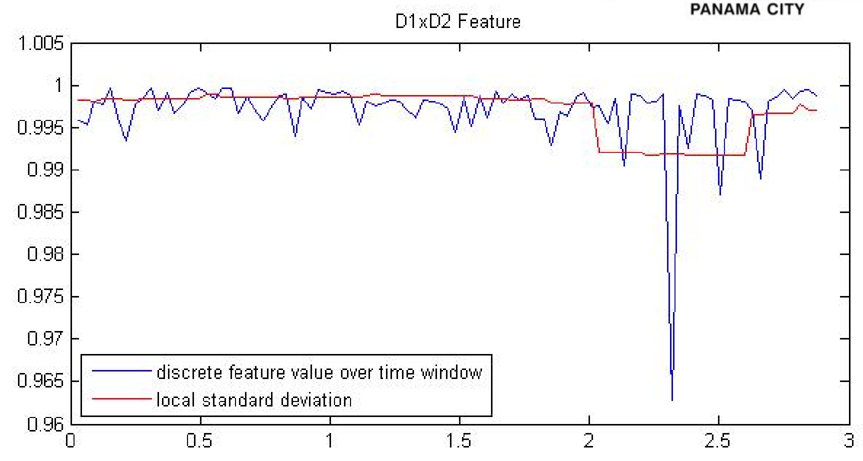


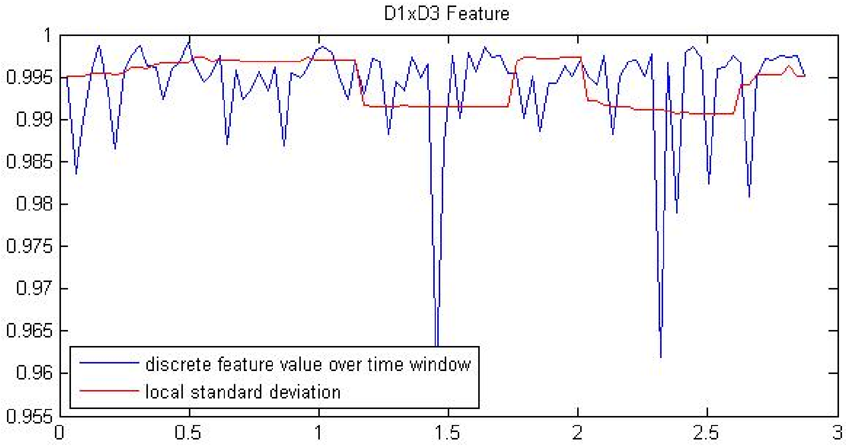


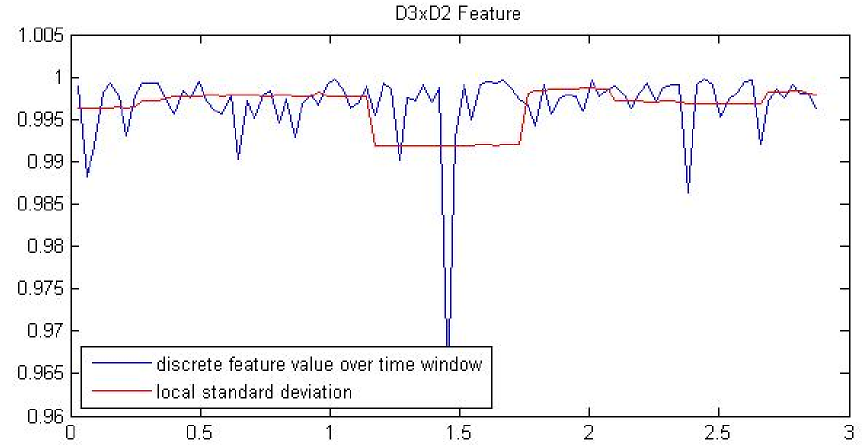
Signal Parameters (Fs = 10000): 90% overlap, 1/64 Fs precision (signal introduced at 0.62s)

Time-dependent feature set: MFSK bookend



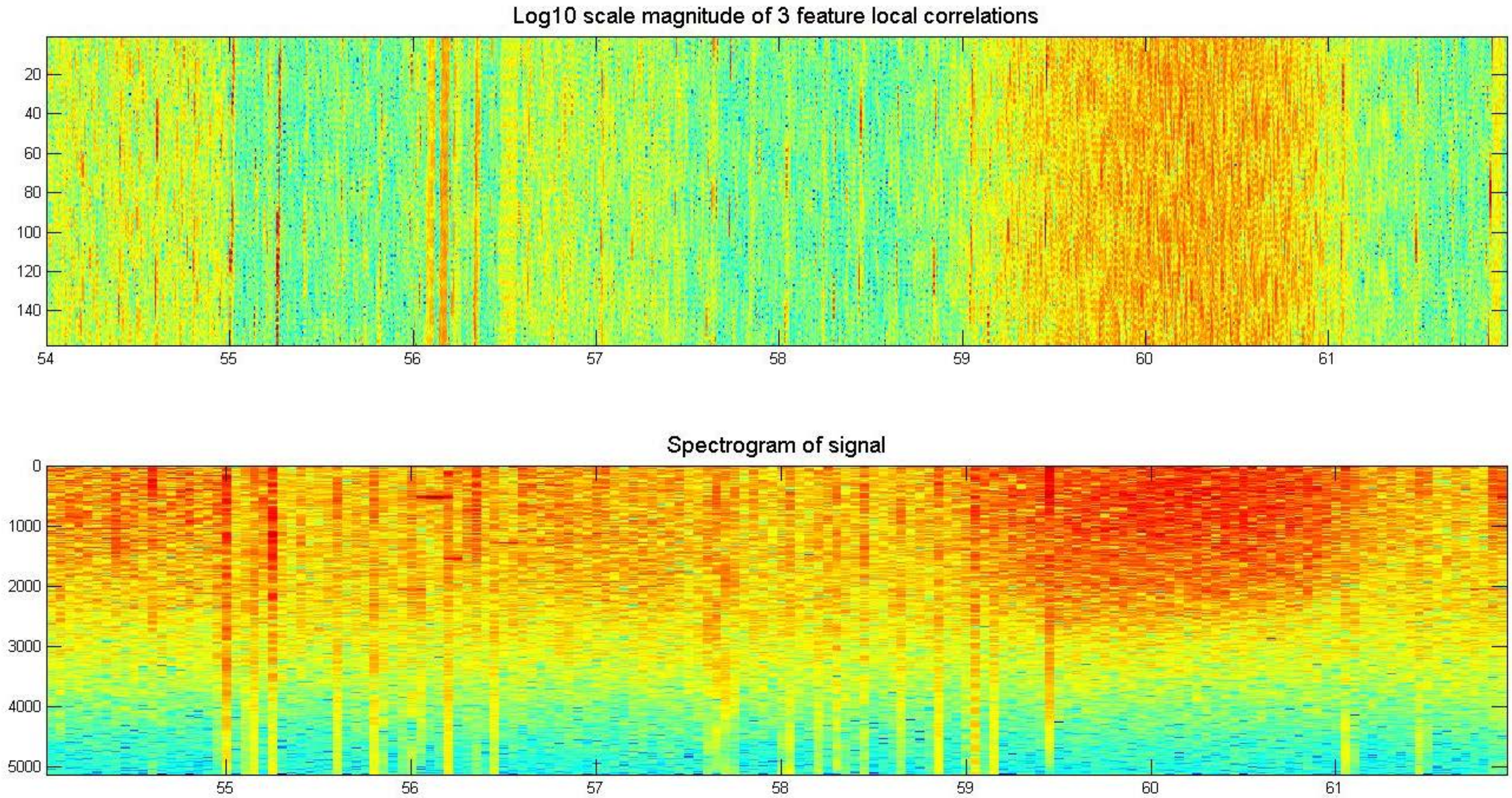




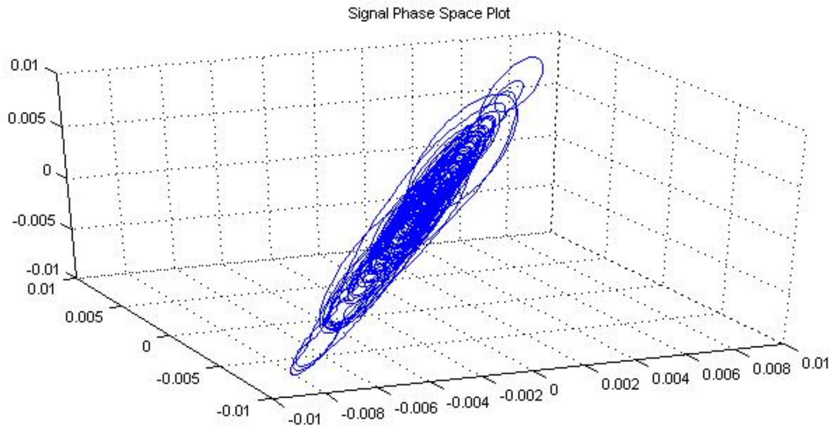


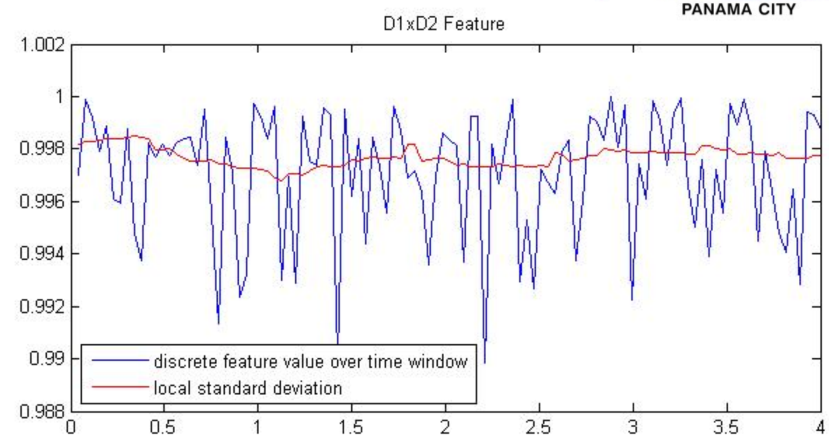
Signal Parameters (Fs = 10000): 90% overlap, 1/64 Fs precision (signal introduced at 1.2s-2.7s)

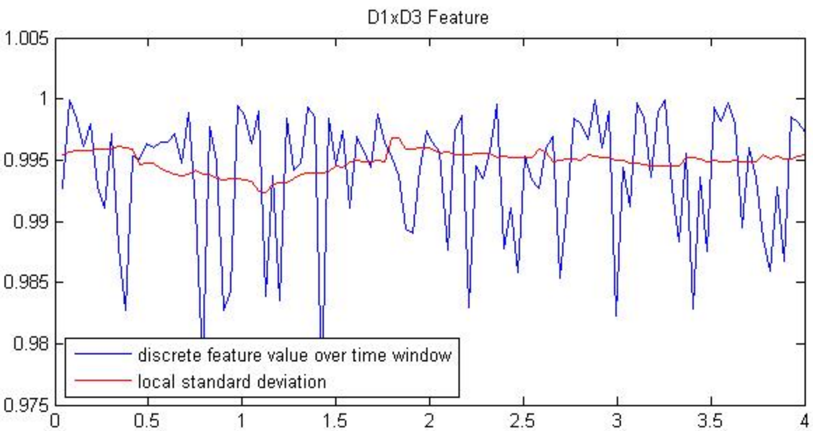
Magnitude feature sets of a MFSK bookend and chaotic signal

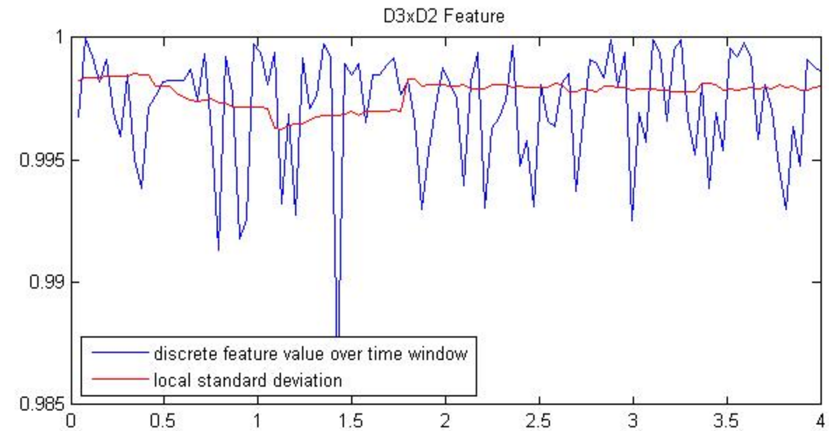


Time-dependent feature set: Red Hind Grouper [5]





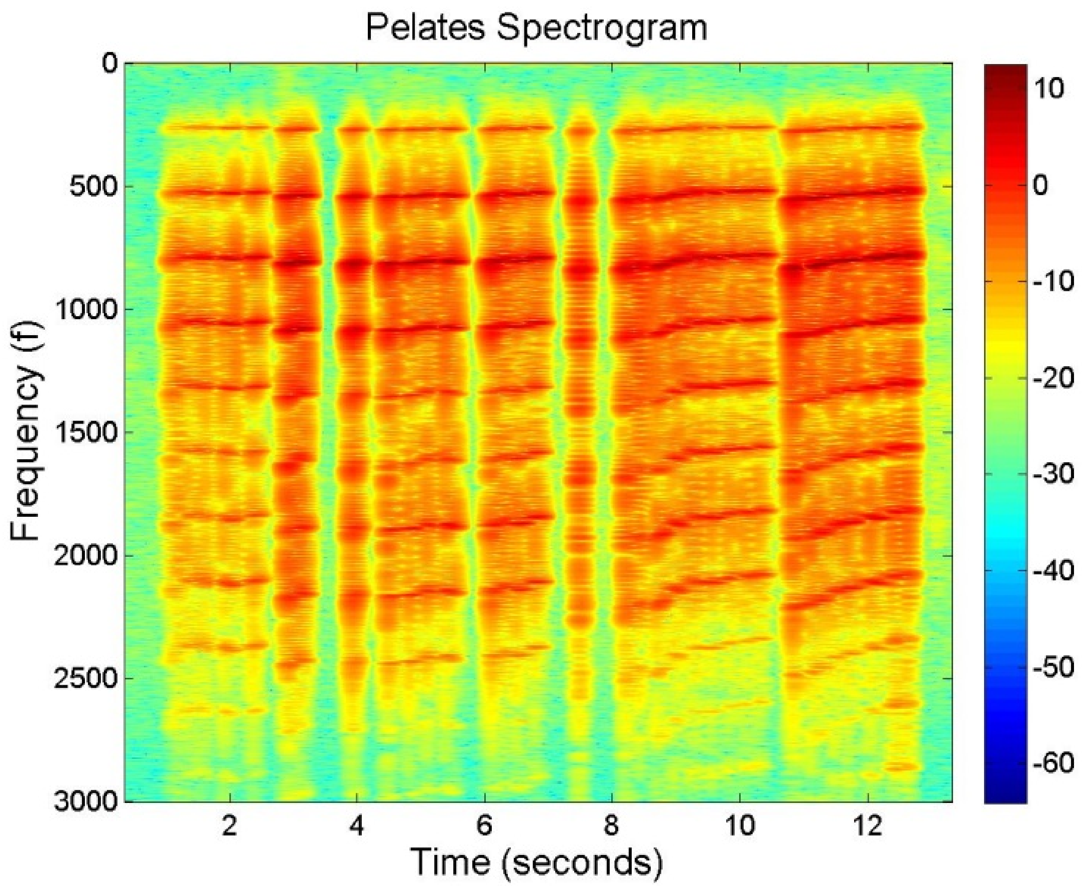




5. Provided by Dr. Pierre-Philippe Beaujean, Florida Atlantic University

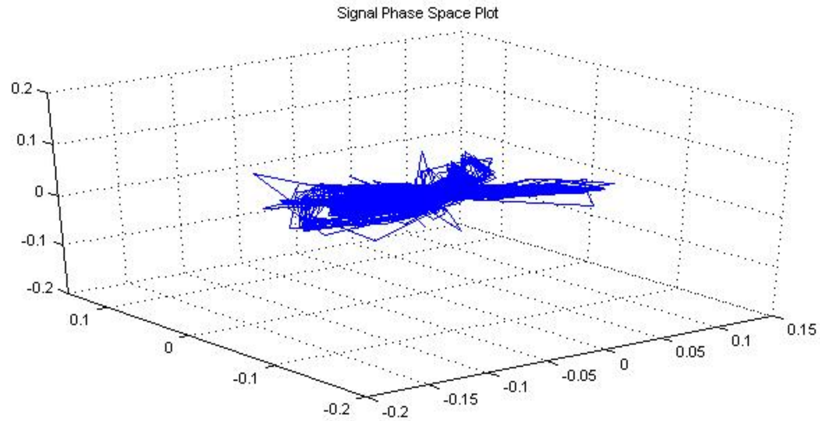
Signal Parameters (Fs = 10000): 90% overlap, 1/64 Fs precision (signal introduced at 0s)

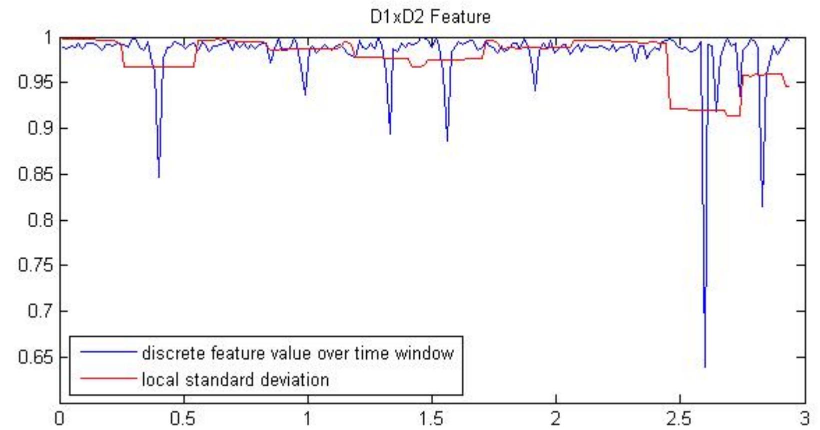
Using reference data provided by Dr. Eric Parmentier, Dr. Michael Fine and Dr. Hin-Kyu Mok (Mike), we analyze Pelates Quadrilineatus for an example of more complex acoustic speech mechanisms. Drs. Mok, Fine and Parmentier make a case for the complex 2-bladder system of Pelates as a form of higher communication [6].

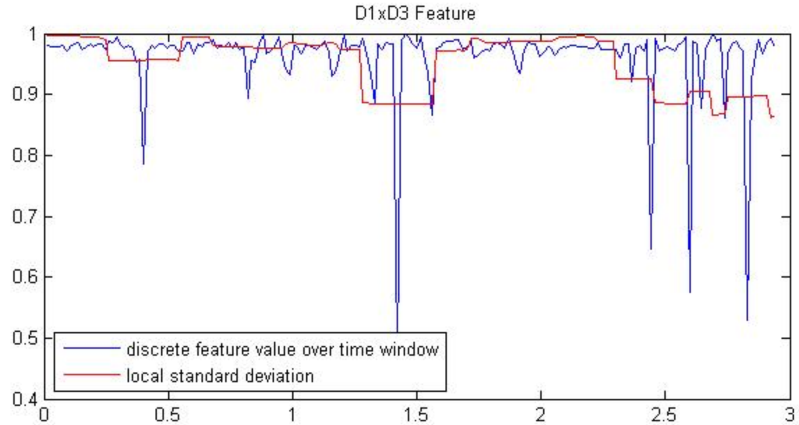


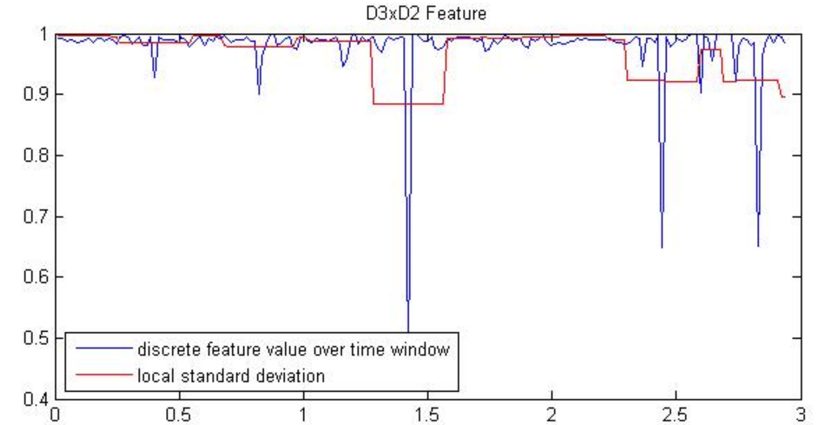
6. Fine, Mok, Parmentier, Sound production by a recoiling system in the pempheridae and terapontidae, J Morphol. 2016 Jun;277(6):717-24. doi: 10.1002/jmor.20529. Epub 2016 Mar 28

Time-dependent feature set: Pelates

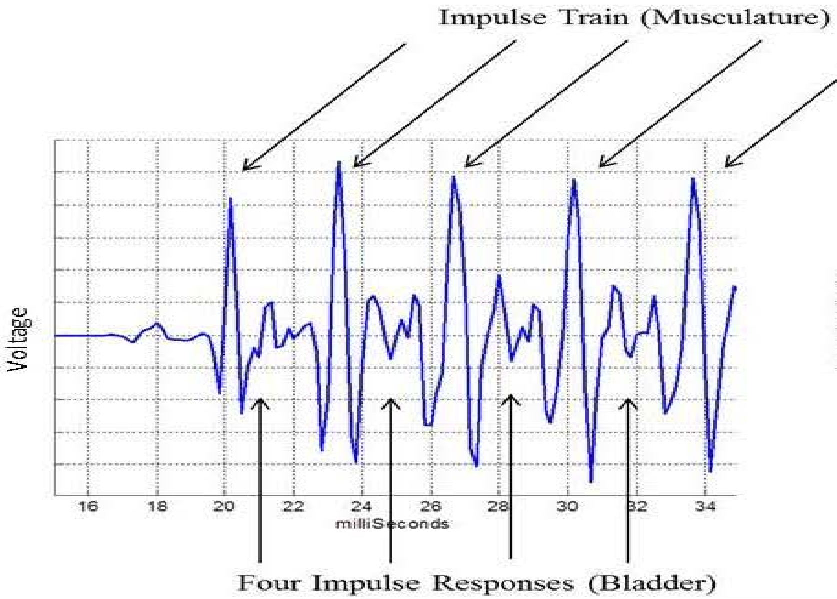


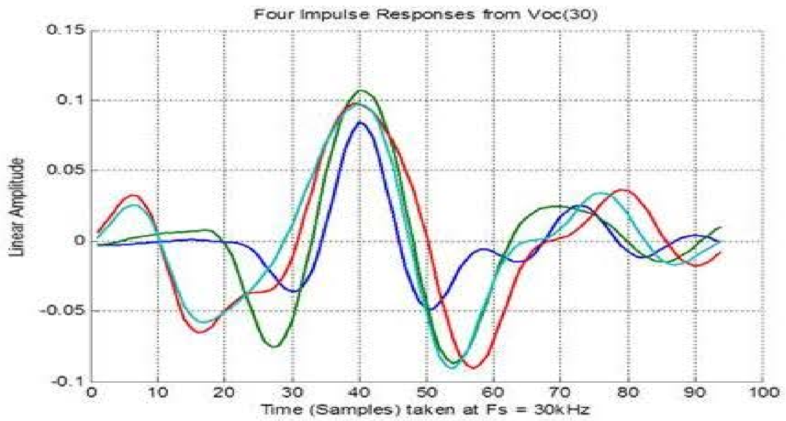


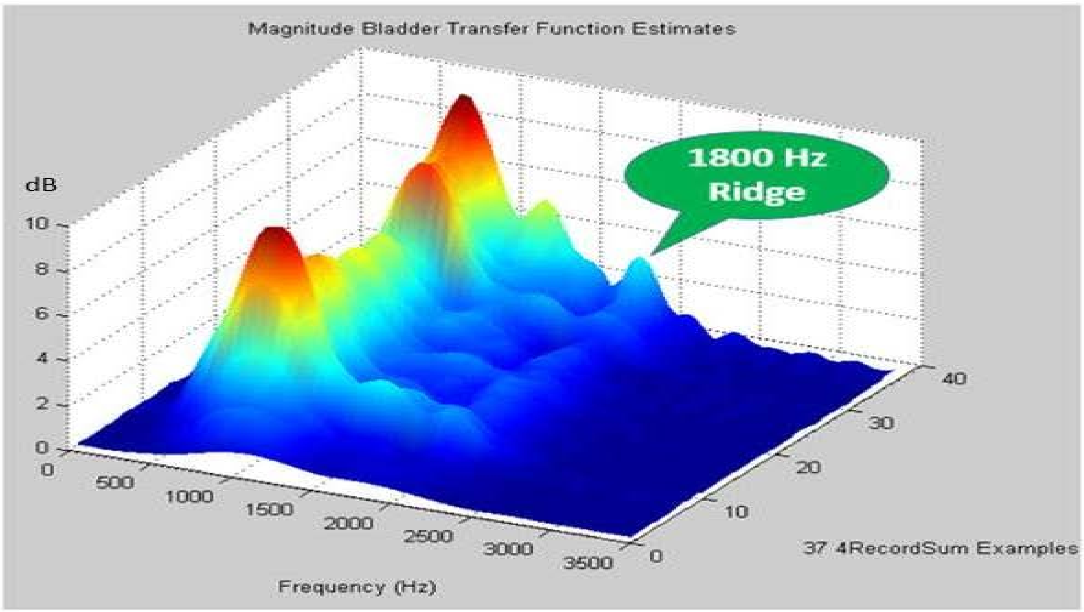




Signal Parameters (Fs = 10000): 90% overlap, 1/64 Fs precision (signal introduced at 0s)







Observing that Pelates utilizes two swim bladdders, a resonance model is constructed to extract modulations from both bladders, the likely source of non-linearity in the vocalization structure.

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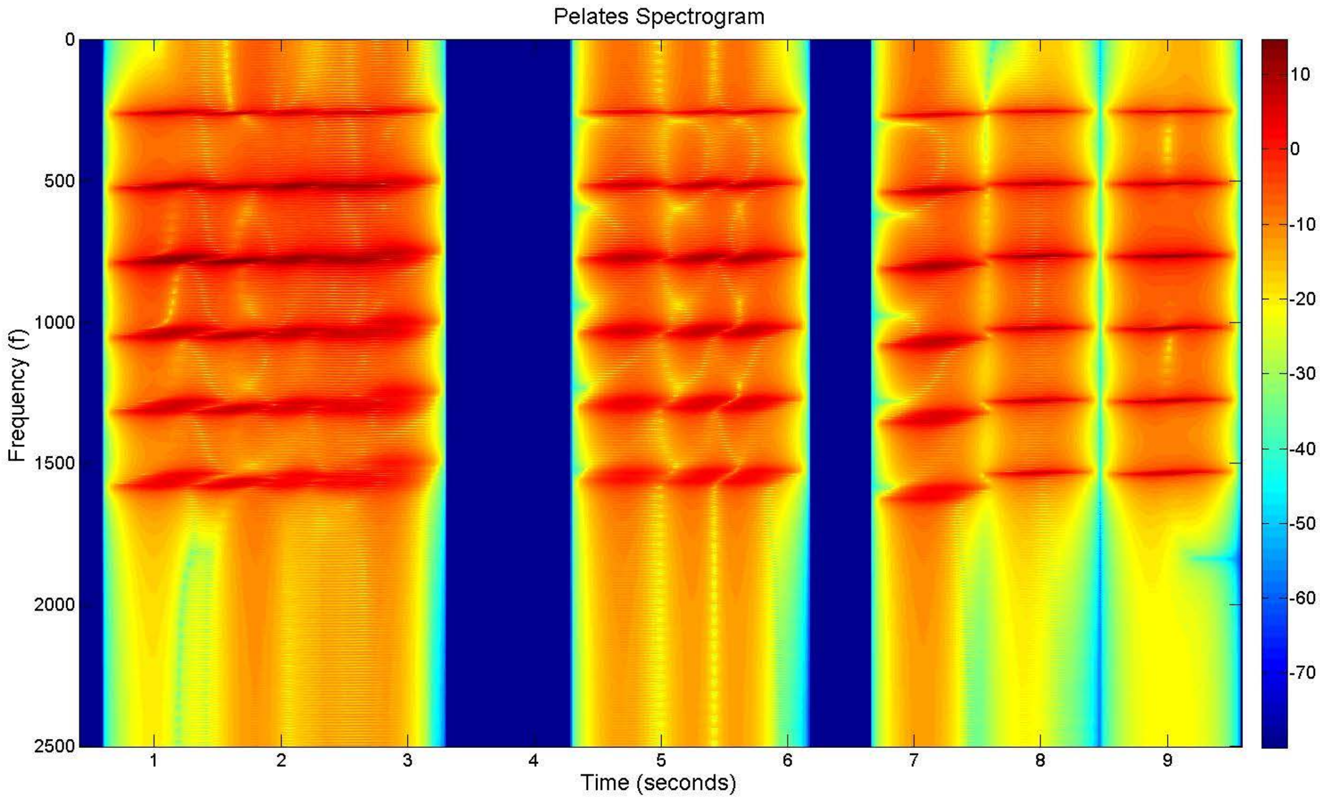
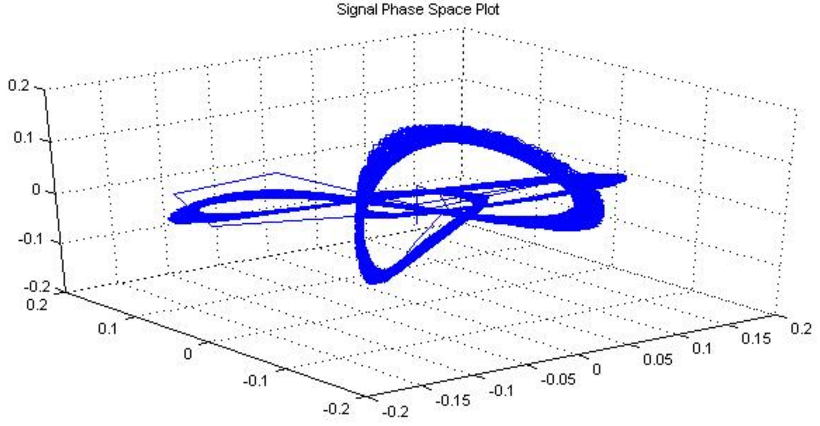
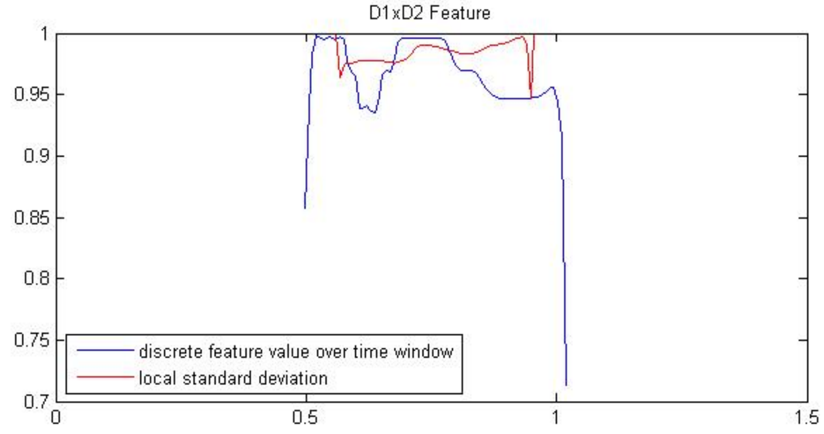
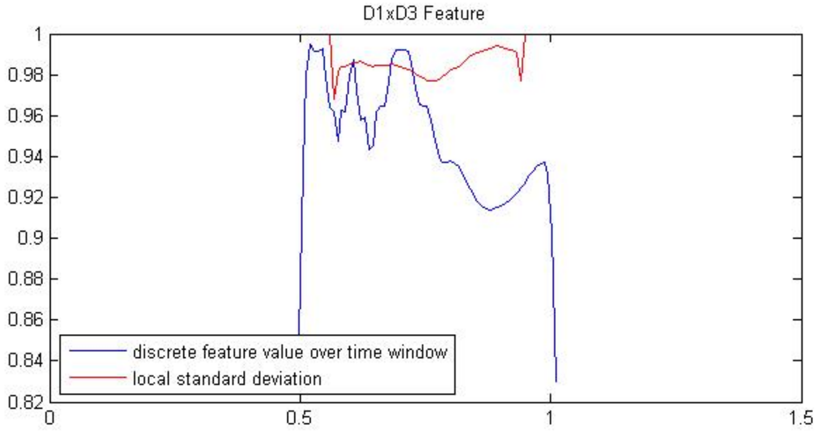
Applying what we know about Pelates, we can synthesize audio as separable carrier information signals: In this model, the information resides in the peaks and valleys of the harmonics associated with the two-voice model.

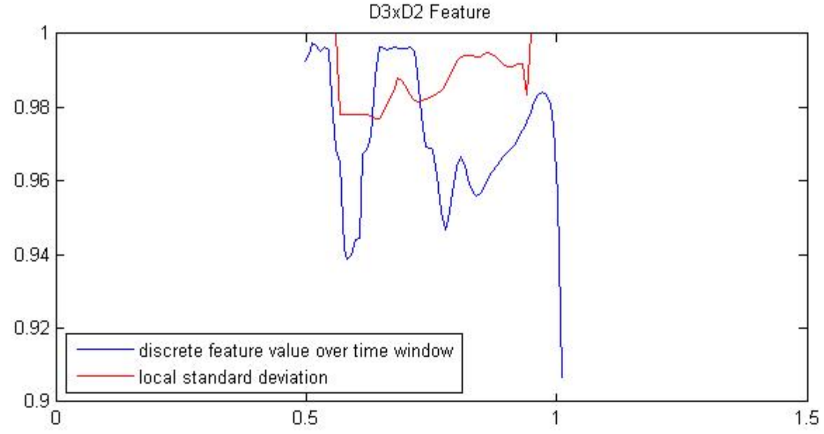


Time-dependent feature set: Synthesized Pelates









Signal Parameters (Fs = 10000): 90% overlap, 1/64 Fs precision (signal introduced at 0.5s-1.0s)

What does the Tx modem need?

- Speech Recognition via MFCC front end
- Spectrum based library of phonemes for classification
- Assignment to tone in-band
- Linear EQ tuned to adequately boost each tone relative to Noise Model of Environment
- Amplified Output to transmit

Since this fish exhibits a set of slightly shifting tones (ostensibly harmonics associated with each bladder), we arbitrarily attempt to encode 2^6 symbols

For this exercise, we use phonemes (create a word based structure) since there are 44 phonemes in the English language [7] that fall within our 2^6 symbol limit

7. https://www.dyslexia-reading-well.com/44-phonemes-in-english.html

What does the Tx modem need?

Speech Recognition via MFCC front end

Spectrum based library of phonemes for classification

Assignment to tone in-band

Linear EQ tuned to adequately boost each tone relative to Noise Model of Environment

Amplified Output to transmit

For this example, we apply the same MFCC and change detection methodology in [8,9] as a front end

8. Matthews, Vector Acoustic Features of the Red Hind Grouper, Doctoral Thesis, Florida Atlantic University (2015)
9. Slaney, Auditory Toolbox, Interval Research Corporation 1994

What does the Tx modem need?

Speech Recognition via MFCC front end

Spectrum based library of phonemes for classification

Assignment to tone in-band

Linear EQ tuned to adequately boost each tone relative to Noise Model of Environment

Amplified Output to transmit

There are a number of ways to define this prior or during operation, for this exercise we use what we already described for the English language

What does the Tx modem need?

Speech Recognition via MFCC front end

↓

Spectrum based library of phonemes for classification

↓

Assignment to tone in-band

↓

Linear EQ tuned to adequately boost each tone relative to Noise Model of Environment

→

Amplified Output to transmit

Assignment in band implies persistent monitoring of noise bands and optimal conductivity, temperature and depth (CTD) measurements for the Sound Velocity Profile (SVP) between Tx/Rx

What does the Tx modem need?

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Speech Recognition via MFCC front end

Spectrum based library of phonemes for classification

Assignment to tone in-band

Linear EQ tuned to adequately boost each tone relative to Noise Model of Environment

Amplified Output to transmit

Typical sound cards support equalization and the ability to revise the power spectrum across discrete bands ensures that the power profile best matches the observed channel bands

What does the Tx modem need?

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Speech Recognition via MFCC front end

Spectrum based library of phonemes for classification

Assignment to tone in-band

Linear EQ tuned to adequately boost each tone relative to Noise Model of Environment

Amplified Output to transmit

The amplifier set at the output (assuming a wideband transmitter ceramic set) must be sufficiently designed to provide optimal response across the entire potential operating band

What does the Rx modem need?

Speech Recognition via MFCC front end

↓

Knowledge of the Rx Spectrum based library of phonemes for classification

↓

Speech conversion

↓

Optional Speech to Machine Language

There has to be some way of getting both modems to establish a protocol to share

If we assume both modems have a discrete set of structures, or there is a baseline data sharing protocol, then either modem can master the other and dictate a strategy or set of strategies

What does the Rx modem need?

Speech Recognition via MFCC front end

↓

Knowledge of the Rx Spectrum based library of phonemes for classification

↓

Speech conversion

↓

Optional Speech to Machine Language

For this example, we apply the same MFCC and change detection methodology in [8,9] as a front end

What does the Rx modem need?

Speech Recognition via MFCC front end

↓

Knowledge of the Rx Spectrum based library of phonemes for classification

↓

Speech conversion

↓

Optional Speech to Machine Language

This can be shared between the modems in a standard information band/protocol or pre-loaded

What does the Rx modem need?

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Speech Recognition via MFCC front end

↓

Knowledge of the Rx Spectrum based library of phonemes for classification

↓

Speech conversion

↓

Optional Speech to Machine Language

This can be conducted via on-board processing – with a true SW defined modem, this can even be left out and put onto on-board CPUs with more control.

What does the Rx modem need?

Speech Recognition via MFCC front end

Knowledge of the Rx Spectrum based library of phonemes for classification

Speech conversion

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Encoding English into Pelates:

Six harmonics with some shift == 6 bits = 2^6 symbols (more than necessary for the total recognized phonemes in the English language)

For this exercise, we use all of the phonemes (create a word based structure) since there are 44 phonemes in the English language

The Goal is to create a system that takes an arbitrary band, defined by persistent monitoring at the Tx/Rx nodes of the environment, then build the upper and lower band based on environmental optimization

Power factors for MFSK are between 50% and 75% lower than PSK (3-6 dB higher power requirement in PSK)

No consideration given to power requirements – transmission paths are assumed to dominate the detection theory metric performance and, while wider band will by definition spread power, selection of the optimal path is presumed to also provide optimal power management

Word based keying allows for reduction in data rate at the expense of potentially higher Bit Error Rate (BER) in the absence of intelligent language algorithms [10]

10. Ghosh et al, **COMPARATIVE STUDY OF BIT ERROR RATE (BER) FOR MPSK-OFDM IN MULTIPATH FADING CHANNEL, International Journal of Advances in Engineering & Technology, July 2012.**

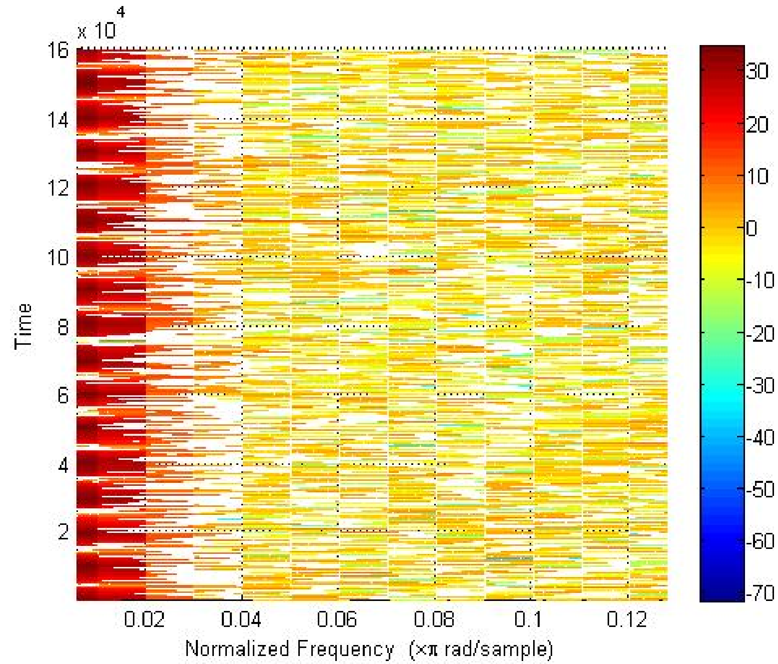
Example input: “Hello World”

Abbreviated truth table for phonemes and harmonics

Harmonic Sign/ Phoneme ID	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25	F26	F27	F28	F29	F30	F31	F32	F33	F34
H0	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1
H1	0	1	0	0	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0
H2	0	0	1	0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
H3	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
H4	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	1	1	1	1	1	0	0	1
H5	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0

We encode 6 tonal bands (the harmonic is largely irrelevant as the loaded power of each band will be adjusted to match a logical “1” or “0” to match our library) that were (presumably) detected and identified by our hypothetical SW defined modem in its natural environment

The ocean has a highly dynamic acoustic noise profile, directly affected by marine life, anthropogenic activity and weather [11]. Reviewing the sample background noise profiles collected during its’ mission, the SW defined modem selects an optimal band for modulating across as a function of background noise and known Transmission Loss (TL) estimates.

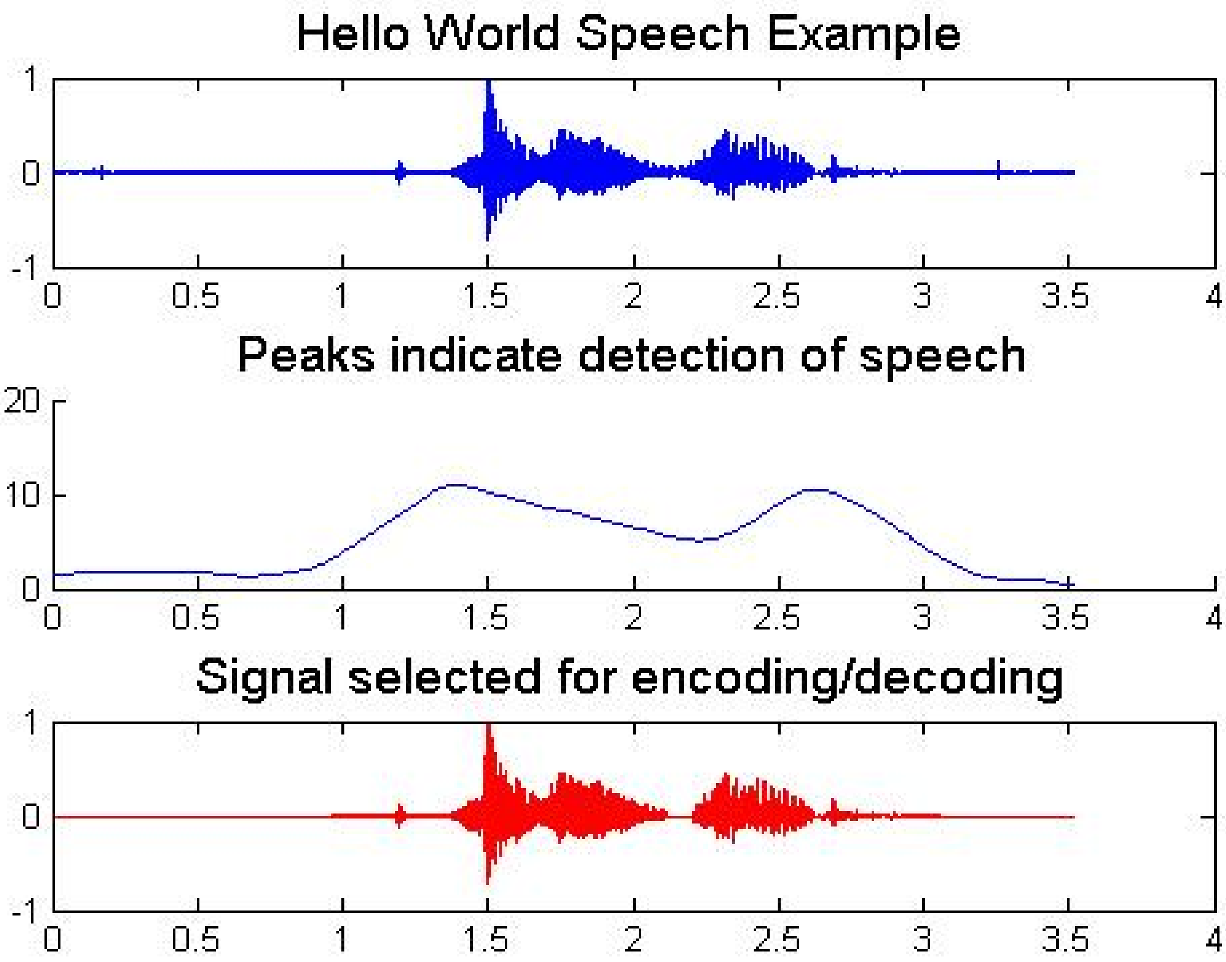


Hypothetical background noise profile (red==bad, yellow==good)

11. Dahl et al, Underwater Ambient Noise, Acoustics Today 2007

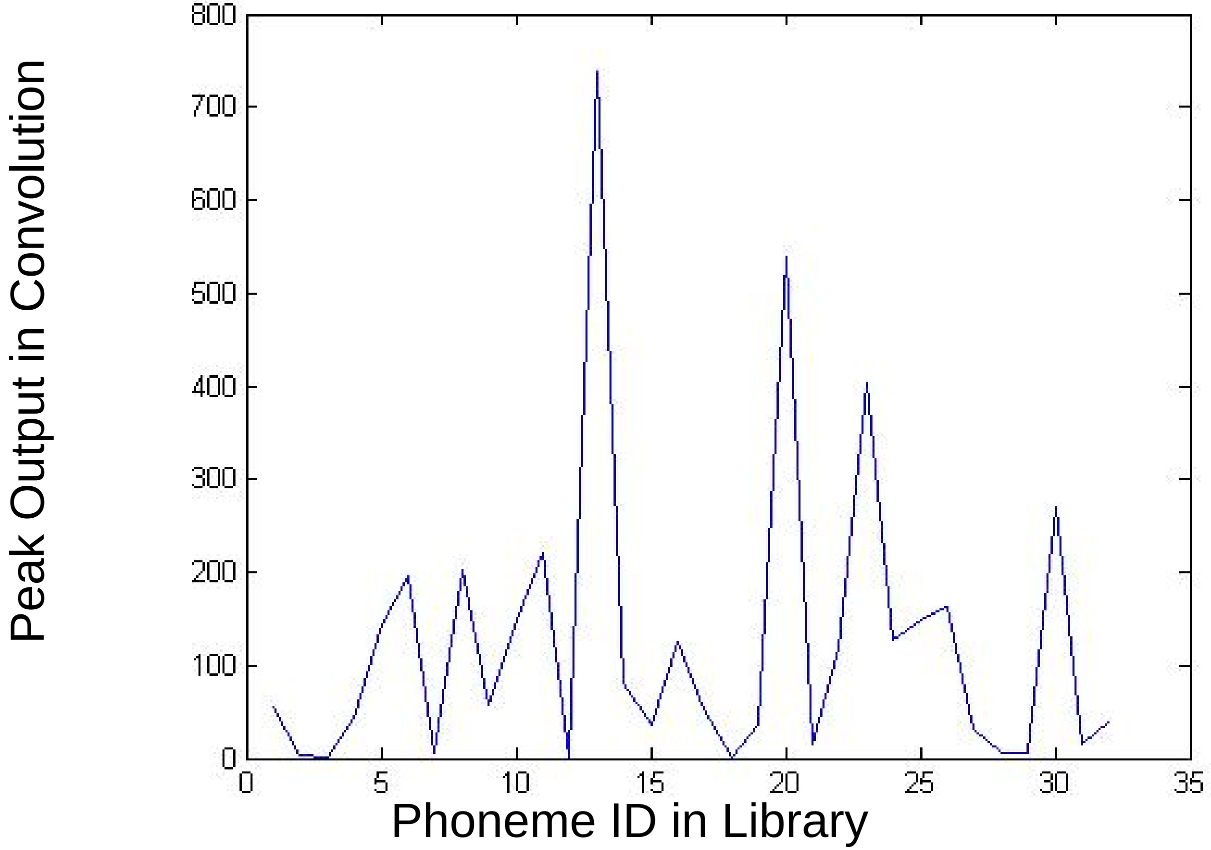
First, a front end system using statistical change detection based on Mel-Frequency Cepstral Coefficients [9] is defined that can be used by the receiver

This does not absolve TL considerations, only serves as the system for recognizing when a word begins (F33), is transmitting, and concludes (F34)



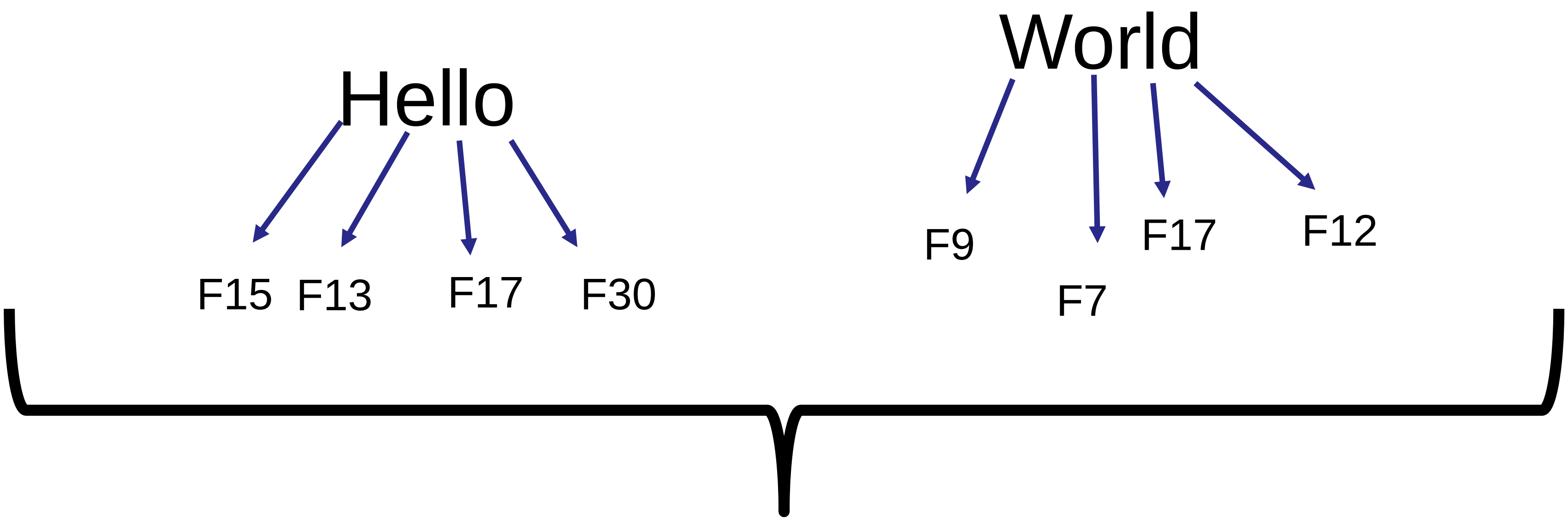
Now each individual word must be parsed via phoneme library and matching:

This does not absolve TL considerations, only serves as the system for recognizing the principle phonemes of the data detected by the front end system



Example: utterance with 4 phonemes identified (peak values statistically measured as “correct” by the library, then sorted into order on the next slide)

Example input: “Hello World” broken down (via library classification) into principle phonemes

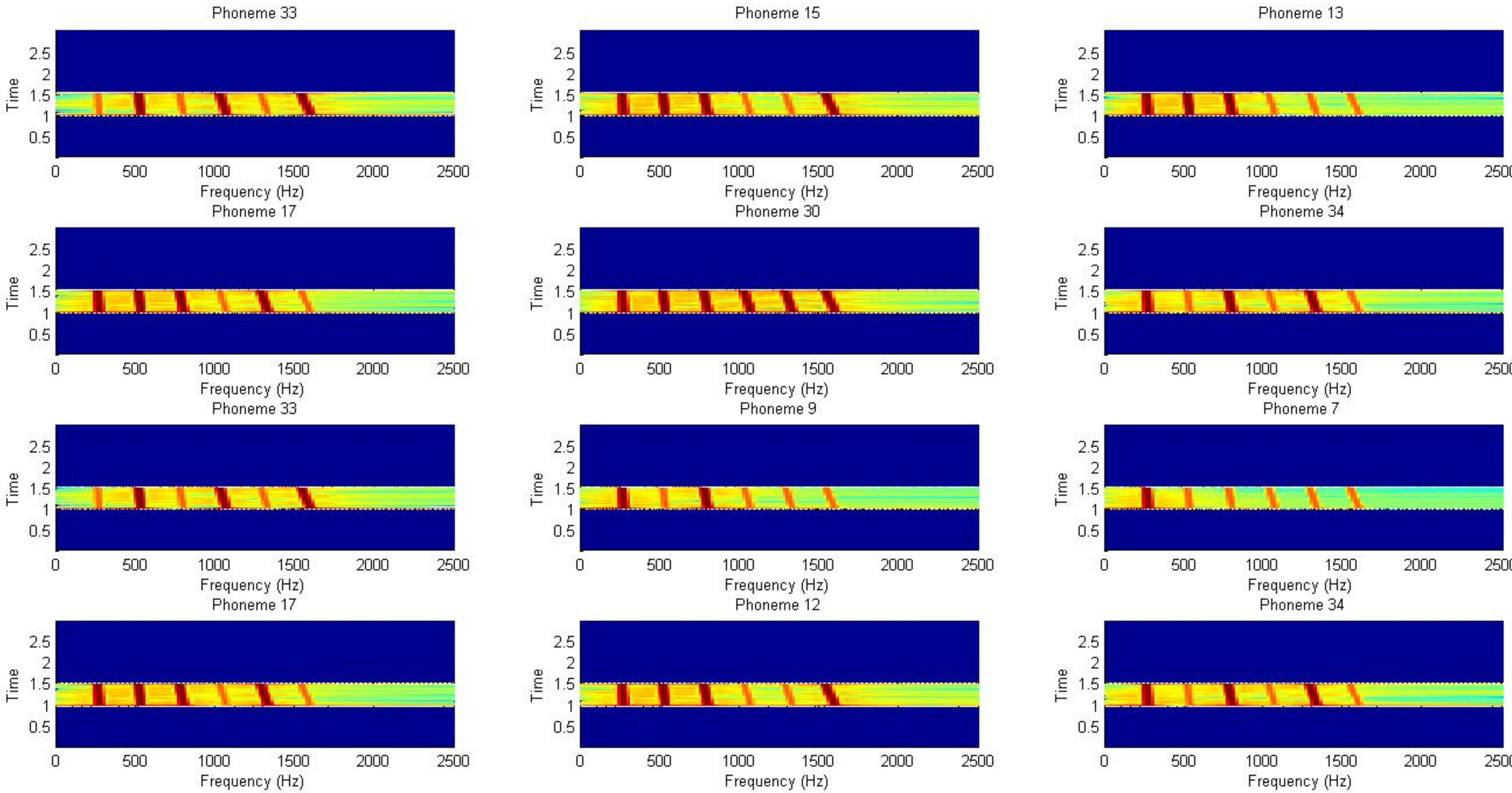


Harmonic Sign/ Phoneme ID	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25	F26	F27	F28	F29	F30	F31	F32	F33	F34
H0	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1
H1	0	1	0	0	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0
H2	0	0	1	0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1
H3	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
H4	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	1	1	1	1	1	0	0	1
H5	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	0

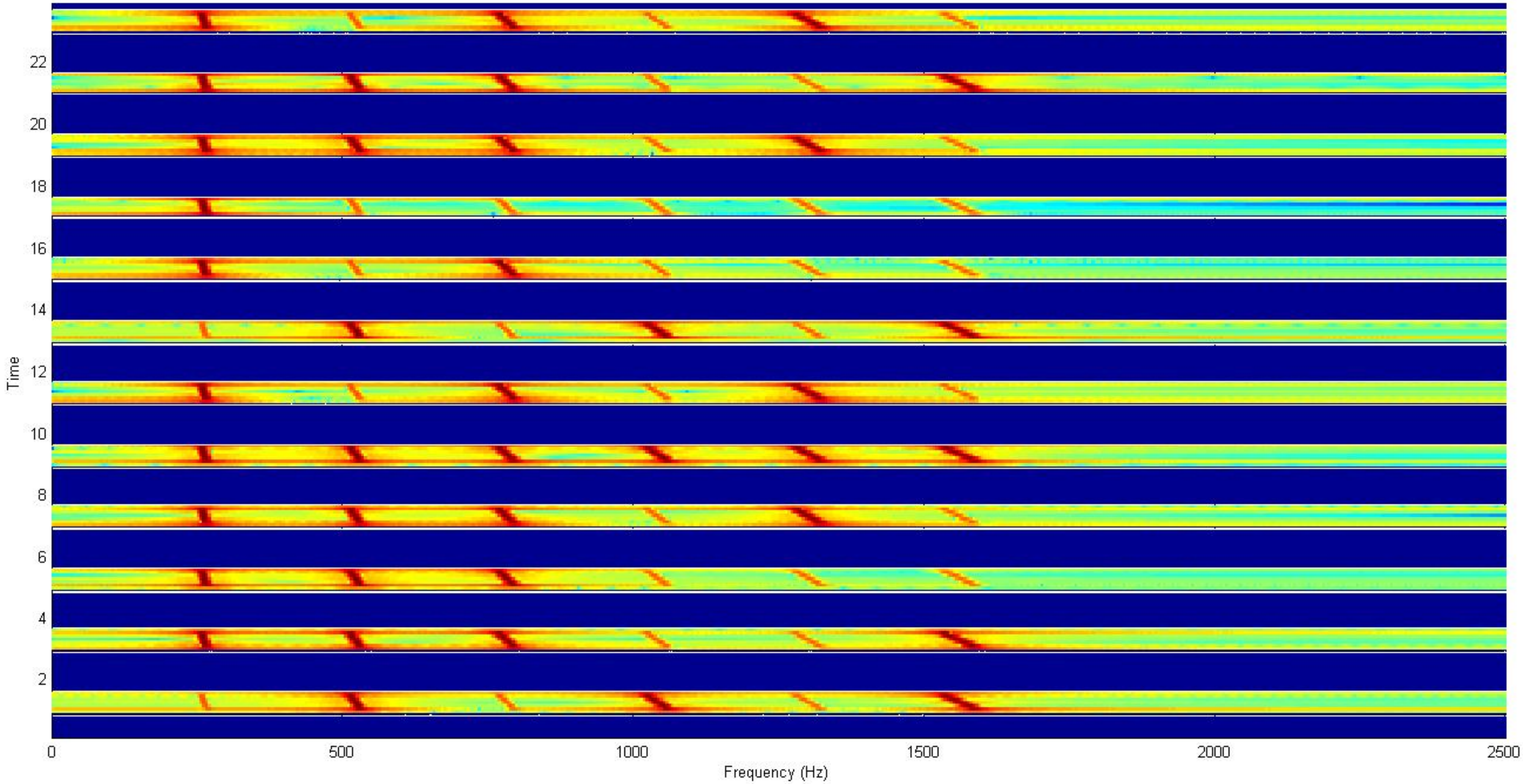
For aural example, the harmonics are damped and padded (0.25 unit magnitude for +s, 0.01 units added across all values)

Individual data packets for transfer

NAVSEA WARFARE CENTERS PANAMA CITY



Complete message (with stop/start bookends) for transmission



Questions?