Guard-free OFDM transmission for Underwater Acoustic Communications

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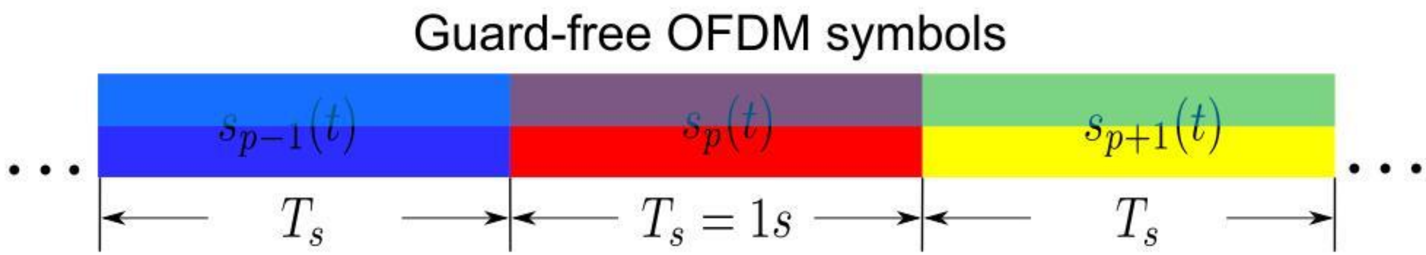
Overview

- Data transmission
- Sea trials / channel model
- Receiver design:
  - ✓ Single-hydrophone receiver
  - ✓ Multiple-antenna receiver
  - ✓ Doppler estimation
- Conclusions

Transmitted signal



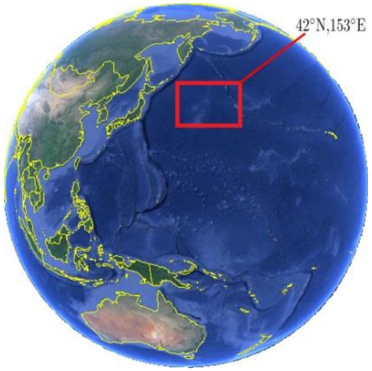
$$s_p(t) = \Re\left\{e^{j2\pi f_c t}\sum_{k=-\frac{N_S}{2}}^{\frac{N_S}{2}}[M(k) + jD_p(k)]e^{\frac{j2\pi kt}{T_S}}\right\} = d(t) + p(t)$$

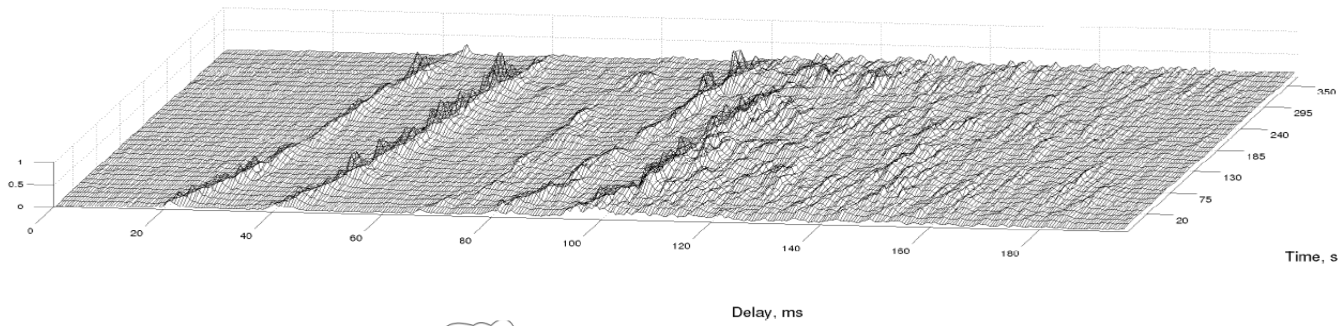
Superimposed data and pilot signals

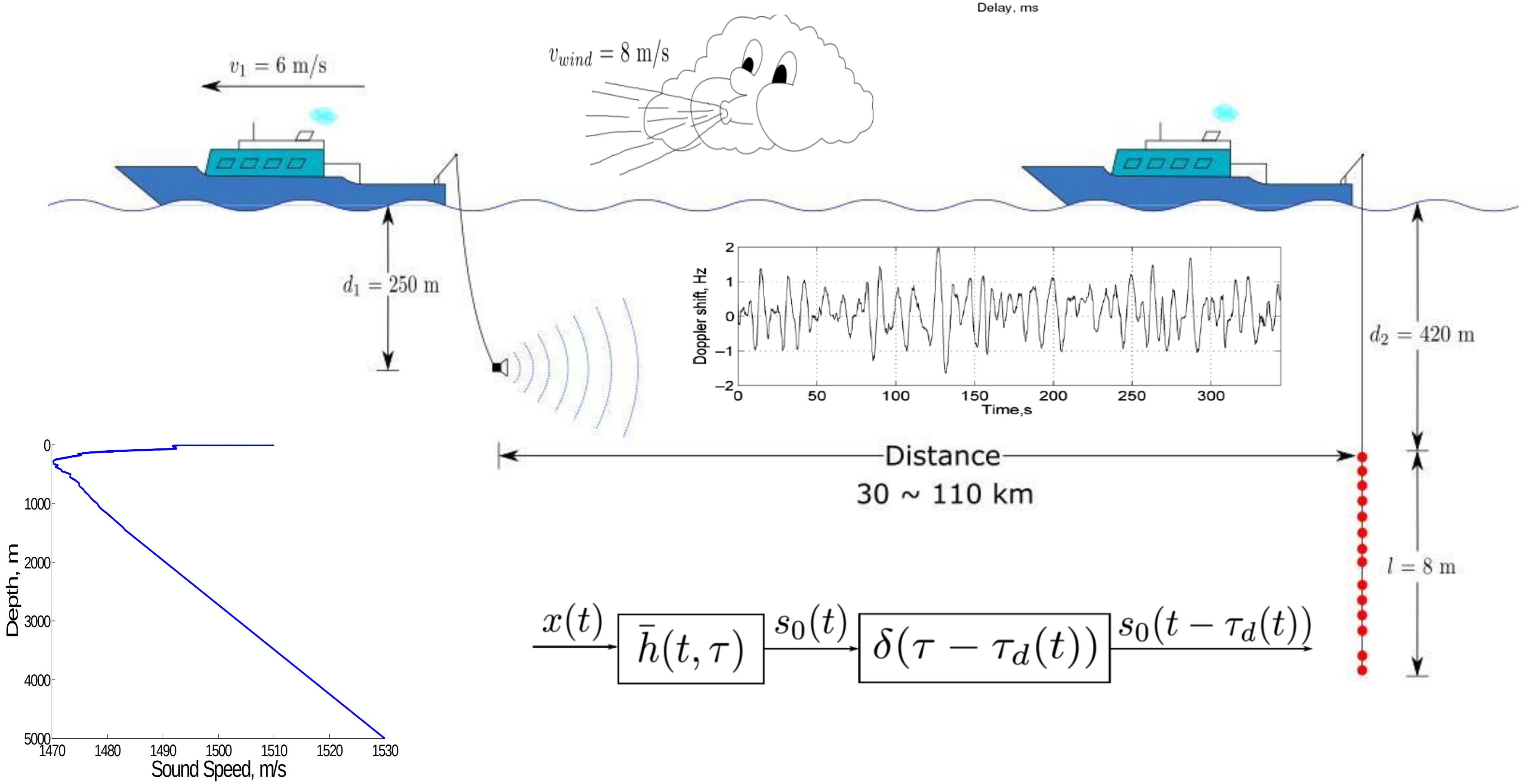
- $f_c = 3072$ Hz
- $N_s = 1024$: number of sub-carriers
- $F = 1024$ Hz: frequency bandwidth
- $M(k) \in [-1, +1]$: pilot sequence
- $D_p(k) \in [-1, +1]$: information data (coded across sub-carriers)
- $p = 1, \ldots, L$: index of an OFDM symbol

Y. Zakharov and V. Kodanev, in *Acoustical Physics*, (1994,1995, 1996, 2000).

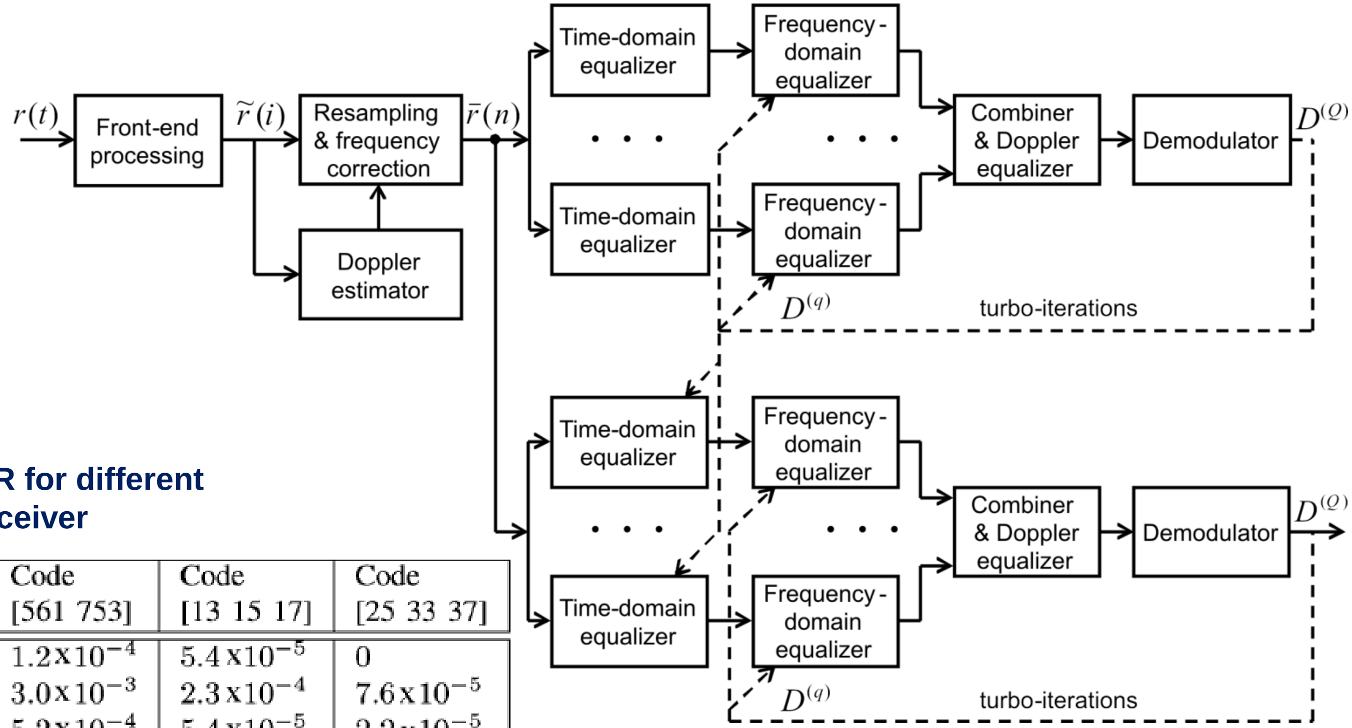
Sea trials


42°N,153°E


Time, s
Delay, ms


$v_1 = 6$ m/s
$v_{wind} = 8$ m/s
$d_1 = 250$ m
$d_2 = 420$ m
Doppler shift, Hz
Time,s
Distance
30 ~ 110 km
$l = 8$ m
$x(t)$
$\bar{h}(t,\tau)$
$s_0(t)$
$\delta(\tau - \tau_d(t))$
$s_0(t - \tau_d(t))$
Depth, m
Sound Speed, m/s

Structure of single-hydrophone receiver

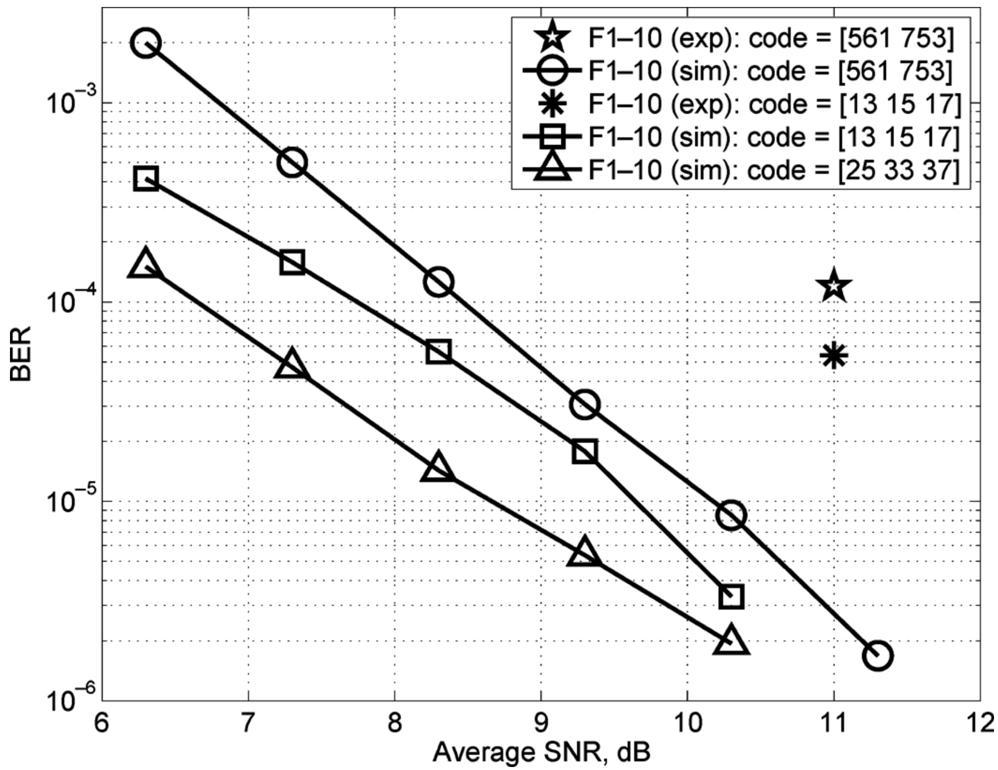


Session F1-10 (79 – 81 km): BER for different configurations of the receiver

Receiver configuration	Code [561 753]	Code [13 15 17]	Code [25 33 37]
1. Full receiver (av. SNR = 11 dB)	1.2×10^{-4}	5.4×10^{-5}	0
2. No oversampling $N_\tau = 1$	3.0×10^{-3}	2.3×10^{-4}	7.6×10^{-5}
3. Oversampling $N_\tau = 2$	5.2×10^{-4}	5.4×10^{-5}	2.2×10^{-5}
4. No fine Doppler estimation	1.9×10^{-4}	7.6×10^{-5}	3.2×10^{-5}
5. No turbo iterations ($Q = 1$)	3.1×10^{-4}	5.9×10^{-5}	3.2×10^{-5}
6. No Doppler equalizer ($L_d = 1$)	2.7×10^{-4}	5.4×10^{-5}	0
7. Zero-order interpolation	7.9×10^{-4}	1.2×10^{-4}	5.4×10^{-5}
8. Linear interpolation	2.1×10^{-4}	5.4×10^{-5}	0
9. Not accurate equalizer delay	1.0×10^{-3}	2.5×10^{-4}	7.6×10^{-5}
10. No frequency-domain equalizer	2.9×10^{-4}	6.5×10^{-5}	0
11. Sparse channel estimation	7.8×10^{-5}	5.4×10^{-5}	0

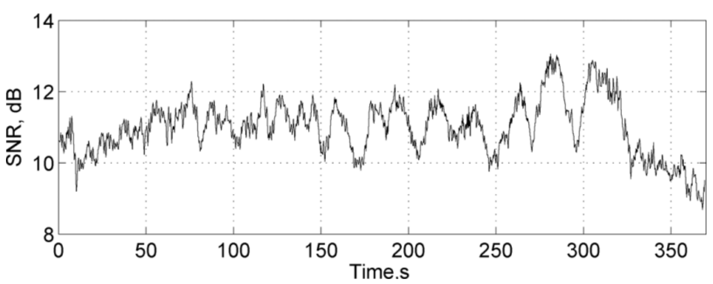
Y. Zakharov and A. Morozov, "OFDM transmission without guard interval in fast-varying underwater acoustic channels." *IEEE Journal of Oceanic Engineering* (2015).

Comparison with an ***ideal*** receiver

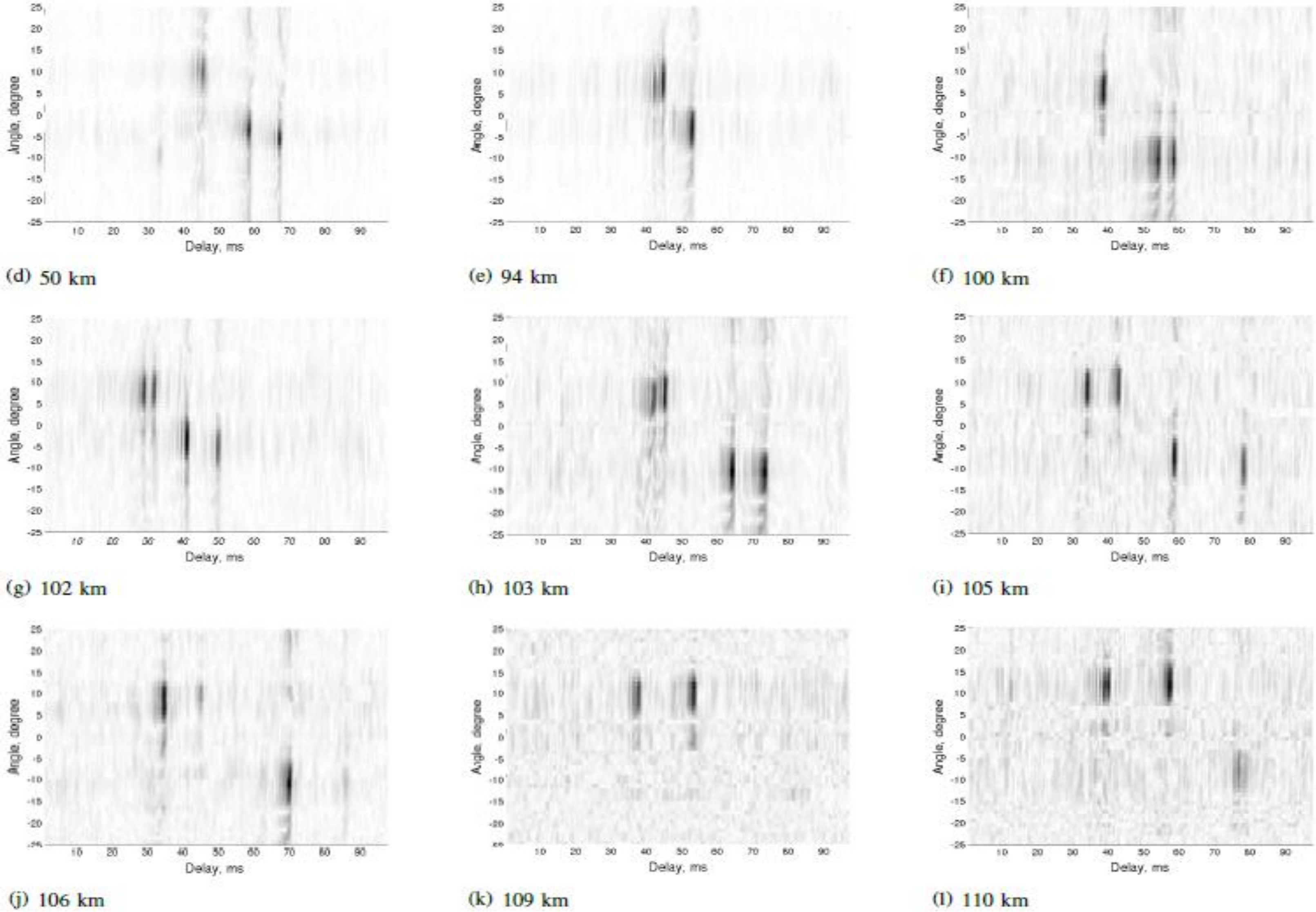


Ideal receiver:

1. The channel is perfectly known.
2. The same multipath delay spread as in the sea experiment.
3. There is a cyclic prefix longer than the channel delay spread, no ISI.
4. No Doppler spread, no ICI.
5. No superimposed pilot, thus no interference from the pilot.
6. The SNR time-variation is the same as in the sea experiment



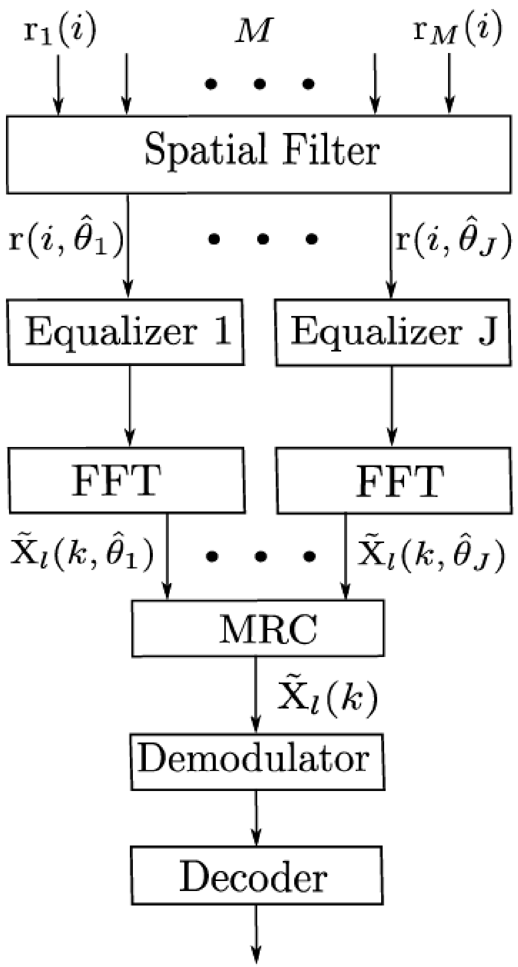
Space-time clustering

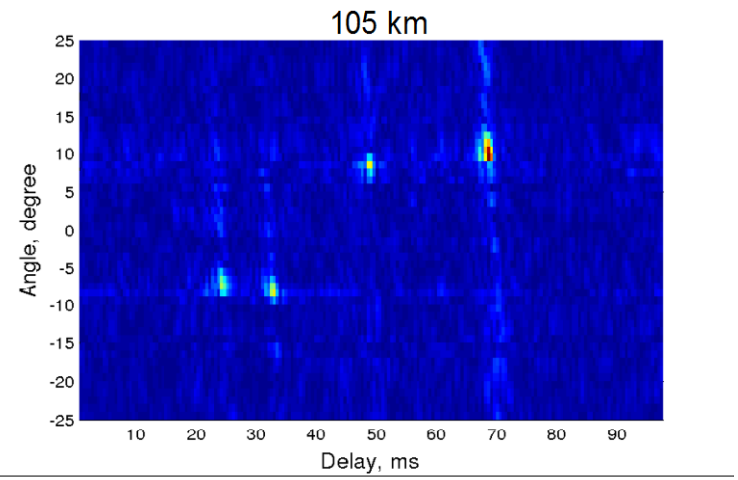


J. Li and Y. Zakharov, "Efficient use of space-time clustering for underwater acoustic communications", *IEEE Journal of Oceanic Engineering*, (2017 to appear).

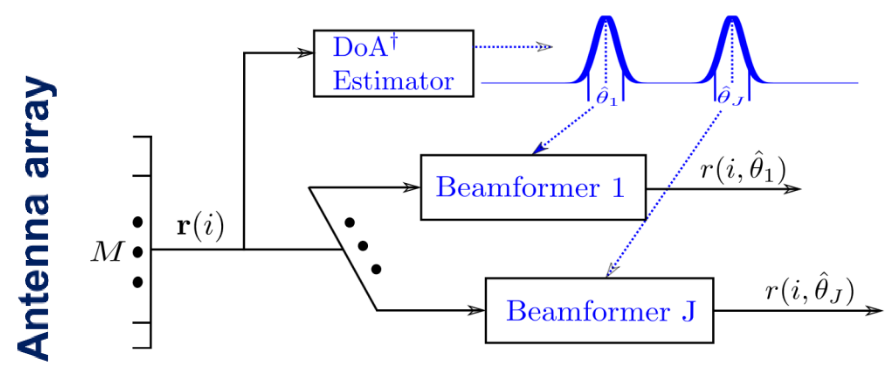
Receiver with space-time processing

Antenna array





Spatial filter:

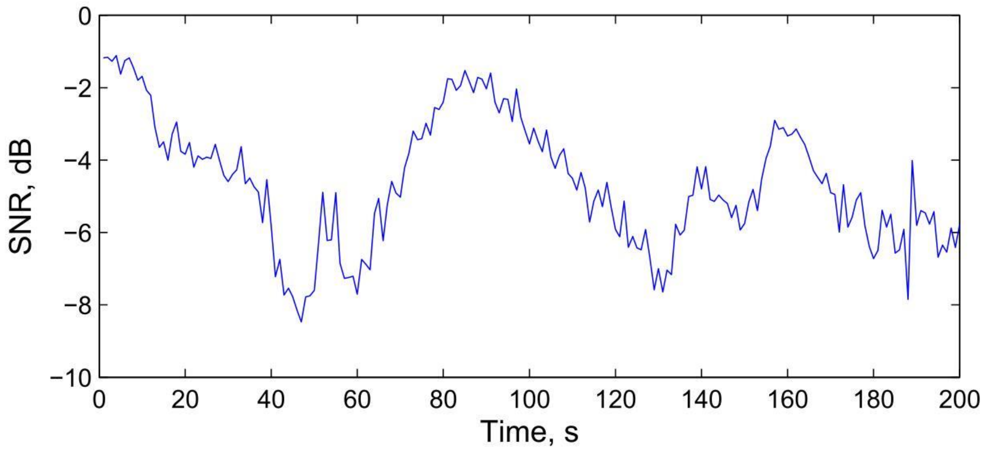


BER performance (105 km)

Receiver	BER(code 1/3)	Complexity(MACs)†
Single hydrophone	0.45	83×10^6
All 14 hydrophones	2.7×10^{-3}	1160×10^6
Single angle 8.4^o	9.1×10^{-2}	100×10^6
Two angles with max powers	8.9×10^{-2}	185×10^6
Clusters (angles 8.4^o and -9^o)	0	185×10^6

code rate : 1/3 [225 331 367]

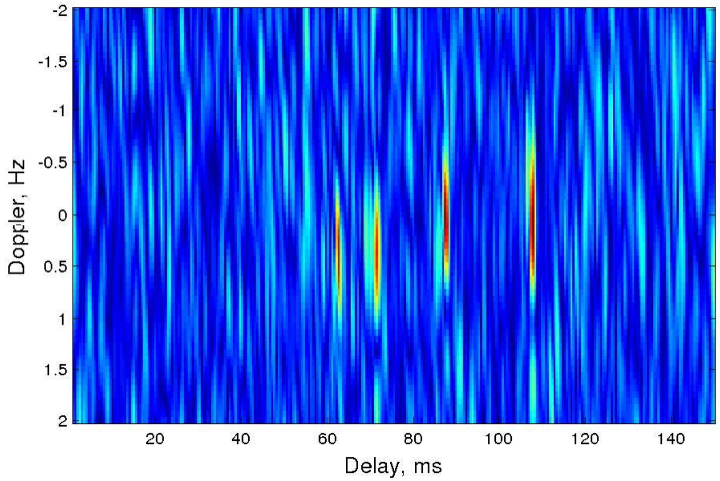
Single-hydrophone SNR:



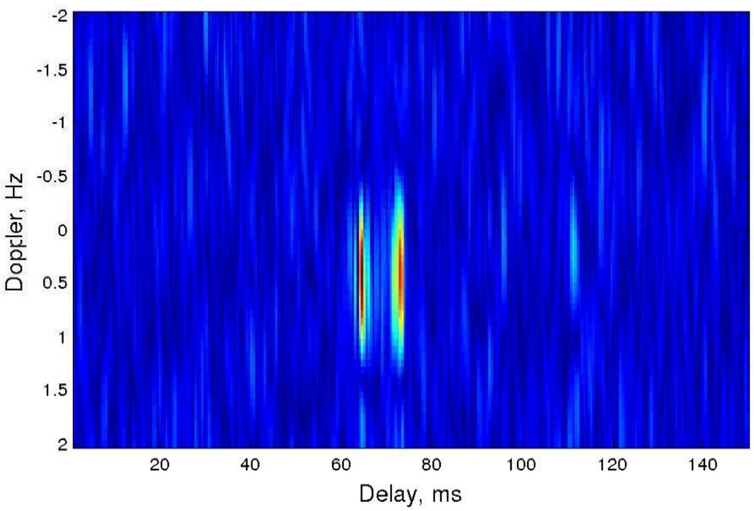
†: multiply-accumulate operations

Reducing the delay and Doppler spread (105 km)

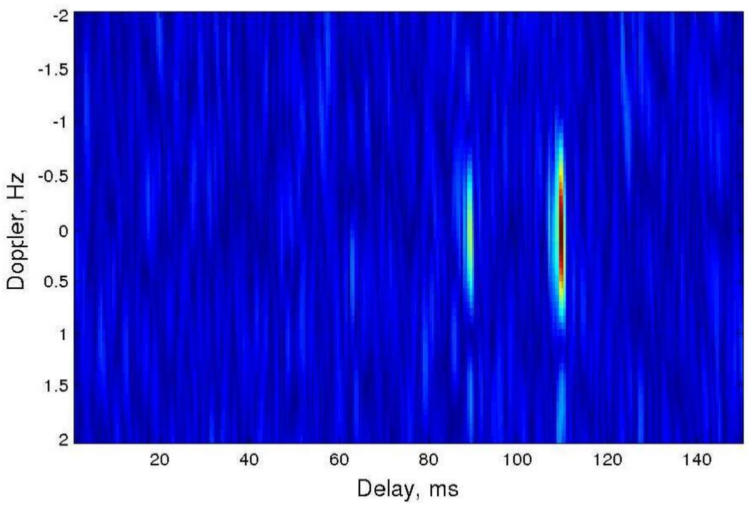
Hydrophone 1:



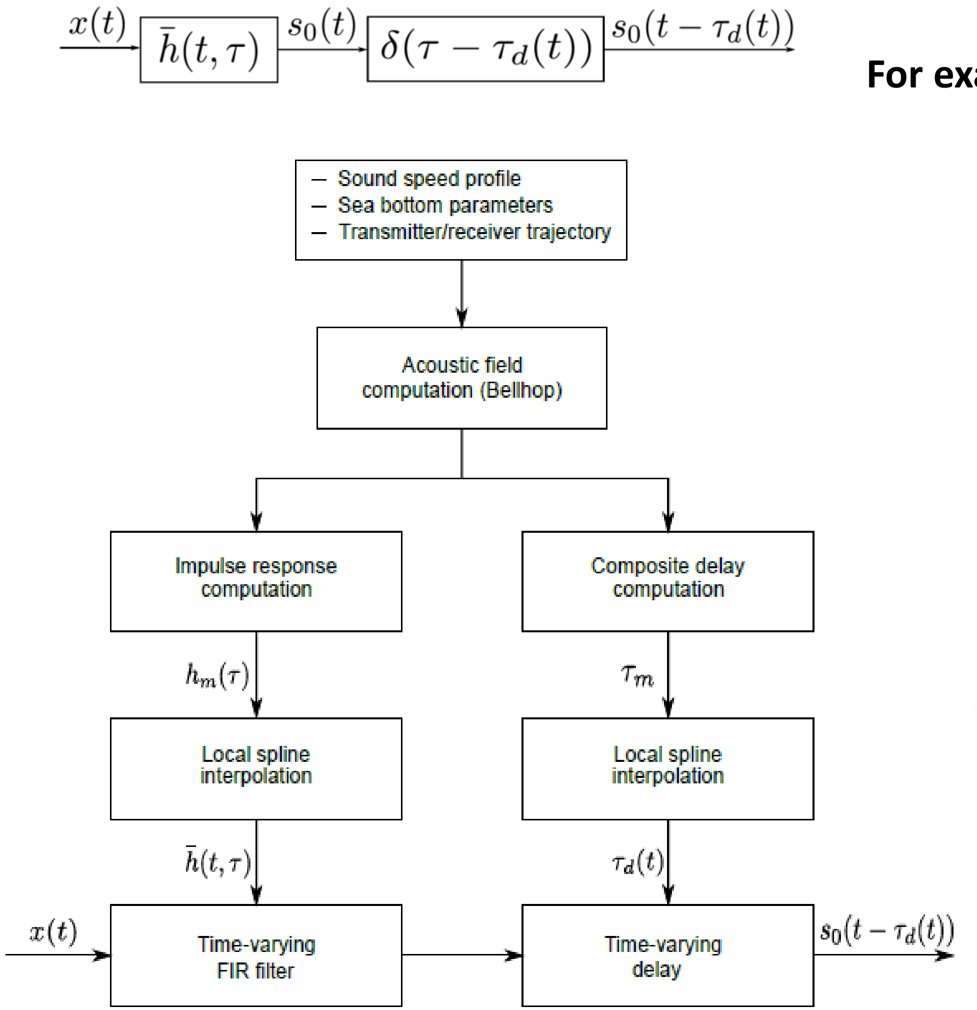
-9^o:



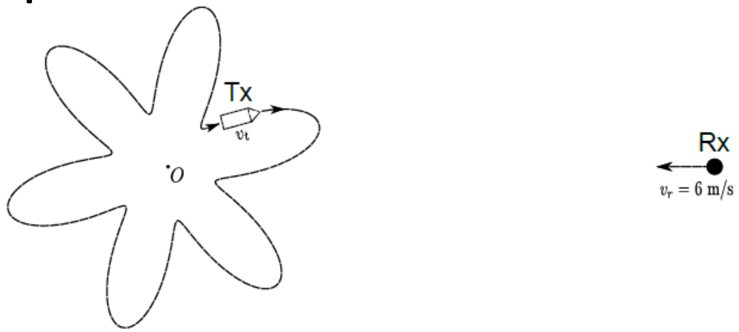
8.4^o:



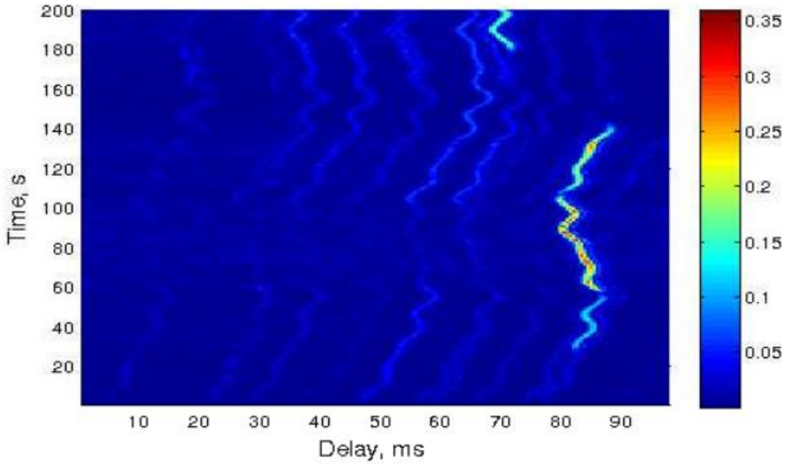
Waymark model: Virtual signal transmission



For example:



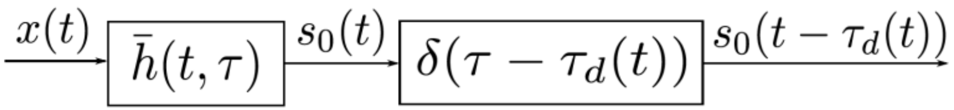
(c) Flower circle movement of the transmitter; O is the center of the flower.



(d) Summer SSP, flower circle movement (5 km).

C. Liu, Y. Zakharov, and T. Chen, "Doubly selective underwater acoustic channel model for a moving transmitter/receiver." *IEEE Transactions on Vehicular Technology* (2012).

Multi-branch autocorrelation (MBA) Doppler estimator



BER PERFORMANCE OF THE RECEIVER WITH THE THREE DOPPLER ESTIMATORS; DATA RATE: 1/2 BPS/HZ.

Doppler estimator	**Code [3 7]**	**Code [23 35]**	**Code [561 753]**
CAF	$4.5 \cdot 10^{-3}$	$8.5 \cdot 10^{-4}$	$2.0 \cdot 10^{-5}$
SBA	0.30	0.34	0.37
MBA	$4.8 \cdot 10^{-3}$	$9.2 \cdot 10^{-4}$	0

CAF: cross-ambiguity function
SBA: single-branch autocorrelation
MBA: multi-branch autocorrelation

Comparing to the CAF method, the reduction in complexity is about 10 times.

J. Li, Y. Zakharov, and B. Henson, “Multi-branch autocorrelation method for Doppler estimation in UWA channels”, *IEEE Journal of Oceanic Engineering*, (2017, under review).

Summary

- Guard-free OFDM transmission makes sense in UWA channels
- Superimposed pilot signals are very useful in dynamic UWA channels.
- Space-time processing significantly improves the detection performance; the cluster combining takes into account the specific UWA propagation and also very useful.
- *Waymark* model allows the virtual signal transmission. It is useful to make complicated “sea experiments”.
- MBA Doppler estimator has performance close to that of the ambiguity function Doppler estimator, but with significantly reduced complexity.