NATO - SCIENCE AND TECHNOLOGY ORGANIZATION
CENTRE FOR MARITIME RESEARCH AND EXPERIMENTATION

Sub-Bands Beam-Space Adaptive Beamformer for Port-Starboard Rejection in Triplet Sonar Arrays

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Summary

This work addresses the problem of Port-Starboard (PS) beamforming for low-frequency active sonar (LFAS) with a triplet receiver array.

The work presents a new algorithm for sub-bands beam-space adaptive beamforming with twist compensation and evaluates its performance with experimental data collected at sea.

The results show that the algorithm provides the ability to solve the PS ambiguity with a strong PS rejection even at end-fire where ordinary triplet beamformers have poor performance, allowing to unmask targets in the presence of strong coastal reverberation and/or traffic noise.

Background

Modern submarines have become much quieter than in the past and their detection with passive systems has become increasingly problematic. Low-frequency active sonar (LFAS) systems are good candidates to fulfill this need.

LFAS sonars are towed systems, such that they are variable in depth and can be deployed in the most favorable acoustic layer.
An LFAS consists of a powerful wideband source and a receiving hydrophone array.

For many reasons, the receiver must be able to solve bearing ambiguity in one single ping.
Furthermore, coastal reverberation should be rejected to have good detection performance even in littoral, shallow water environments.

This is not possible with single line array receivers since they are cylindrically symmetric and therefore cannot discriminate port from starboard. One possible solutions is the use of Triplet arrays.

A towed array consisting of hydrophone triplets is able to perform direct PS discrimination by using the small time delay of signals received by the hydrophones on the Port and the Starboard sides of the array.
However, the specific PS beamforming for triplets is far from trivial.

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Cooperative Anti Submarine Warfare (CASW)

The most efficient and economic way to monitor the ocean is through **networks** of **small**, **intelligent** and **cheap** ocean observing platforms (the trend started from 90s)

Acoustic source: fixed and/or towed.

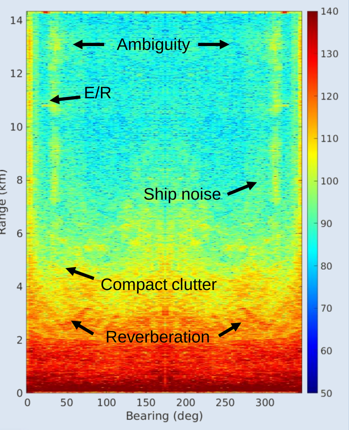
Ship: NRV Alliance - used as a remote Command and Control (C2) Centre and as an additional receiver node.

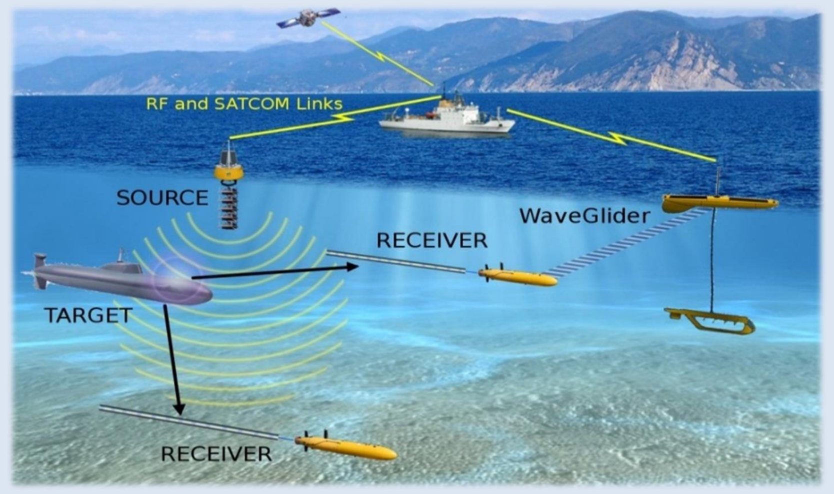
Static Nodes: Gateway buoys - network infrastructure (communication) and can be sensorized to provide coverage of an area for extended time periods.

Mobile Nodes (robots): use their mobility to improve the area coverage and to optimize the network performance based on the current tactical situation.
Wavegliders (communication nodes).
AUVs: OEX Groucho and Harpo, 4.3 m 1 m/s cruise speed towing arrays.

Littoral Undersea Characteristics

- Environmental variability/uncertainty
- High clutter and reverberation
- Ship noise





Adaptive Beamformer in Triplet Sonar Arrays

Hydrophone triplet: three equispaced hydrophones +
+ Non acoustic sensor (Roll Pitch Yow)

An array of hydrophone triplets is able to perform direct P/S discrimination using the time delay of signals received by the P and S sides of the array

P/S triplet beamforming far from trivial

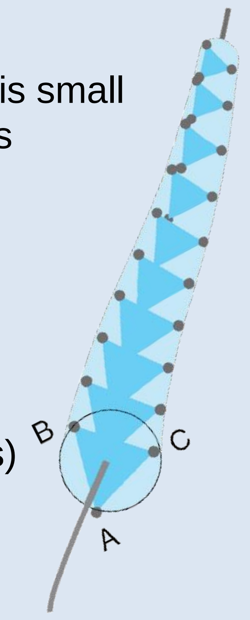
- The ratio of array diameter to the acoustic wavelength is small
- Small phase difference between the three hydrophones
- Sensitive to phase error due to bad roll measurements

Cardioid Beamformer

- Most adopted technique
- Kidney shaped directivity pattern
- A notch is steered in the ambiguous direction
- Poor performance at end-fire (front and back directions)

Adaptive Beamformer

- Minimum Variance Distorsionless Response (MVDR)



$$Z(k,\theta) = \sum_{\alpha=1}^{N_\alpha} Z^{(\alpha)}(k,\theta)$$

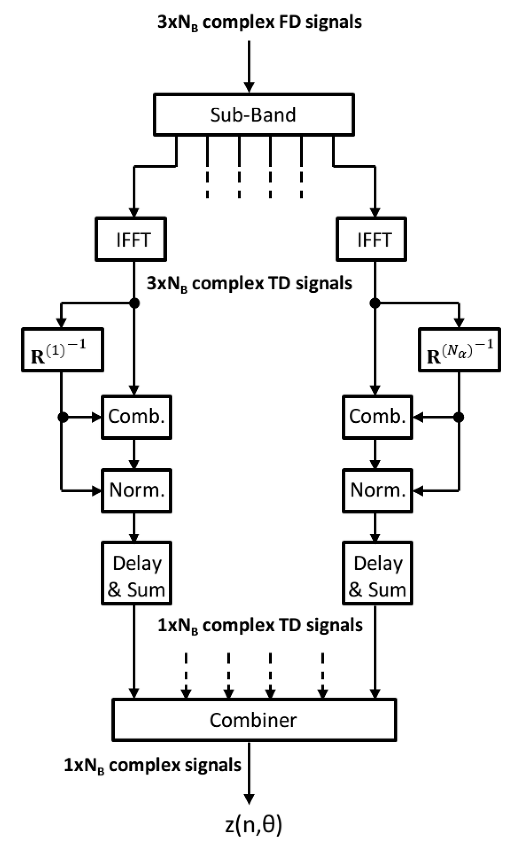
$$Z^{(\alpha)}(k,\theta) = \frac{\boldsymbol{d}^H \widehat{\boldsymbol{R}}_\alpha^{-1}}{\boldsymbol{d}^H \widehat{\boldsymbol{R}}_\alpha^{-1}\boldsymbol{d}} \left[\boldsymbol{p}(k,\theta,\beta) \circ \boldsymbol{Y}^{(\alpha)}(k,\theta)\right]$$

twist compensation: $\boldsymbol{p}(k,\theta,\beta)$; sub-band split: $\boldsymbol{Y}^{(\alpha)}(k,\theta)$

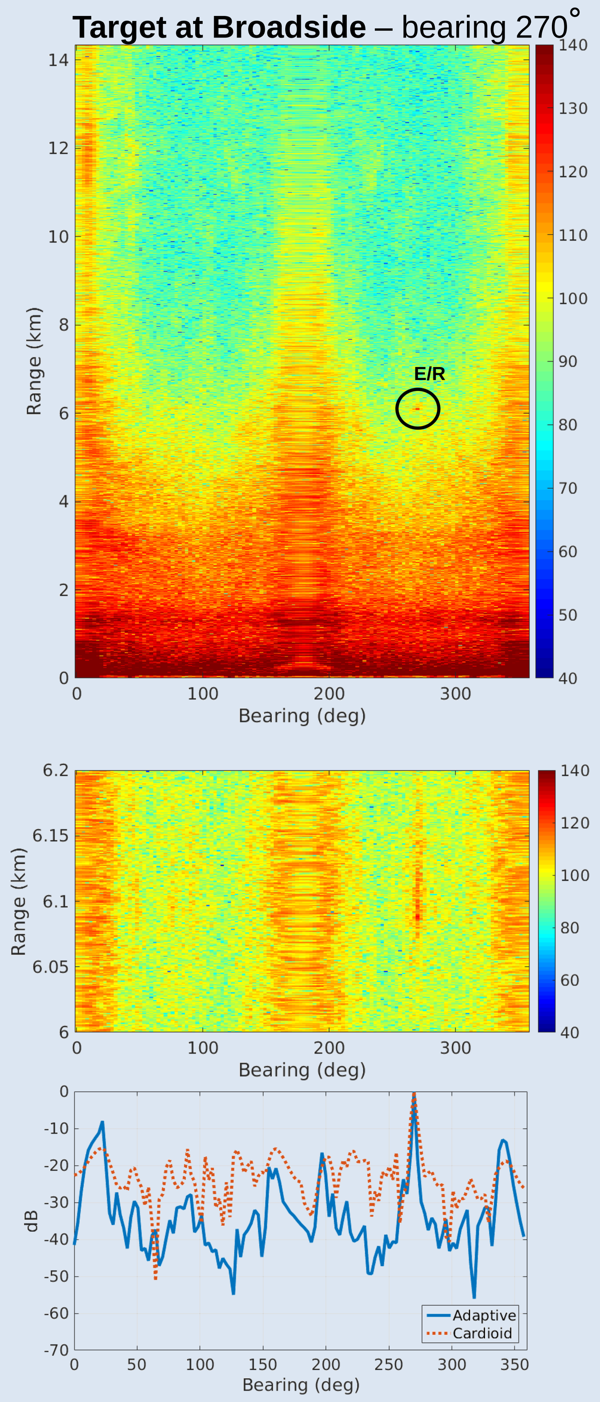
$$p_j = e^{-i4\pi k r sin\theta cos((j-1)\gamma+\beta/2) sin(\beta/2)/c}$$

$$d_j = e^{i2\pi k r[sin\theta sin((j-1)\gamma)]/c}$$

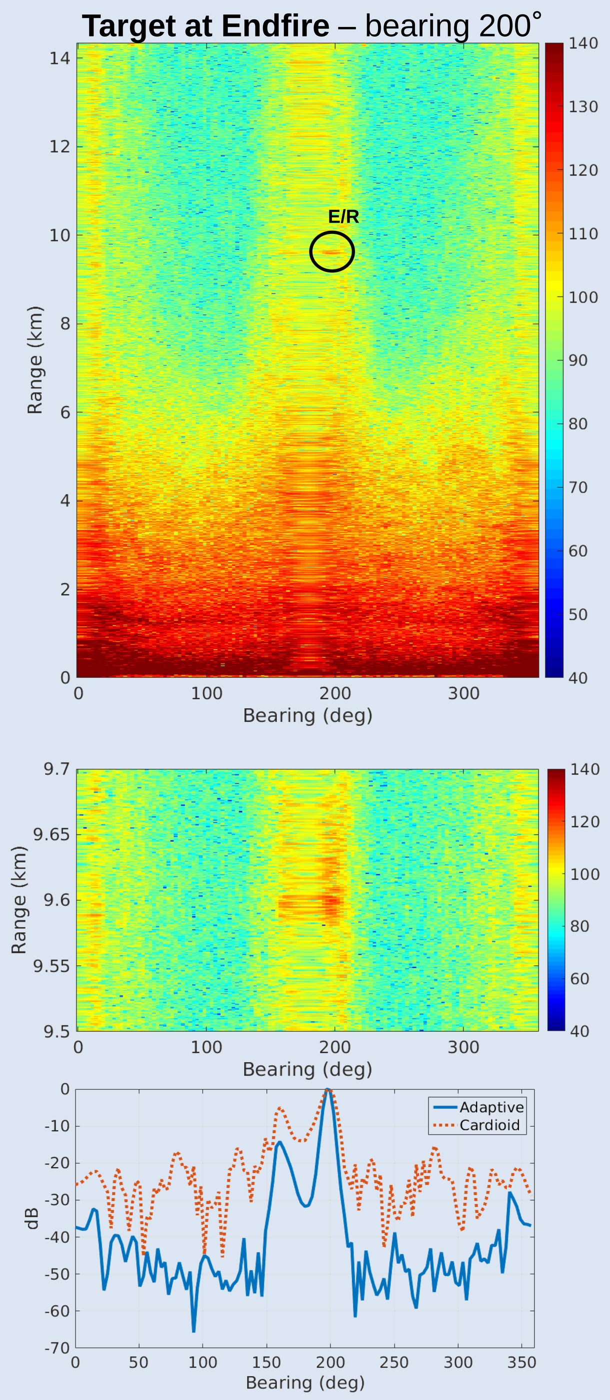
- The noise correlation matrix is estimated with the received signals
- Sub-banding: the covariance matrix is independent on frequency in each sub-band.
- The beamformer is valid for broadband transmitted signals (high range resolution)
- Twist Compensation to compensate phase errors due to wrong hydrophone positioning
- Adaptations to the new environment can be made very fast (rapidly change environment)



Results with Real Data Recorded at LCAS16 Sea Trial



- **P/S rejection**: **Adaptive 28 dB**
  Cardioid 18 dB
- Cardioid in its ideal configuration
- Beamformers reject the target at the noise floor
- **SNR of Adaptive is 10 dB higher than Cardioid**
- **Adaptive** has an **higher range/bearing resolution**

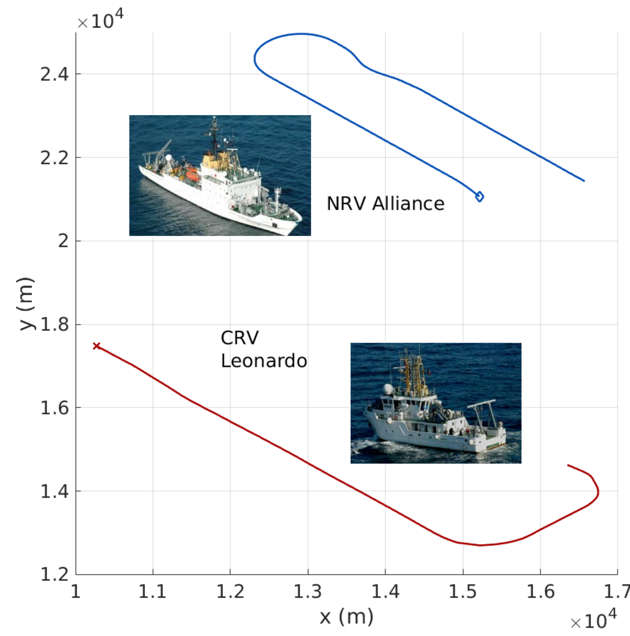


- **P/S rejection**: **Adaptive 16 dB**
  Cardioid 5 dB
- Cardioid has poor P/S rejection
- Adaptive is still able to discriminate P&S directions
- **SNR of Adaptive is 10 dB higher than Cardioid**
- **Adaptive** has an **higher range/bearing resolution**

Analyzed Dataset

- **LCAS16 sea trial (Littoral Continuous Active Sonar 2016)** conducted in the Gulf of Taranto, Italy
- **SLICTA Triplet Array** – designed and developed at **NATO STO CMRE**
- **Echo-Repeater** (E/R) acting as an artificial target
- Adaptive Beamformer has a strong PS rejection even at endfire and also when both the array and the target are maneuvering.
- **NRV Alliance** - towing SLICTA Triplet Array + **CRV Leonardo** - towing Echo-Repeater artificial target
- **Cross-Run** - array and target are sailing in opposite directions
- **U-turn** - challenging for array twist, sonar system are usually switched-off due to bad measurements
- **Maneuvering Target at end-fire** - conventional triplet beamformers have poor PS rejection

Proposed beamformer is able to detect the target for the whole run duration



Beam Collapse Plot

- Collects the maximum value along bearing direction for each range in all the received pings
- Array maneuver starts at 10:00 UTC
- Persistent Clutter up to 9 km + Ship Noise (vertical stripes)

Normalized Beam Collapse Plot

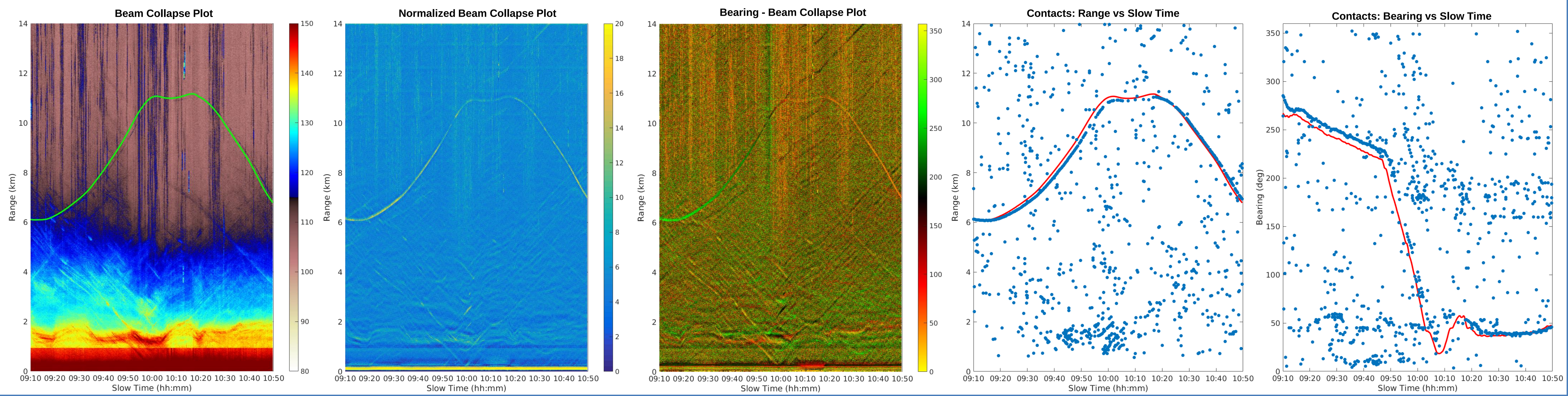
- Normalization: Ordered Statistics – Constant False Alarm Rate (OS-CFAR)
- Target detected with an high SNR in the whole run duration

Bearing Beam Collapse Plot

- Color-scale indicates the bearing direction of the strongest received echo
- Target at broadside-port before maneuver and at end-fire during and after maneuver

Contacts Plot

- Sonar contacts after detection and clustering (Range and Bearing)
- Target detected in the correct position for the whole run duration
- During maneuver the target is rapidly moving from broadside-port to end-fire front/starboard.
- Very few ghost contacts in the ambiguous direction + False alarm due to clutter and ship noise



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