Target Detection in Sea-Clutter Using Stationary Wavelet Transforms

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NATO SPECIALIST'S MEETING-SET-239
26 Oct 2016

Australian Government
Department of Defence
Defence Science and Technology Group

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Outline

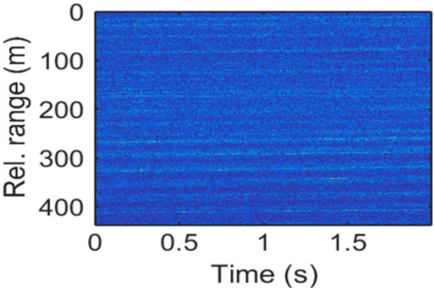
Detection Problems

What are the challenges?

- Small target
- Interferences

Sea-spike: strong returned power in time caused by breaking waves on top of sea-surface.

- Breaking waves lasting for a short time before dying out.
- Other persisting on the order of seconds.



Discrete Wavelet Transform

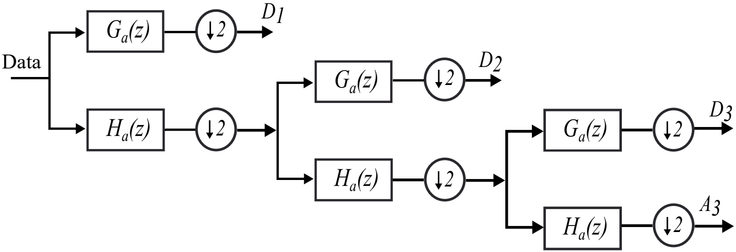
- Discrete wavelet transform (DWT) using two sets of filters:

$$A_k(n) = \sum_{m \in z} h_a(2n - m) A_{k-1},$$

$$D_k(n) = \sum_{m \in z} g_a(2n - m) A_{k-1}$$

where h_a and g_a are the analysis low- and high-pass filters. A_k and D_k are the approximate and detail sub-bands at k-level.

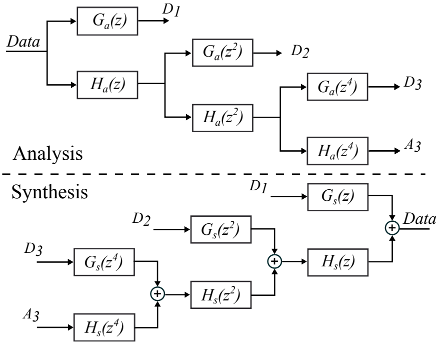
- Multi-resolution analysis (MRA):



Stationary Wavelet Transforms

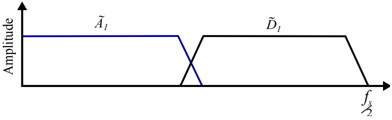
Stationary wavelet transforms (SWT) are used for the investigation.

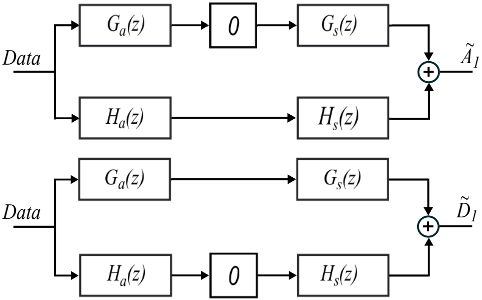
- No decimation: Avoids artefacts from aliasing when reconstructing subbands because SWT is shift-invariance, the advantage over the DWT.
- MRA: Filter is upsampled at each level, thereby maintain multi-resolution as in DWT.
- Perfect reconstruction.



Subband Isolation and Reconstruction

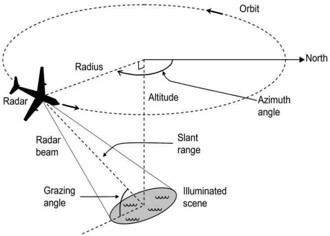
- Apply SWT along the slow time domain using Daubechies 4 mother wavelet.
- Isolate a subband and then reconstruct the signal to focus on different spectral regions.
- The result is the low- and high pass filter.





Ingara radar

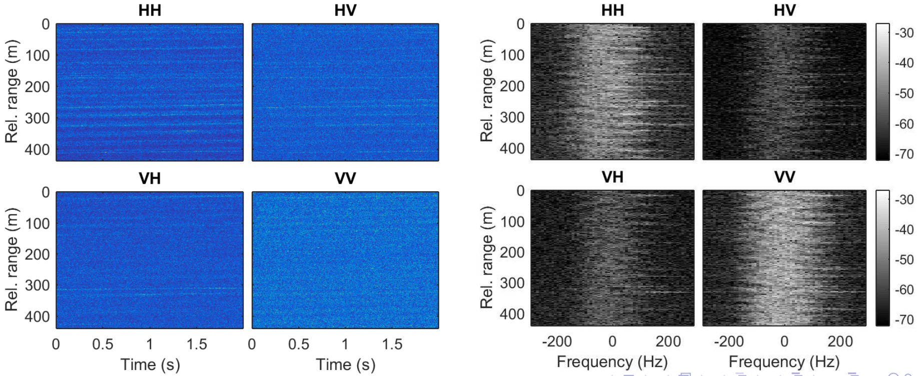
- X-band fully polarimetric radar.
- Patch antenna transmits either horizontal or vertical polarisation, then receives both.
- Antenna is mounted underneath a Beech 1900C aircraft and can rotate 360°.
- Radar has a maximum bandwidth of 600 MHz, 1 kW transmit power.
- Azimuth two-way 3 dB beamwidth is $\sim 1°$.
- Sea-clutter data has:
  - 200 MHz bandwidth / 0.75 m range resolution.
  - PRF is $\sim$ 600 Hz.
  - Full-pol mode alternates horizontal and vertical transmit ? halves the effective PRF to $\sim$ 300Hz.



Ingara Sea-Clutter

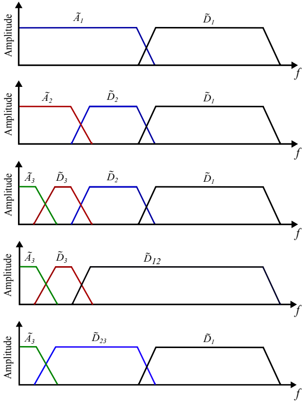
Dual polarised data with PRF of 575Hz; upwind direction; Douglas sea state: 4-5; grazing angles: 30.5° to 35.5°.

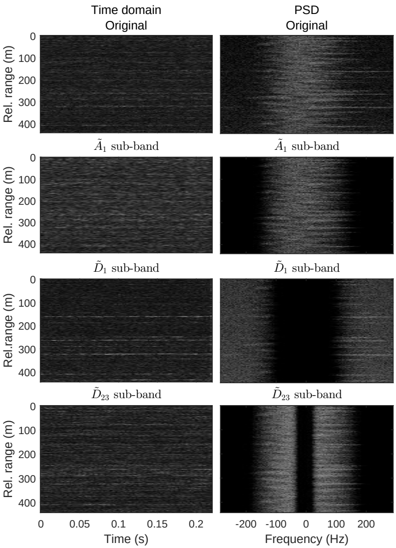
- HH polarisation: Horizontal transmitted and received data. Sea-spikes spread over a wide range of frequency (PSD iamges). It is chosen for our experimentation.



Multiresolution analysis:

- Bandpass filter: the bandwidth of the decomposed signal is split in haft at each level.
- Combination: selections of bandwidths for filtering.



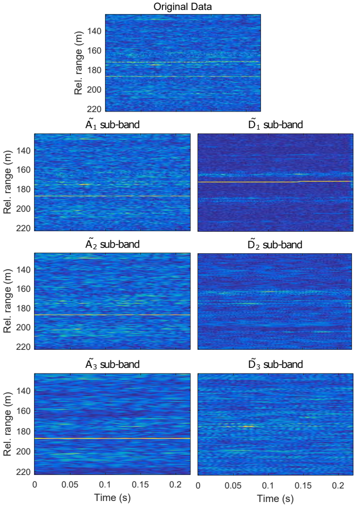


Preliminary Testing with Simulated Targets

Simulated stationary (lower) and moving (top) targets are injected to the data.

- Stationary target is always in $\tilde{A}_k$ subband and appear brighter at lower resolution.
- Moving target is maintained in $\tilde{D}_1$.

Note: The subsequence detail subbands, $\tilde{D}_2$ and $\tilde{D}_3$, has very little or no information about the targets for these type of target.



Detection Investigation

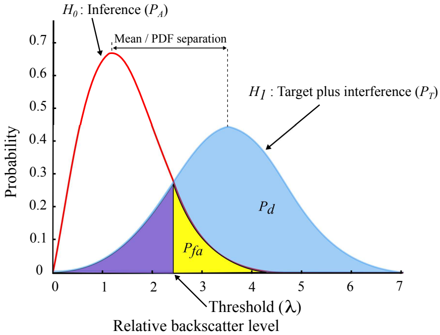
- Hypothesis test
  H_0: Interference (clutter + noise).
  H_1: Interference plus target.
- Probability of detection

$$P_d = \int_{\gamma}^{\infty} P_T(z)dz$$

- Probability of false alarm rate

$$P_{fa} = \int_{\gamma}^{\infty} P_A(z)dz$$

γ is the detection threshold.

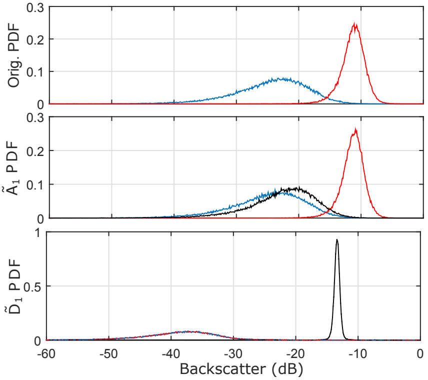


PDF Separation Aanalysis

A target with SIR of 10 dB is injected to all range bins. PDF of interference (int.) only and int. with a target are computed.
Blue: int. only; **Red**: int. + stationary target; **Black**: int. + moving target.

- Stationary target: good PDF separation.
- Moving target: larger PDF separation.

The little information about the moving target is maintained in $\tilde{A}_1$. It is reverse that no information about the stationary target is maintained in $\tilde{D}_1$ reconstructed subband.

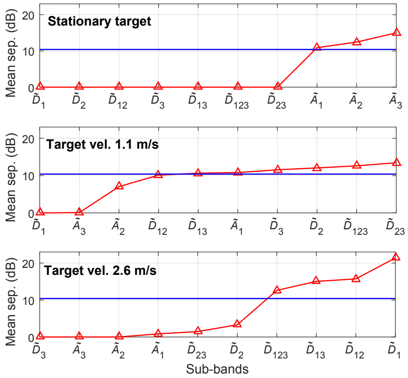


Mean Separation of MRA

The target is now injected to all range bins and the 3-level multiresolution analysis (MRA) is investigated.
Target velocities: 0 m/s (stationary), 1.1 m/s and 2.6 m/s.

Mean separations show that:

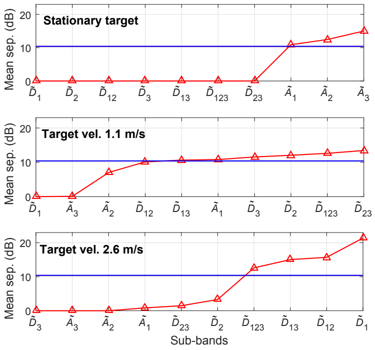
- Stationary target: bigger mean separation at low resolution reconstructed subbands ($\tilde{A}_k$).
- Moving target: larger separation at higher detail resolution reconstructed subbands ($\tilde{D}$) and depending target velocity.

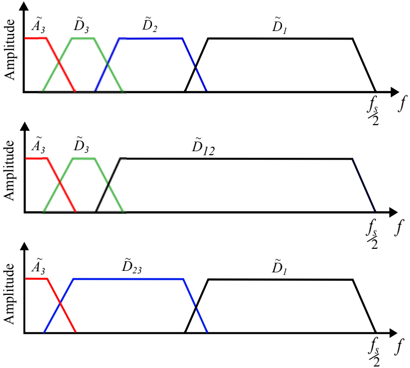


Subband Selection Based on Mean Separation

From the mean separations, we can select for the detection:

- Analysed subbands: $\tilde{A}_1, \tilde{D}_1, \tilde{A}_2, \tilde{D}_2, \tilde{A}_3, \tilde{D}_{12}, \tilde{D}_{23}$
- The method is good only if target velocities are know prior to the selection.





Entropy Subband Selection

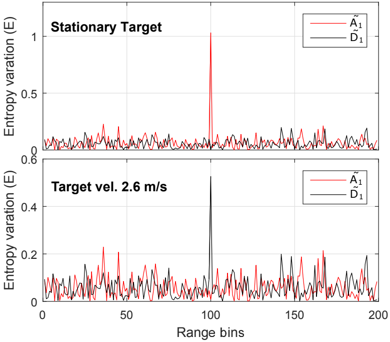
Determining the 'best' reconstructed subband to use for the detection.
Entropy is a measure of information content in a set of measurements.
For the random variable X, the entropy for the r^{th} range bin is:

$$H_r(X) = -\sum_{n}^{N} p_n \log(p_m / w_m)$$

where N is the number of bins for the histogram, p_n is the bin probability and w_n is the bin width.

- The entropy value varies with the variance or spreading of the histogram.
- To avoid the variation if the target is less or greater than the clutter

$$E_r(X) = | H_r(X) - \langle H \rangle |$$

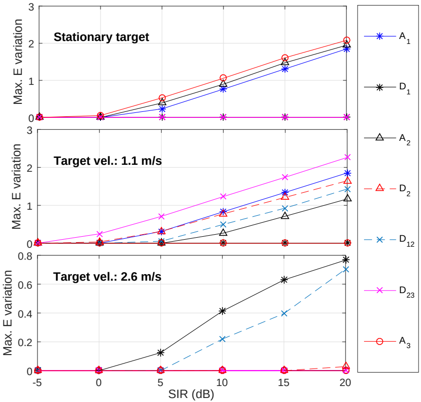


The variation is greatly influenced by the target with SIR = 10 dB bin: 100.

Entropy Reconstructed Subband Indicator

The same Swerling-0 target is injected and maximum entropy of the analysed subbands are measured with target SIR is varied from -5 to 20 dB.

- Biggest increase found for:
  - Stationary - A_3
  - Moving 1.1 m/s target - D_{23}
  - Moving 2.6 m/s target - D_1
- These results match the mean separation results.
- Similar results found for Swerling 1 fluctuating target.



Entropy metric can be used as sub-band indicator.

Entropy Reconstructed Subband Indicator

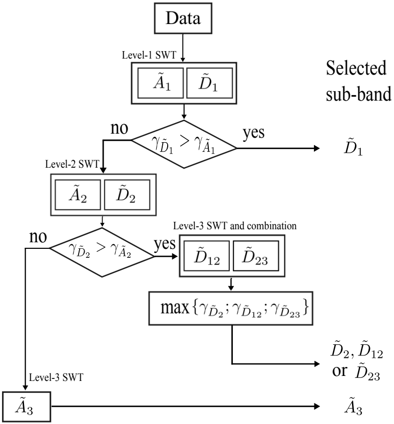
The subband with the biggest maximum entropy is the subband with the most information about the target.

- Subband maximum entropy:

$$\gamma_{subband} = max\{E_{subband}(X)\},$$

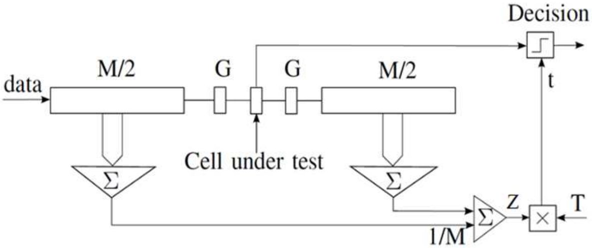
(subband: $\tilde{A}_1, \tilde{D}_1, \tilde{A}_2, \tilde{D}_2, \tilde{A}_3, \tilde{D}_3, \tilde{D}_{12}, \tilde{D}_{23}$)

- Proposed indication scheme using logic comparison on the same level SWT (Figure).
  - Faster computation.
  - Matching the mean separation (for the target with 10 dB SIR).



Detection Implementation

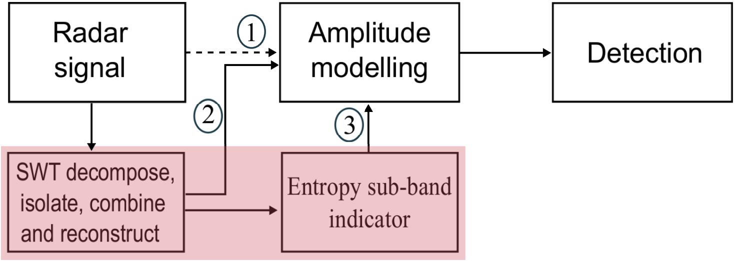
- Using HH upwind data of a CPI (128 pulse or 0.2 second).
- Swerling 0 (non-fluctuating) targets are injected with the SIR varied from 0 to 20 dB.
- Detection performance is quantified with Monte-Carlo simulation using 160 iterations with desired $P_{fa} = 10^{-3}$.
- Cell-Averaging CFAR (CA-CFAR) is used with local average over 32 range bins and with 2 guard bins.
- Threshold multiplier, T, is determined by K+Rayleigh model fit.



Detection Comparison

Three detection schemes are presented for the comparison:

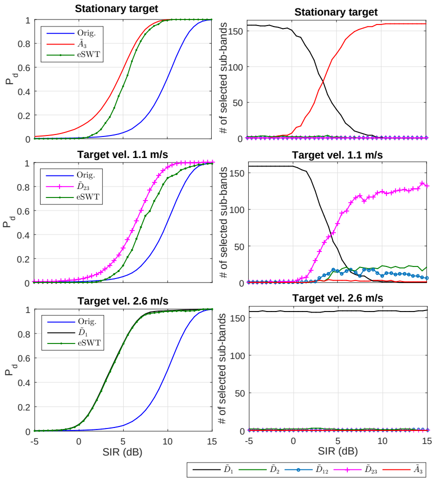
- Conventional detection scheme.
- Detection of target with known velocity.
- Detection of target with unknown velocity and entropy sub-band indicator (eSWT).



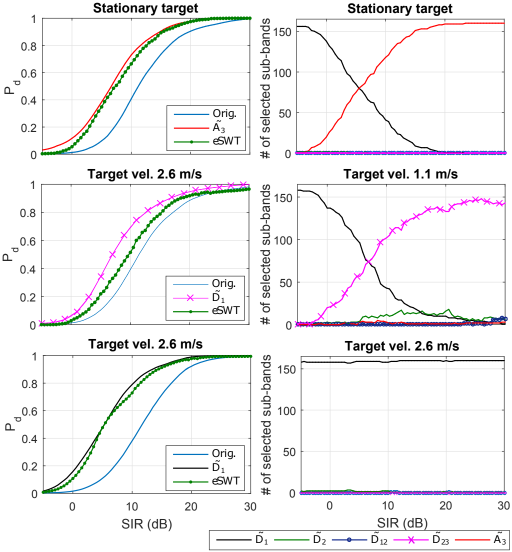
Detection Comparison

Detection of Swerling 0 (non-fluctuating) target

- Detection results on left show improvements over the original range / time data of up to 7 dB for all targets (stationary and moving).
- Number of correctly chosen reconstructed subbands is shown on right as a function of SIR.
  - First two target cases have a transition around 3 dB.
  - Consistent result for fast moving target.



Swerling 1 target



Summary

The stationary wavelet transform (SWT) - undecimated transform is investigated.
We presented:

- Isolates technique to reconstruct a subband of interest back to the range / time (data) domain.
- MRA on the sea-clutter and its impact on the target by investigating the mean separation of each reconstructed sub-band.
- Subband selection using an entropy metric which works for both stationary and moving targets.
- Detection performance results showing a significant improvement over a conventional CA-CFAR of up to 7 dB.

For Further Reading I

Ward, K.;Tough, R. and Watts, S.
Sea Clutter: Scattering, the K Distribution and Radar Performance.
Institution of Engineering and Technology, 2013

Duk, V; Ng, B; and Rosenberg, L.
The potential of 2D wavelet transforms for target detection in sea-clutter.
IEEE Radar Conference, 2015.