High Resolution Time-Frequency Representation of Narrow-Band Transient Signals

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1 Summary

Time-frequency analysis of narrow-band signals can be applied to a variety of problems. This report shows that high-resolution time-spectra can be used to detect a narrow-band transient in a very reliable way. Time-spectral processing can be viewed as a "poor man's matched filter" in situations where the signal source cannot be controlled. As an example the application in a research sonar, where received signals are subject to further analysis, is demonstrated. In this application time-frequency detection may additionally serve as a *quality assessment* or *quality enforcement* tool which eliminates extremely noisy signals and provides a clean ensemble for a subsequent classification algorithm, for example.

2 Introduction

With the advent of very high speed, precision A/D converters much of the sophisticated signal processing is shifting from the electronic analog domain to digital signal processing algorithms. Today, the acquisition of signals with an upper band-limit of one Megahertz merely requires basic signal pre-conditioning electronics, all further processing such as filtering, rate-conversions, and signal detection can be applied after the signal has been digitized.

This report puts a focus on a time-frequency method for signal detection. Generally time-frequency processing received much attention in the context of *wavelet-analysis*. However, the time-frequency representation based on a wavelet spectrum is difficult to relate to physical signal properties.

This approach is different. It is based on *Fourier-spectra*. The signal is analyzed to derive a parametric spectral model. A Fourier-spectrum can then be computed with arbitrary frequency resolution. The parametric model is calculated on a sample by sample basis. Thus, a sonogram of a signal may be computed with unlimited frequency resolution and a resolution in time as small as δt, where δt is the sampling interval.

3 An Example

The features of the parametric approach are best illustrated on an example taken from a hypothetic sonar application. The task here is to detect the signal in a reliable way in a noisy environment in order to measure "time-of-flight" as in a

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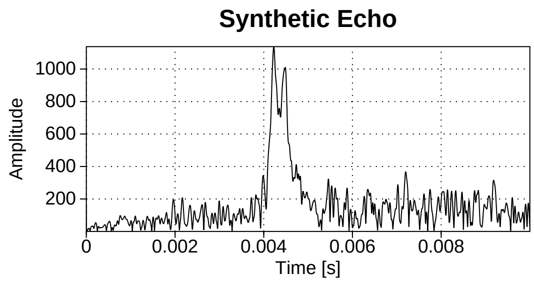

Figure 1: Envelope of a Synthetic Echo from a 50 kHz Sonar

depth-sounder application for example.

The approach taken here is to apply time-frequency conditions for detection.

The detection conditions are simply:

- □ a signal level sufficiently high above the ambient noise as measured in **time-domain**.
- □ amplitudes around the expected sonar frequency sufficiently high above ambient noise levels in **frequency-domain** *at the same time*.

Only when both conditions apply is a signal detected. The second condition, in particular, enables signal detection with a very low false alarm rate on narrow-band sonar signals. It acts as a narrow bandpass filter at the input of the detection algorithm, which eliminates out-of-band noise very efficiently.

Figure 1 shows a 50 kHz sonar return from shallow water. Simulated water-depth is 3 m, the transmit pulse has a duration of 0.4 ms. The noise is of uniform distribution restricted to the signal band. Signal to noise ratio (S/N) is 20 dB and the signal's full waveform was digitized at a rate of 1 MHz. Only the envelope of the signal is shown in figure 1.

Without any further processing the echo time-series, consisting of 10000 samples is now submitted to the detection algorithm. While the parametric model is calculated for every sample, the spectrum from 48 kHz to 52 kHz is computed for every 10th δt interval. The 4 kHz band is evaluated at 200 frequencies with a res-

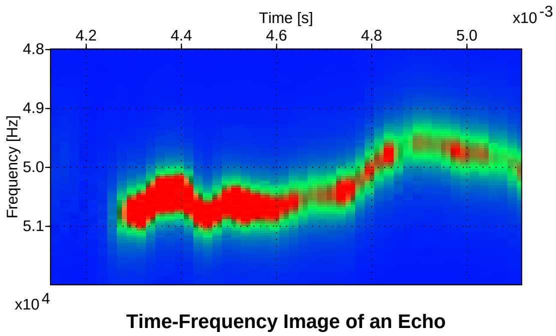

Figure 2: Sonogram from a 50 kHz Sonar Return

olution of 20 Hz.

The result is shown in figure 2 in form of a sonogram. The onset of the signal was detected at 4.13 ms, at the origin of the graph in figure 2, which also displays the spectral *signature* of the echo over time.

A three dimensional view of the sonogram (figure 3) may serve to illustrate how well the spectral peaks in the sonar return are defined in a time-frequency representation.

The algorithm is very fast and *real-time* capable. It does not require that the entire signal has been acquired before processing begins. The parametric spectral estimate is computed on a sample-by-sample basis. True real-time performance depends only on signal digitization rate in relation to processor speed.

3.1 Noise Performance

In order to evaluate the reliability of the detection, signals with different S/N ratios were submitted to the algorithm. For each of the thousand experiments for each noise level, the signal was constant but contaminated with different realizations of pseudo random noise. The noise was of uniform distribution and added to the signal. Signal plus noise were then bandpass-filtered to simulate a bandpass in an analog signal pre-conditioning circuit. Signal and noise characteristics are summarized in table 1.

The results of two trial-runs with 1000 signals for each noise level are listed in

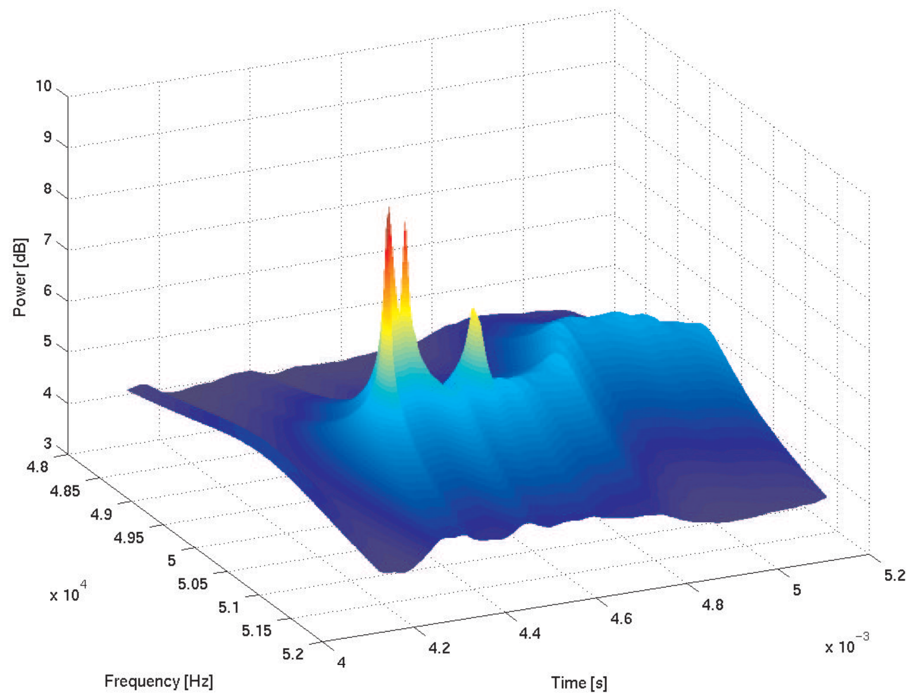

Figure 3: 3D-Sonogram from a 50 kHz Sonar Return

Table 1: Signal Properties

Carrier Frequency	50 kHz
Signal Duration	0.4 ms
Bandpass	40 kHz - 60 kHz

Table 2: Performance at Different S/N Ratios, Range 3 m

	Experiment 1			Experiment 2		
S/N [dB]	Hits	Misses	No Detection	Hits	Misses	No Detection
32	999	1	0	994	6	0
26	994	6	0	998	2	0
20	995	5	0	993	7	0
14	996	4	0	992	8	0
12	972	9	19	969	8	23
10	635	7	358	633	20	347

table 2. A single trial was considered a *Hit* when the signal was detected within the interval from 0.0036 to 0.0046 Seconds. The true first break occurs at 0.004 s. A *Miss* was scored when the signal was detected outside the interval. When the signal was not detected at all, the outcome was summed into the column *No Detection*. The *Hits*, *Misses* and *No Detection* counters sum to 1000 independent runs for the initial and repeat experiments for each S/N ratio.

Performance is remarkably constant with over 99% hits down to a S/N ratio of 12 dB where the signal is not detected at all in about 2% of the trials. Detection breaks down when S/N drops to 10 dB and in 35% of the cases no signal is detected. However, even here the *false alarm rate* is still under 5%. If a signal is detected, the reliability of the "time-of-flight" measurement is still high.

The noise tolerance of the detection algorithm can be tuned to a particular application. For a demonstration, the algorithm is tested with a synthetic 50 kHz echo from a depth of 180 m and a break-off S/N of 6 dB. The echo was sampled at 125 kHz, which is only 2.5 times the Nyquist frequency. So a high oversampling ratio is not a pre-requisite for the algorithm to perform well. The details of this test are summarized in table 3. The higher noise tolerance obviously trades off against a loss in accuracy even at higher S/N ratios where the number of *Misses* increases.

4 Algorithm Key Features

- ☐ Detects start and end of signal portion above noise level

Table 3: Performance with higher Noise Tolerance, Range 180 m

	Experiment 1			Experiment 2		
S/N [dB]	Hits	Misses	No Detection	Hits	Misses	No Detection
20	964	36	0	953	47	0
14	962	38	0	957	43	0
10	958	42	0	953	47	0
6	803	42	155	841	40	119

- Keeps noisy data from entering subsequent processing, no more "hand edititing" of noisy datasets
- Time-Phase spectra may be used to accurately range grazing angle retuns (e.g. Multibeam data)
- Time-Spectra hold promise as input to a classification scheme

5 Applications

- Quality Assurance
  - Transmitter Monitoring
- Doppler Shift Tracking
  - Ultrasound Flow-Meters
  - Ultrasound Velocity Logs
- Passive Monitoring of Structures and Mechanical Devices
  - Failure Prediction
  - Noise Monitoring
  - Resonance Alarm
- Sonar Detection
  - Time-of-Flight measurements
  - Target Tracking
  - Target Classification