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Removing Periodic Noise to Detect Weak Impulse Events

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Exact Localisation of Underground Explosion

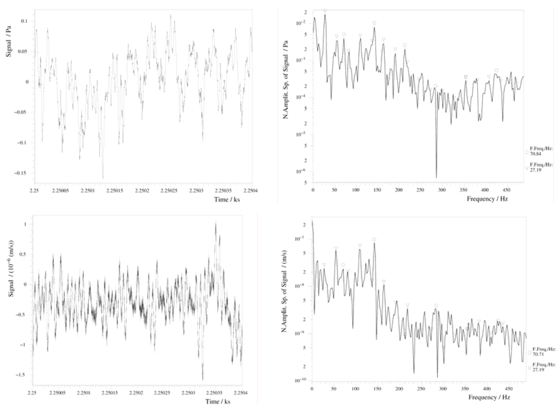
Teleseismic detections of an underground explosion result in localisation uncertainties on the order of 10 km. In order to find radioisotopes in the soil as indicators of a nuclear explosion, an CTBTO on-site inspection needs to localise the epi- or the hypocentre much better, maybe to around 0.1 km.
For this purpose a local seismic network can be set up shortly after the event in the area of interest determined from teleseismic signals. The purpose is to detect weak aftershocks which will occur for several weeks – from cracking and falling rocks around and in the cavity. Extreme sensitivity is required to detect the weak aftershock signals.

Impulse Signals and their Spectra

Aftershock events are single impulses which change form during propagation due to different seismic wave types with different velocities and to reflection at layer boundaries. Nevertheless, seismic signals received retain the impulsive character. Their spectrum is broad-band (see impulse figures right of centre).

Masking by Periodic Noise

Seismic signals measured at the surface can be masked by periodic noise from machinery, road traffic, propeller aircraft or helicopters. In experiments, we have measured acoustic and seismic signals of tanks, trucks, propeller aircraft and helicopters.[1-4]
Spectra of periodic signals consist of discrete lines at the fundamental frequency and its harmonics.



Signal (left) and spectrum (right) of a landed helicopter at about 1 km distance. Top: acoustic, bottom: seismic. In the spectra two harmonic series can be found stemming from the main (triangles) and the tail (circles) rotor, respectively.

Theoretical Expression for the Spectrum of a Sinusoid

Sinusoid in time domain $s(t) = A_0 \sin(2\pi\nu_0 t + \phi_0)$

Apply shah function $\frac{1}{\Delta t}\mathrm{III}\left(\frac{t}{\Delta t}\right) = \frac{1}{\Delta t}\sum_{k=-\infty}^{\infty}\delta\left(\frac{t}{\Delta t} - k\right)$

Apply Hann window $h(t) = \left[\frac{1}{2} - \frac{1}{2}\cos\left(\frac{2\pi t}{T}\right)\right]\cdot\Pi\left(\frac{t}{T} - \frac{1}{2}\right)$

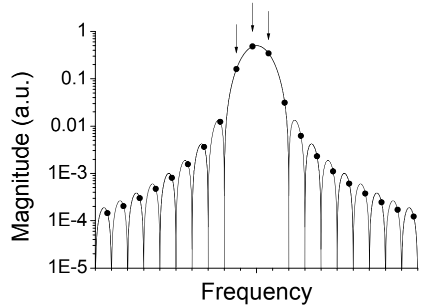
Fourier transform $G(\nu) = \int_{-\infty}^{\infty} f(t) e^{-i2\pi t\nu}\mathrm{d}\nu$ with $f(t) = s(t)\cdot\frac{1}{\Delta t}\mathrm{III}\left(\frac{t}{\Delta t}\right)\cdot h(t)$

Expression for complex spectrum (= discrete Fourier transform)

$$
\begin{aligned}
G(\nu) = i\frac{A_0}{4\sqrt{3}N}\Big[&\sin(\pi T(\nu-\nu_0))\Big(2\cot(\pi\Delta t(\nu-\nu_0)) \\
&- \cot\left(\pi\left(\Delta t(\nu-\nu_0) - \frac{1}{N}\right)\right) \\
&- \cot\left(\pi\left(\Delta t(\nu-\nu_0) + \frac{1}{N}\right)\right)\Big)\cdot e^{i(\pi T(\nu-\nu_0)-\phi_0)} \\
&- \sin(\pi T(\nu+\nu_0))\Big(2\cot(\pi\Delta t(\nu+\nu_0)) \\
&- \cot\left(\pi\left(\Delta t(\nu+\nu_0) - \frac{1}{N}\right)\right) \\
&- \cot\left(\pi\left(\Delta t(\nu+\nu_0) + \frac{1}{N}\right)\right)\Big)\cdot e^{i(\pi T(\nu+\nu_0)+\phi_0)}\Big]
\end{aligned}
$$

Fitting Line Parameters to a Given Spectrum

The three highest points have most of the power and are least influenced by lines at other frequencies. The line parameters frequency, phase and amplitude are fitted to these points by the non-linear Levenberg-Marquardt method. Start values for frequency and amplitude are gained from the three points. Various thresholds define when iterations are to stop and if a fit is acceptable. When a one-line fit is not convincing, then a fit with two neighbouring lines is tried (using five points).



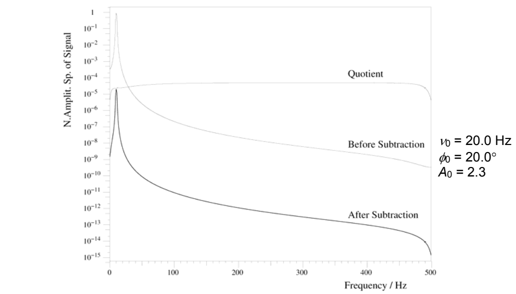
Theoretical spectrum of one sinusoid (dots mark discrete Fourier transform).

Finding Lines in a Spectrum

To be accepted as a valid line for subtraction, a peak must fulfil the following criteria:

- It must have a minimum height above the background.
- Its width must be below a threshold.
- The theoretical line must approximate the peak well enough (normalised sum of squared deviations at the three highest points below a threshold).

Subtracting a Theoretical Line

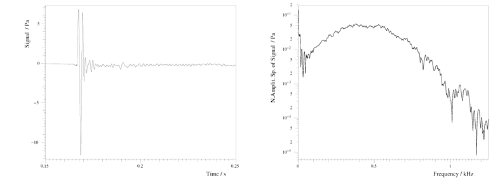


Original spectrum of one sinusoid ("Before Subtraction"), remaining difference after subtracting theoretical spectrum of line with parameters from fit ("After Subtraction"), and quotient of both. The difference is due to slight deviations of the fitted parameters.

Lines are fitted and subtracted one after the other, ranked by amplitude.

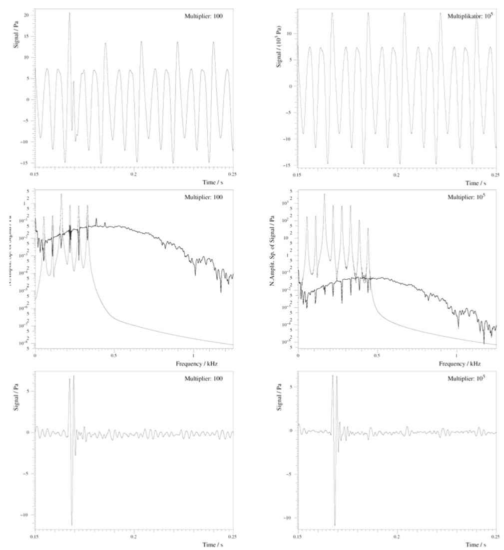
Testing the Performance

An acoustic impulse is used as the test signal.



Acoustic impulse in time domain　　Spectrum of impulse (lowest quarter)

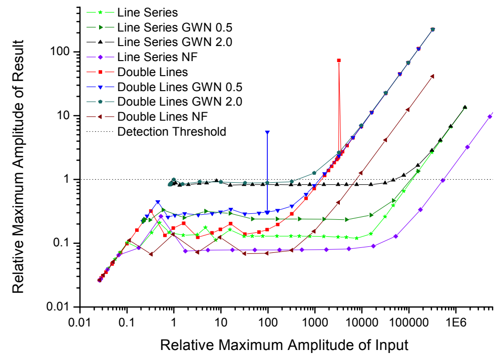
Synthetic signals from various combinations of lines are superposed with their amplitudes modified by a common factor between 1 and 10^8.



Impulse superposed with line series (8 lines, 55-440 Hz). Multiplier 100 (left column), 10^5 (right column). Top: signal; centre: spectrum, found and fitted lines, subtracted spectrum; bottom: back-transformed time signal.

Results

Various sets of lines were tested: harmonic series of 8 lines ("Line Series"), 8 lines at varying distances ("Line Series NF"), 10 lines with 3 close pairs (3 and 5 Hz mutual distance) ("Double Lines"), 10 lines with at least 25 Hz neighbour distance ("Double Lines NF"). Also, Gaussian white noise of rms value 0.5 and 2.0 Pa was added ("GWN").



Peak-to-peak value of corrected signal before the impulse divided by p-p-value of impulse versus the same ratio before correction.

With a detection threshold of 1, line amplitudes can be reduced by a factor 10^5-10^6 for widely spaced sets and by about 10^3 for sets with close neighbours.

Conclusions

- The present algorithm allows to reduce the contribution of periodic noise in synthetic signals by several orders of magnitude, promising detection of much weaker impulse-type events.
- Lines in spectra of real signals are not always found and fitted satisfactorily (not shown).
- There are possibilities for improvement: better inclusion of absolute phase, full inclusion of contri-butions centred at negative frequencies, better treatment of two neighbouring lines, adjustment of thresholds.

The procedure is generic and can be applied to any kind of signal. Further research is needed to assess the performance limits in detecting seismic events in the presence of periodic noise.

Selected References

1 J. Altmann, S. Linev, A. Weiß, Acoustic-Seismic Detection and Classification of Military Vehicles – Developing Tools for Disarmament and Peace-keeping, Applied Acoustics **63** (10), 1085-1107, 2002.
2 J. Altmann, Acoustic and Seismic Signals of Heavy Military Vehicles for Co-operative Verification, Journal of Sound and Vibration **273** (4-5), 713-740, 2004
3 R. Blumrich, Sound Propagation and Seismic Signals of Aircraft Used for Airport Monitoring, Verification – Research Reports, no. 10, Hagen: ISL, 1998.
4 F. Gorschlüter, Messung, Erkennung und Unterdrückung periodischer akustischer und seismischer Störsignale, Diplomarbeit, FB Physik, TU Dortmund, 2009 (unpublished).