The challenges in the acoustic detection of ultra-high energy neutrinos

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Team: Justin Vandenbroucke, Giorgio Gratta (Stanford U.)

Talk layout

1. Short introduction
2. Theoretical simulation of neutrino acoustic signal
3. Description of experiment
4. Lightbulb calibration
5. Data and types of events
6. Detection of neutrino acoustic signal in coherent noise

Ultra High Energy (UHE) Neutrino Sources ($\gtrsim 10^{18}$ eV)

Hypothetical sources (biggest):
- gamma ray bursts,
- active galactic nuclei,
- decay of heavy objects ("top-down" mechanisms).

Also (smaller):
- galactic mechanisms (from cosmic ray interactions with baryons),
- Greisen-Zatsepin-Kusmin mechanism (reaction of protons of energy $>5 \times 10^{19}$ eV with cosmic microwave background radiation).

Very small:
- atmospheric background.

Measured UHE Cosmic Ray fluxes:
~ 100 $km^{-2}y^{-1}$ above 10^{18} eV,
~ 1 $km^{-2}y^{-1}$ above 10^{19} eV,
~ 1 $km^{-2}century^{-1}$ above 10^{20} eV.

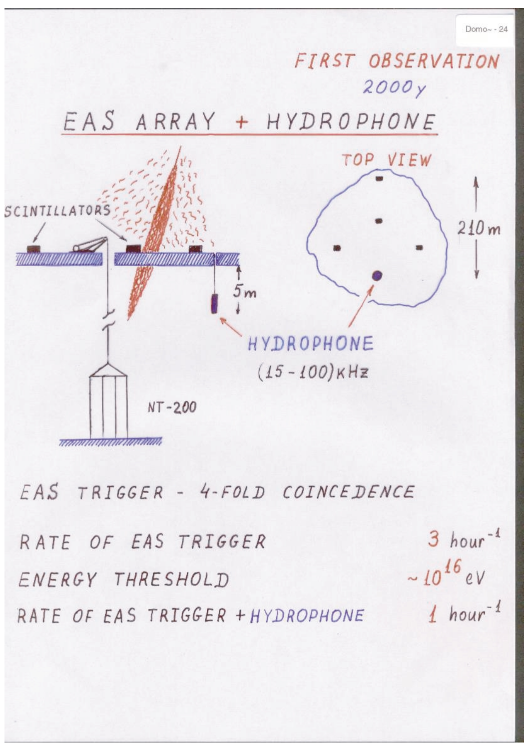
Previous work on acoustic detection of UHE neutrinos

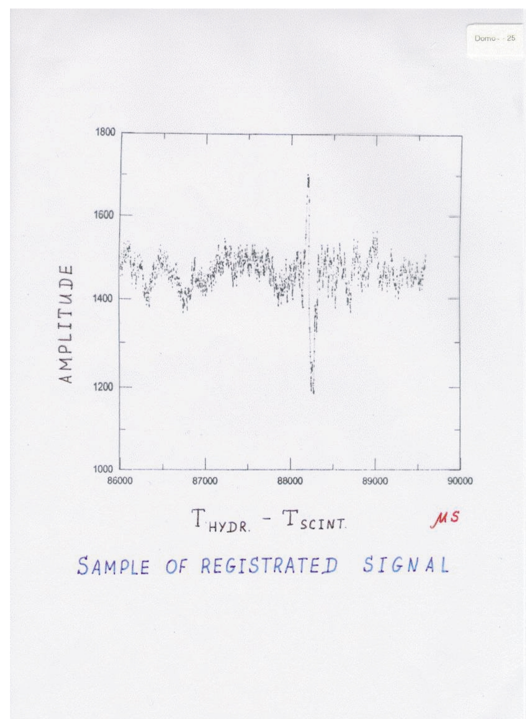
- Acoustic detection was first proposed by Askarjan in 1957

- DUMAND (project was not realised)

- Sulak et al. (1979) -
  experimental measurements of sound production
  by 150 MeV - 28 GeV proton beams in water

- Baikal Neutrino Project (Domogatsky, unpublished talk, presented at Neutrino 2000):

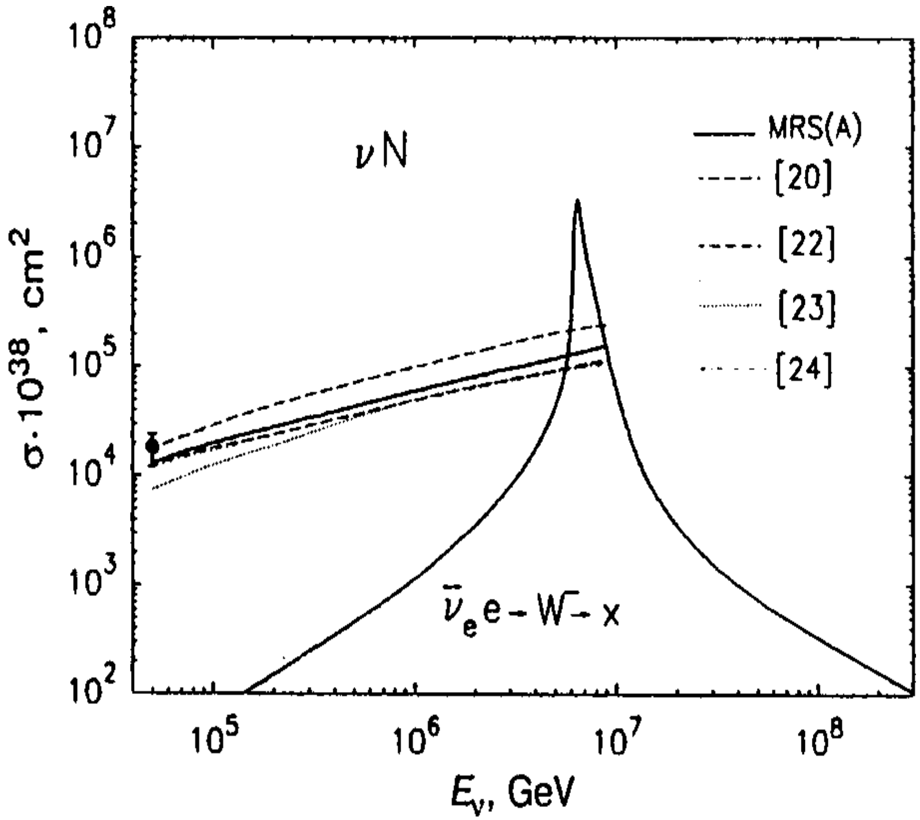




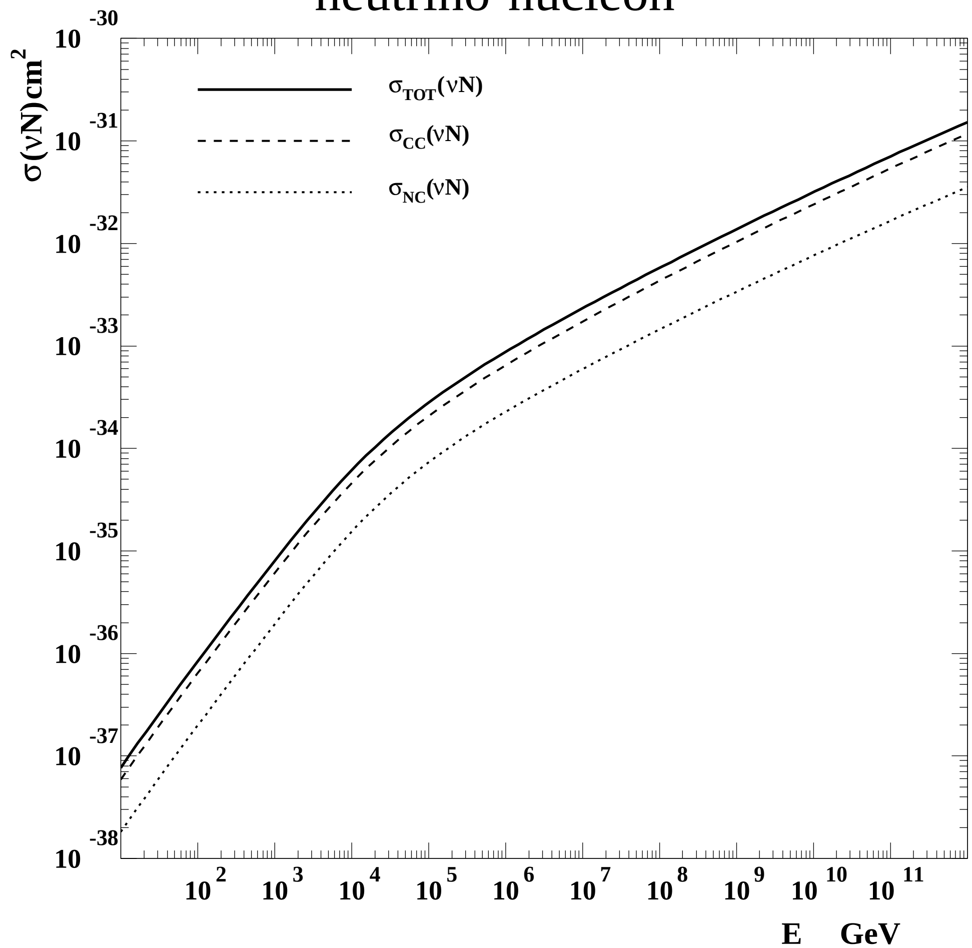
Neutrino-induced shower in water (1)

1. Are created by collision with nucleons

Butkevich et al., 1998:
neutrino/antineutrino-nucleon
antineutrino-electron



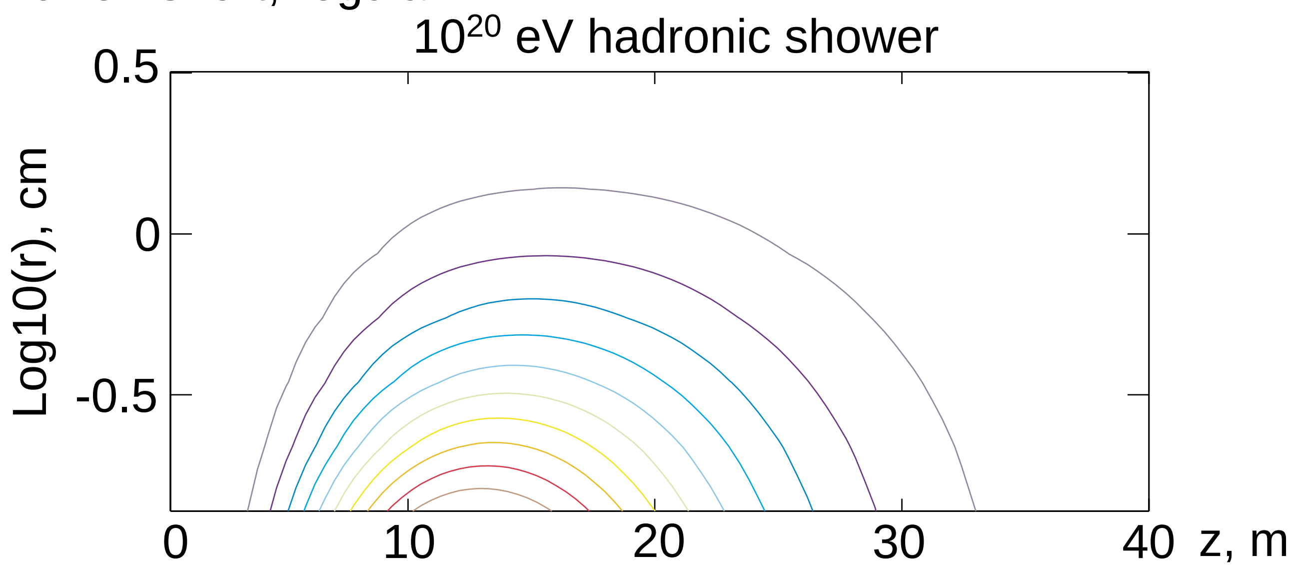
Kwiecinski et al., 1998:
neutrino-nucleon



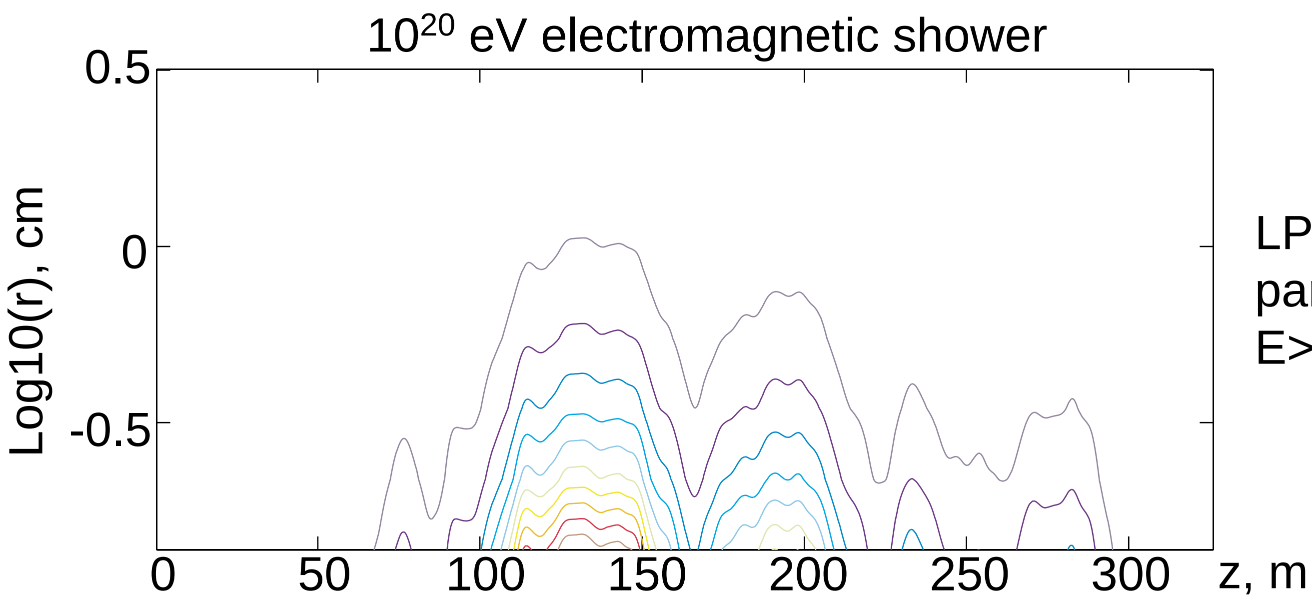
2. ~80% energy goes into lepton, ~20% into hadronic shower.
3. Muons and tau leptons (created by ν_μ and ν_τ, correspondingly) do not produce detectable acoustic showers.

Neutrino-induced shower in water (2)

- hadronic shower: short, regular

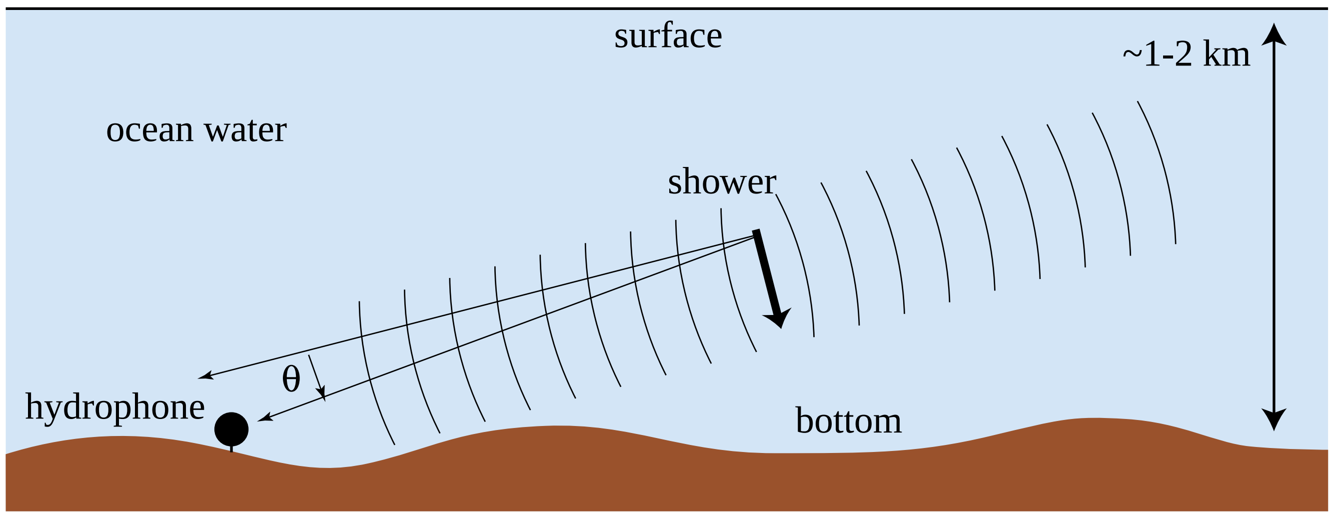


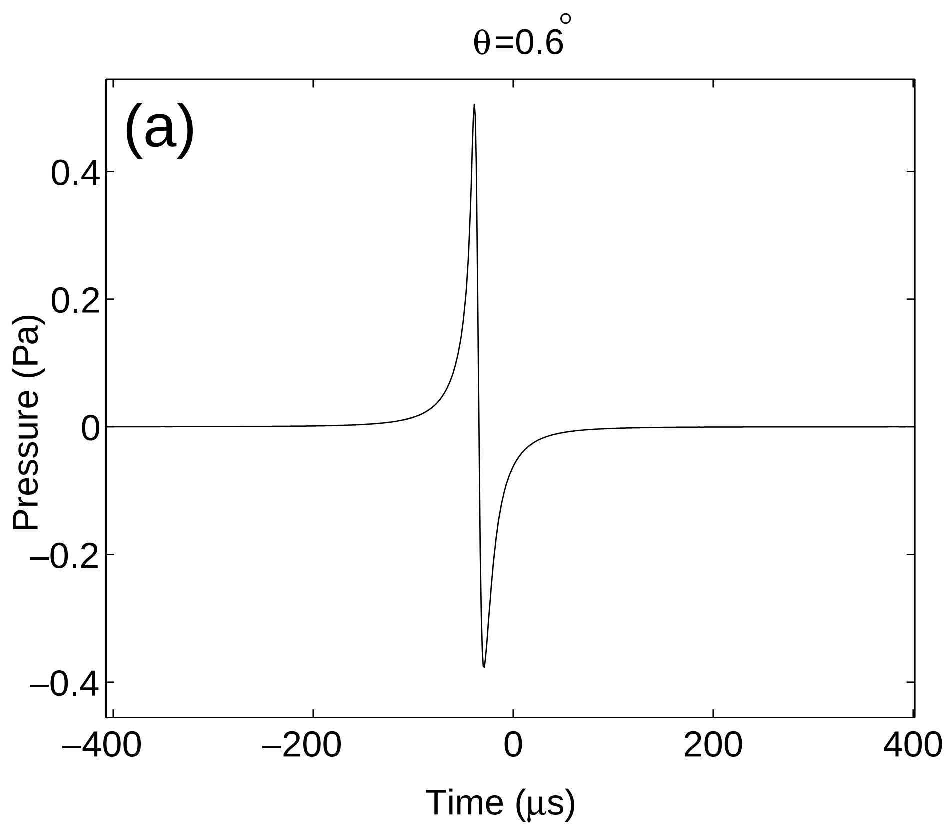
- electromagnetic shower: elongated and has substructure due to Landau-Pomeranchuk-Migdal (LPM) effect (decrease of electromagnetic cross-sections in dense media)

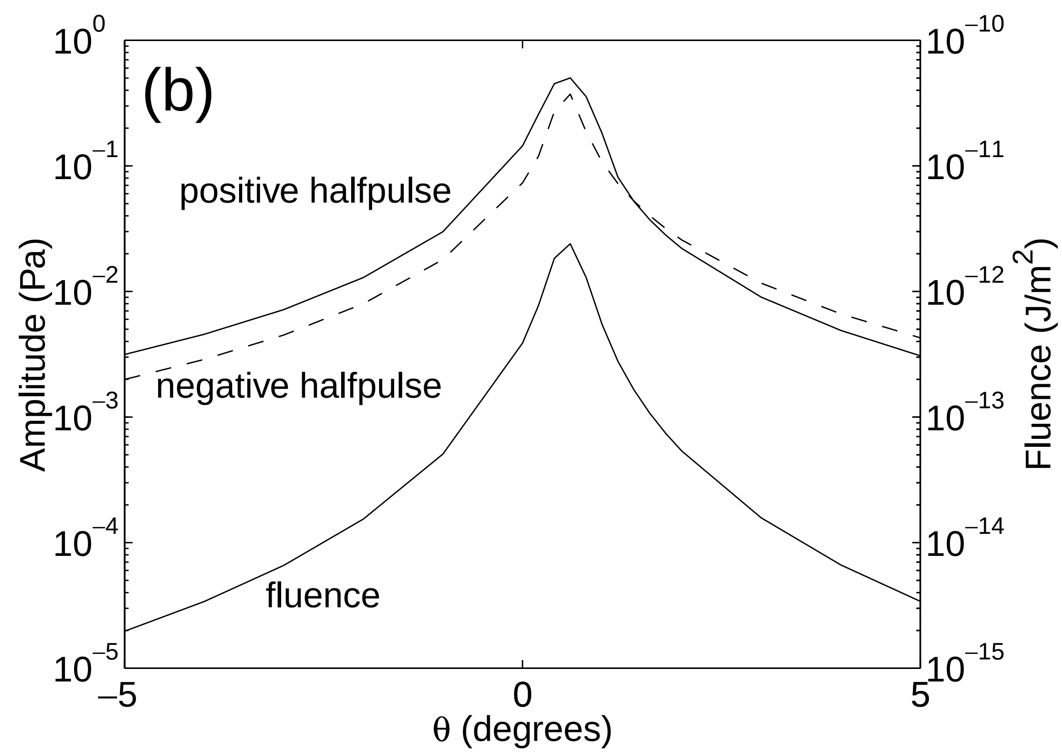


LPM: important for particles of $E>2\times10^{15}$ eV

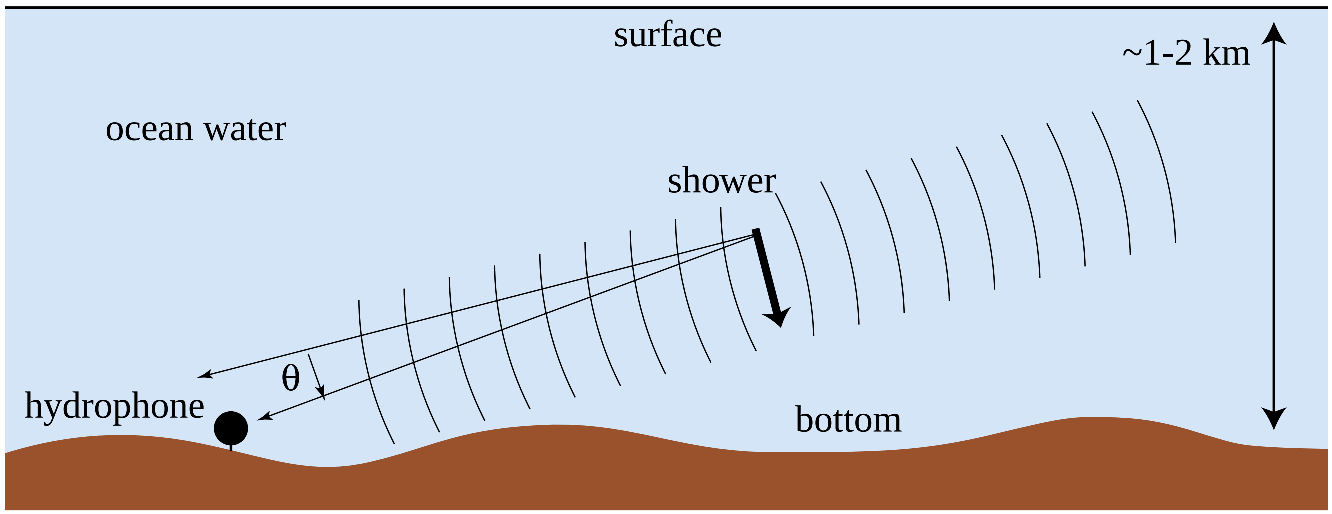
Acoustic pulse calculations: 1. Hadronic shower

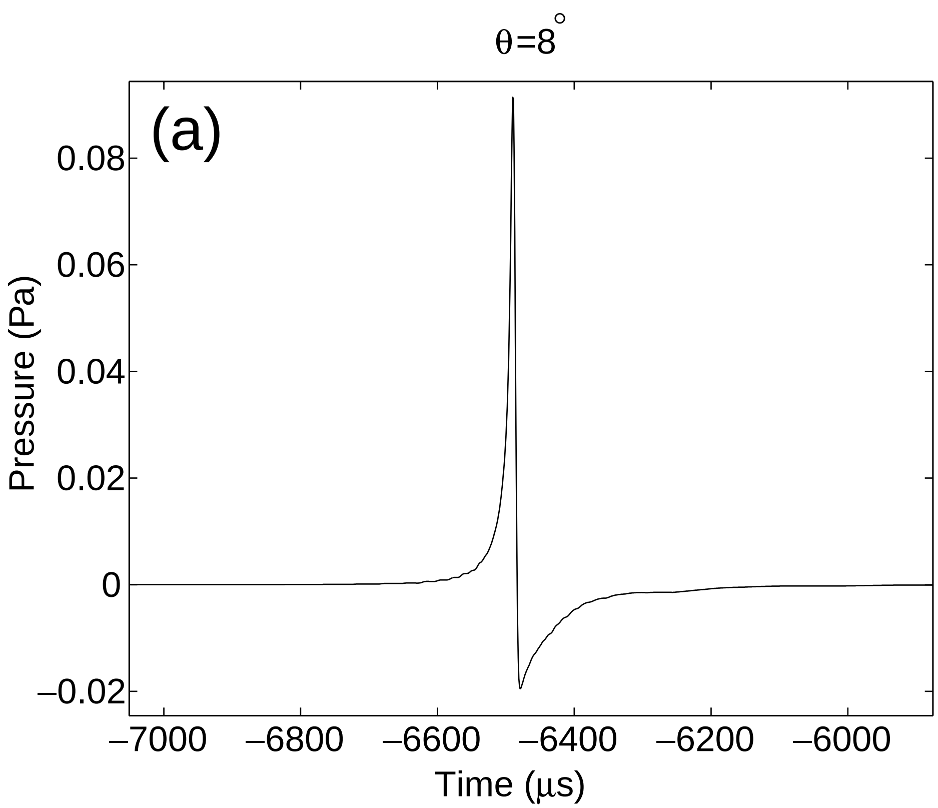


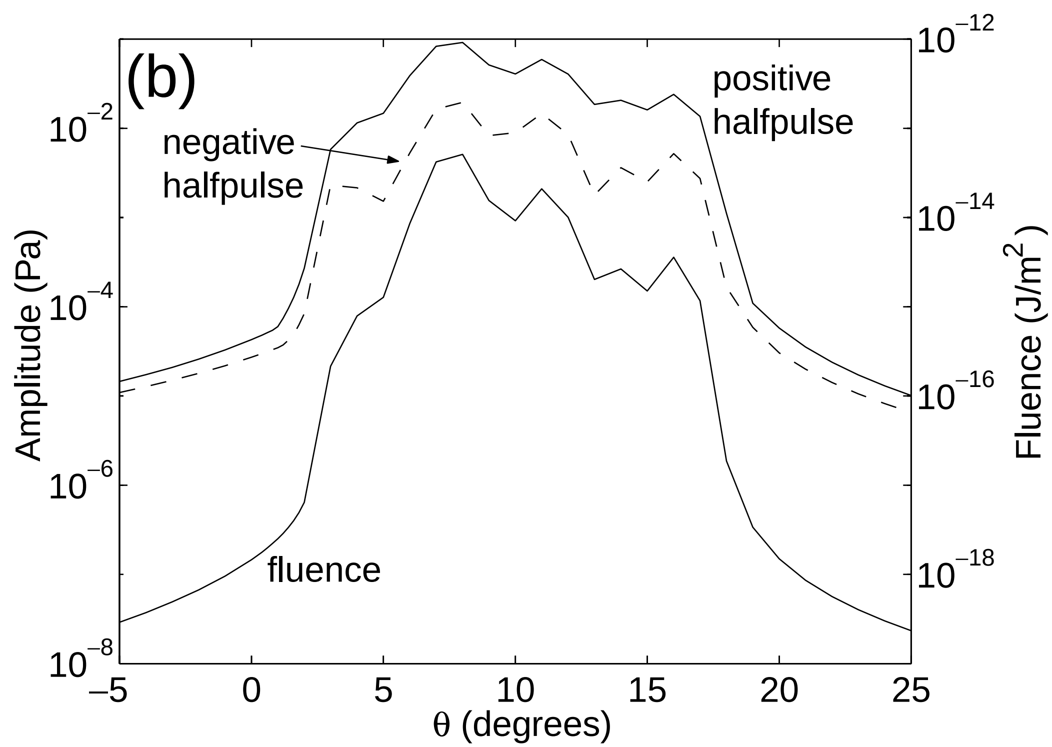




Acoustic pulse calculations: 2. Electromagnetic shower





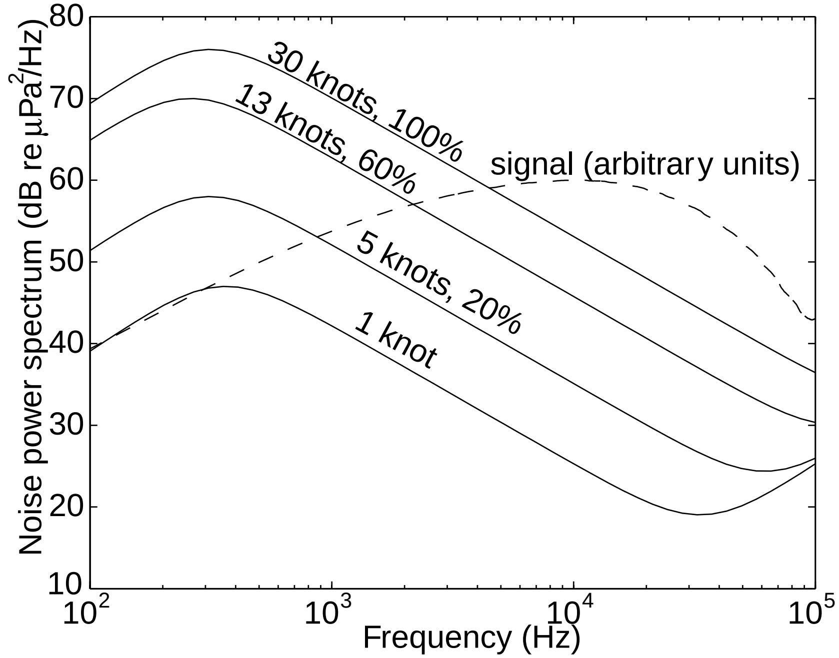


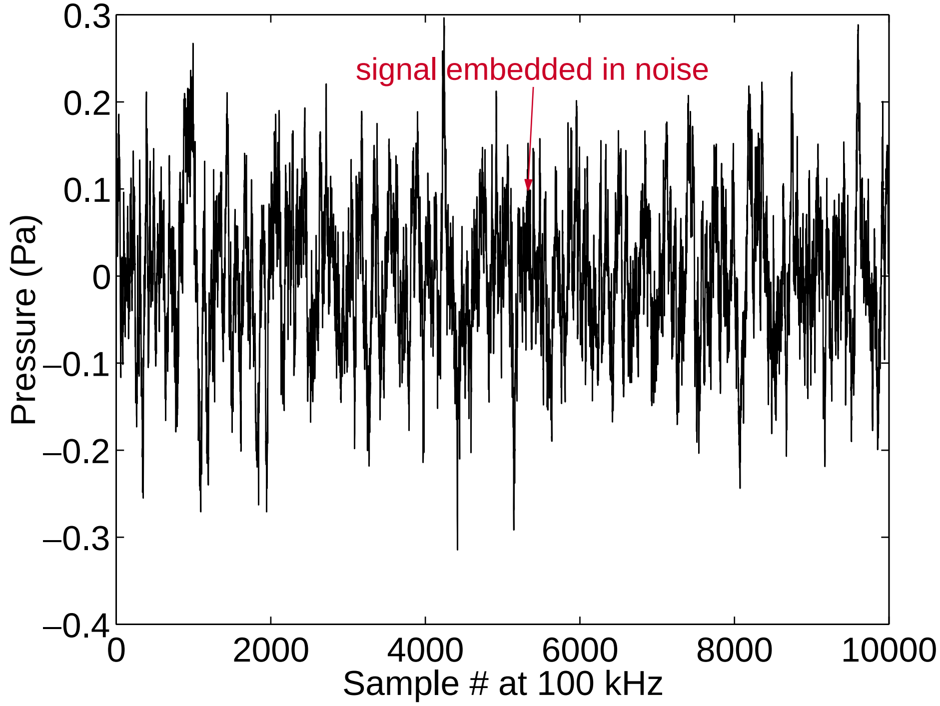
Matched filter as an optimal detection algorithm in Gaussian noise

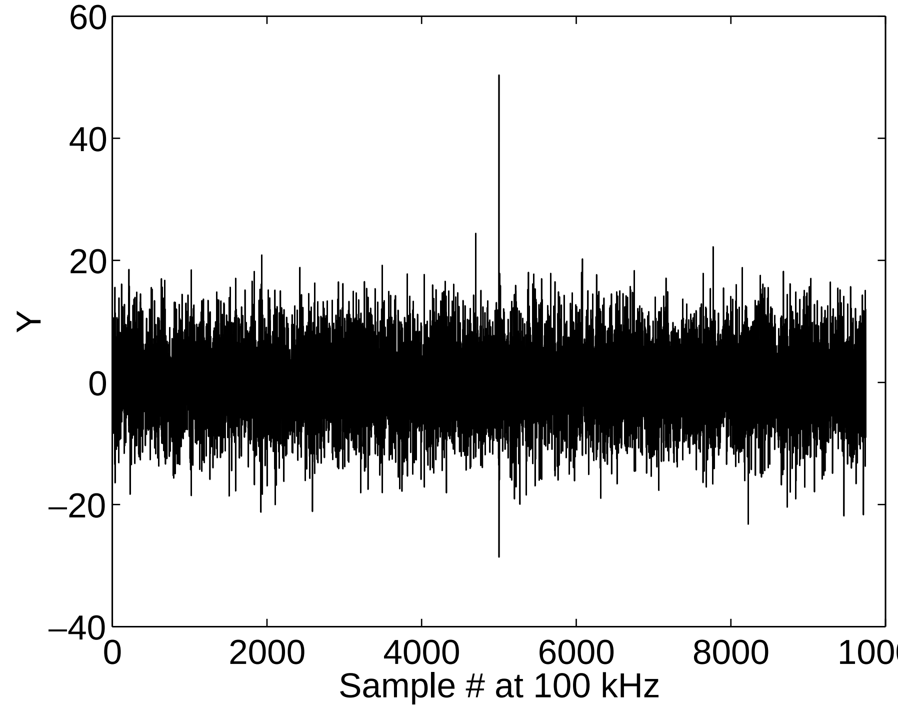
Matched filter technique is based on maximizing the likelihood of signal presence and uses the differences in noise spectrum and signal spectrum.

The matched filter which is used is a digital filter:

$$Y_k = \Sigma H_i X_{k-i}$$

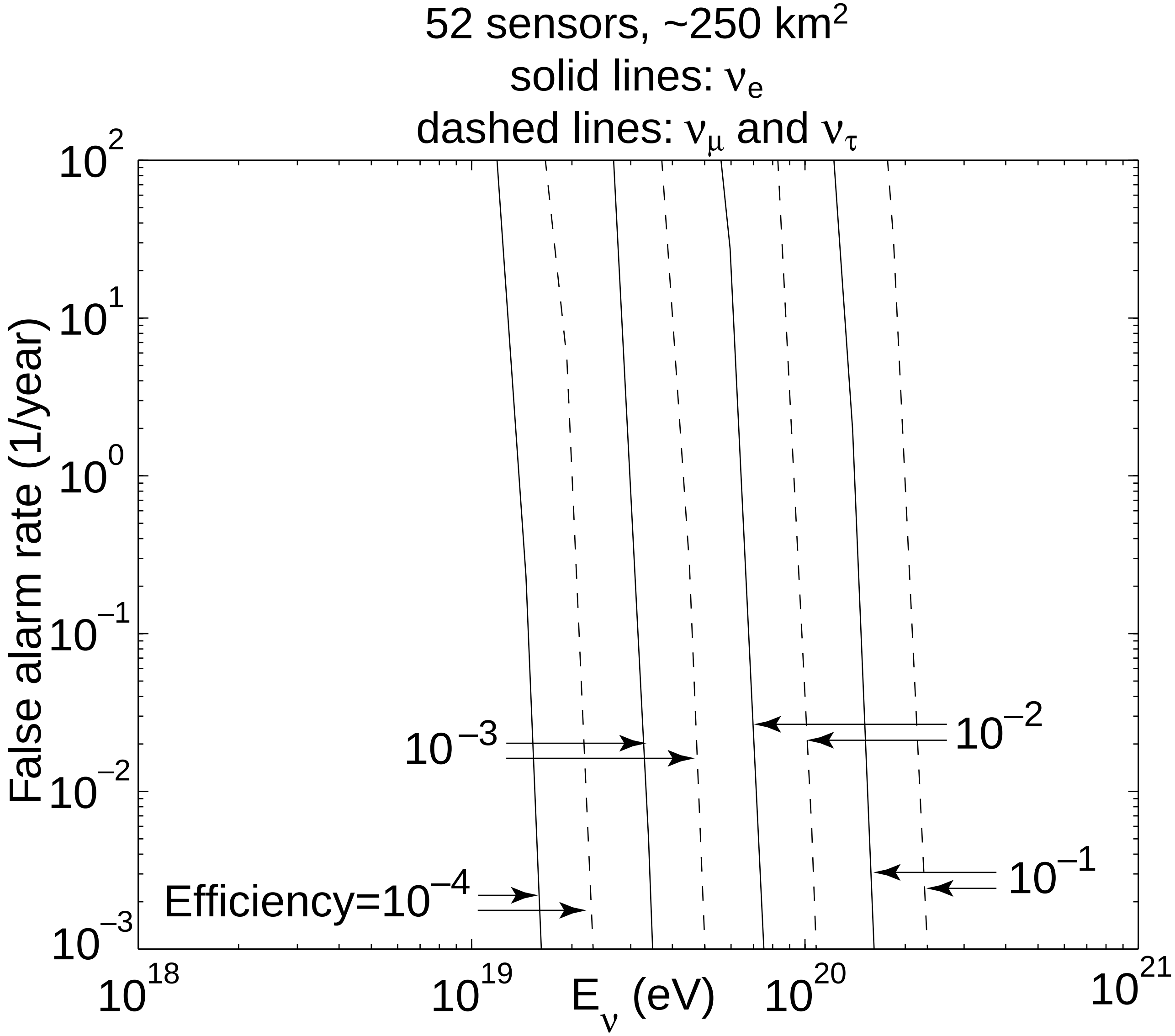






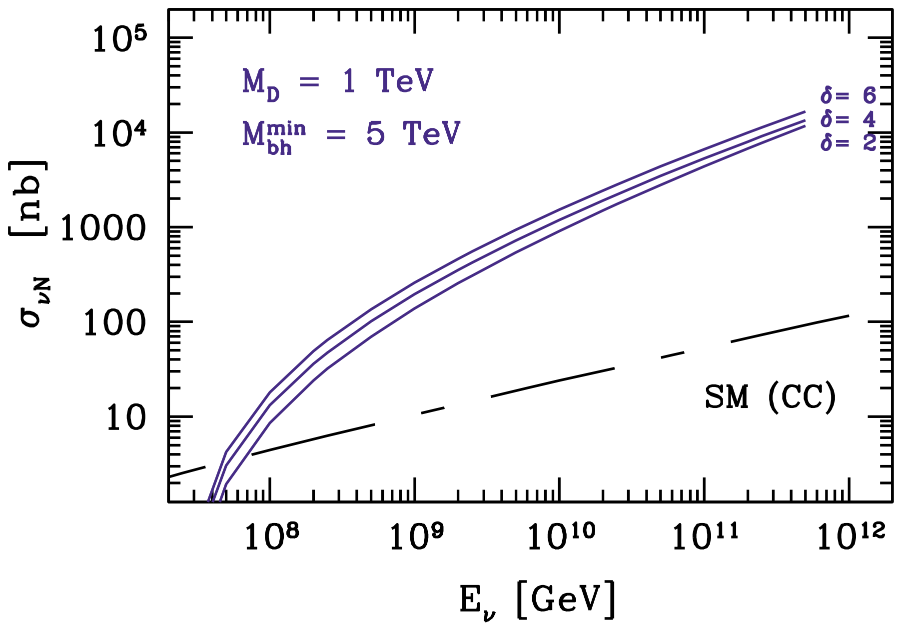
The theoretical prediction of sensitivity: the false alarm rates and the efficiency

Efficiency is defined as the fraction of neutrinos that are detected in respect to those that interact. There are *false alarms* due to gaussian fluctuations. Both efficiency and false alarm rate are determined by the threshold. To be detectable, ν event rate has to be higher than the false alarm rate.

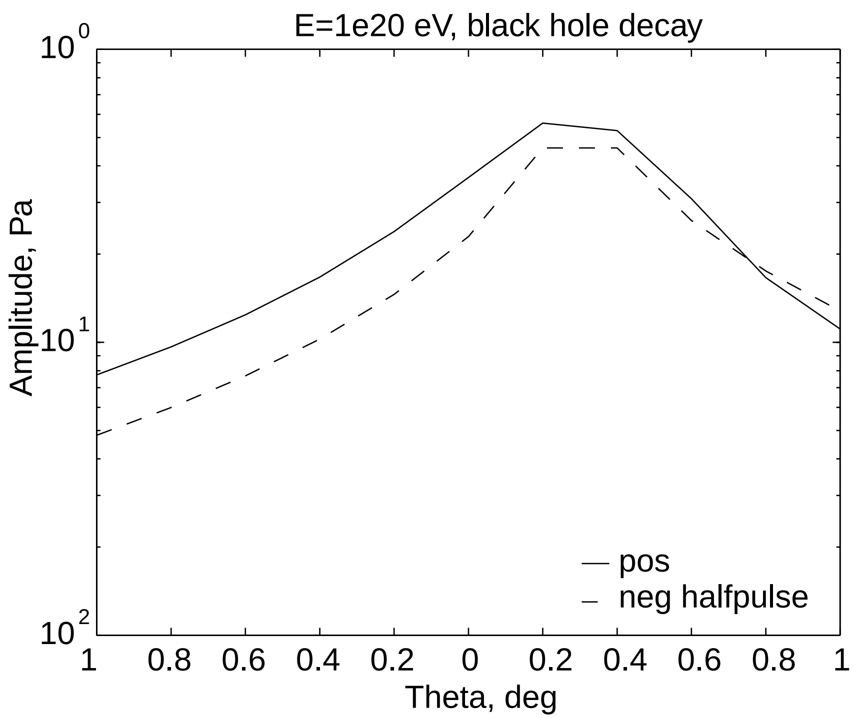


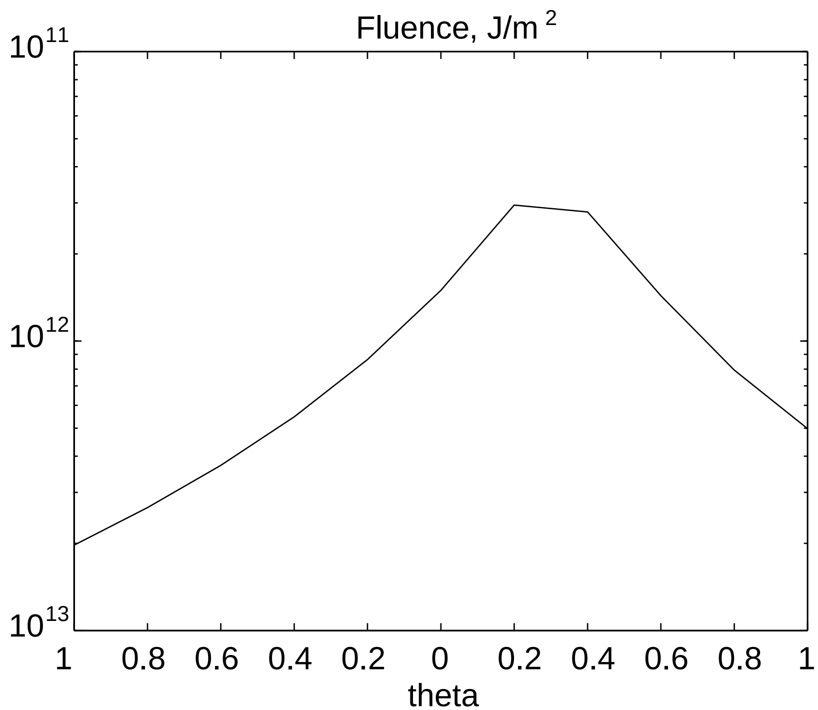
Large extra dimensions (hypothetical)

Ringwald and Tu, 2001

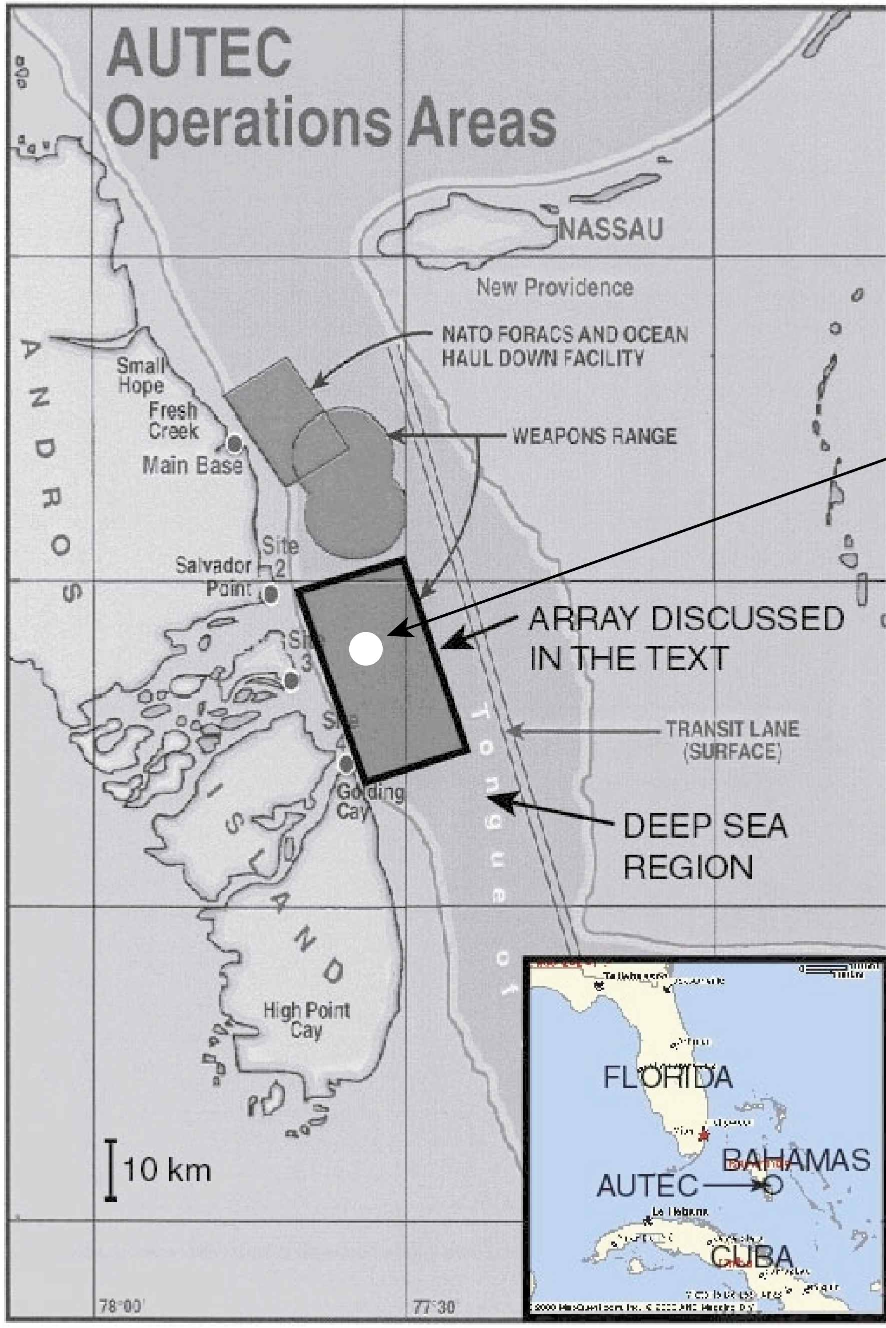


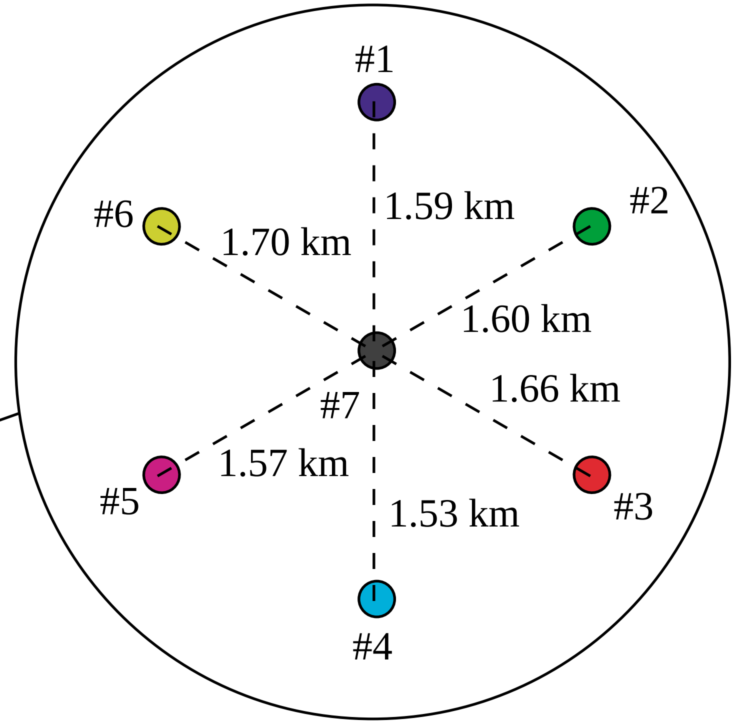
The theory of Large Extra Dimensions predicts a TeV order of fundamental Planck scale. When large extra dimensions are present, a UHE neutrino interacts to create a black hole which then decays to ~10 GeV partons in CM ref. frame, or ~ 1000 TeV in the lab frame.





The US Navy Atlantic Undersea Test and Evaluation Center





hydrophone subset used
in the experiment
(set up at Bahamas by
J. Vandenbroucke)

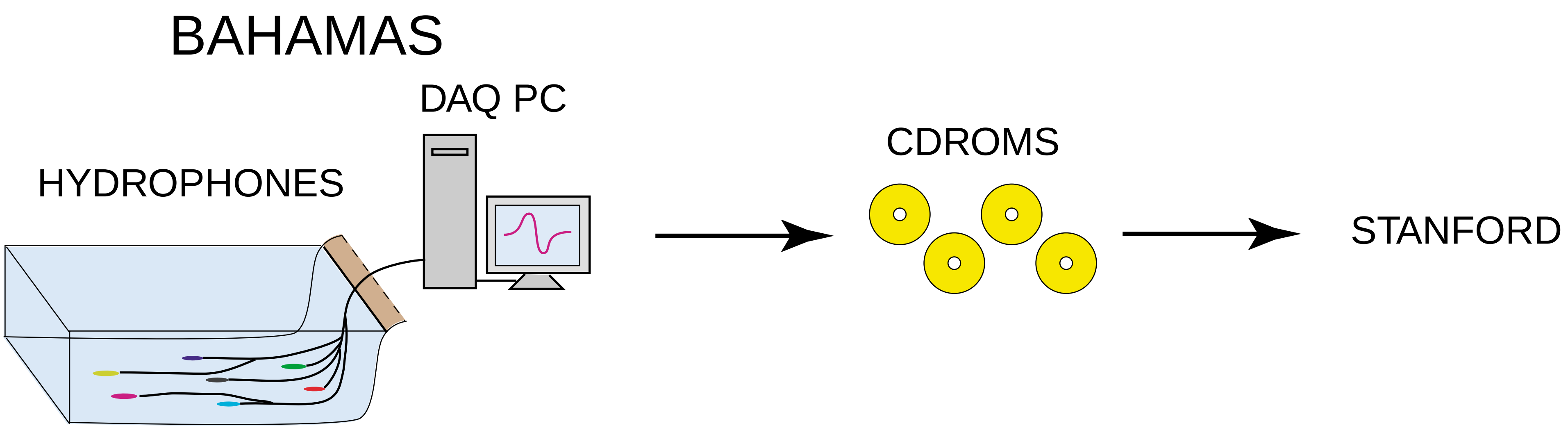
hydrophone depths are 1550-1600 m

AUTEC Site 3

AUTEC experiment setup

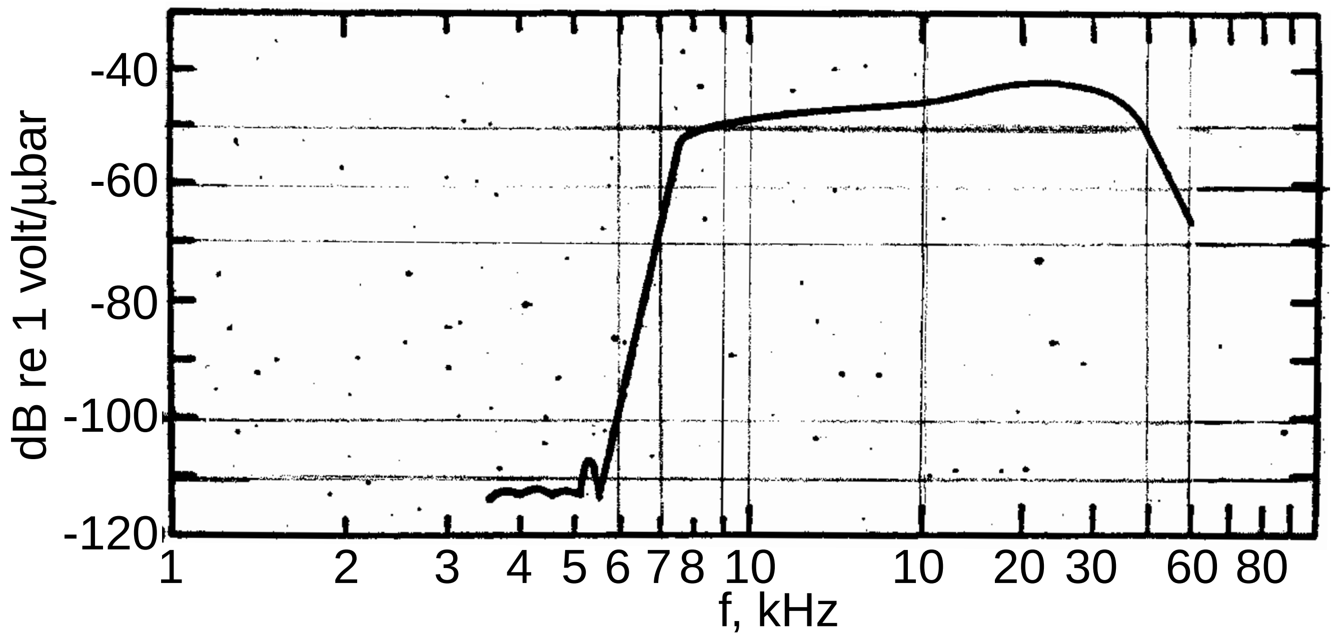
- Dell 8100 PC with 1.7 GHz Pentium 4 processor and CD writer
- National Instruments PCI-MIO-16E card with BNC 2110 interface
- Data acquisition software written in Labview 6.0
- Data are currently saved on CDs in zip format (1 CD/day)
  (in future, on a hot-swappable hard drive with FireWire interface)

Technical difficulties:
- crosstalk (~6%) between certain channels,
- spike noise (example shown later).



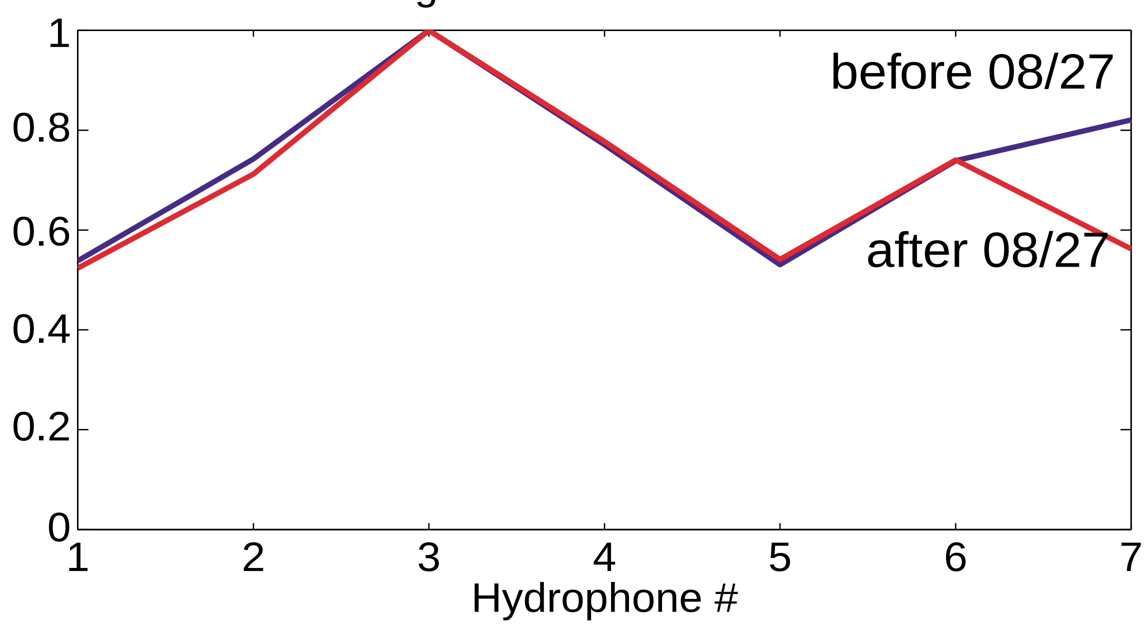
Hydrophone system properties

1. Transfer function

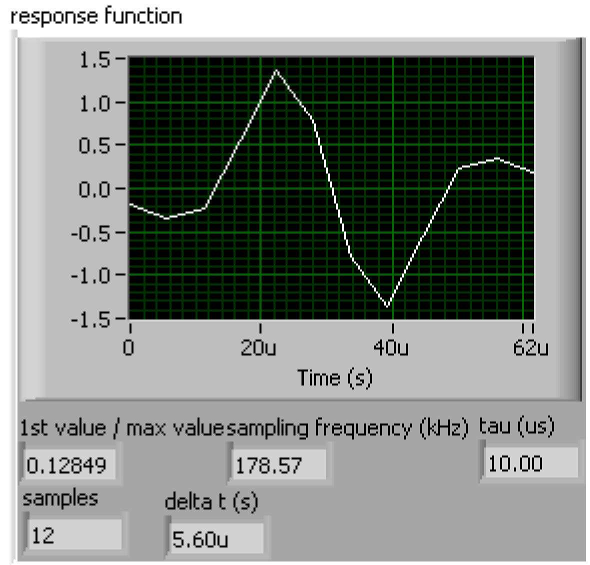


2. Variability in the gain

Relative gain inferred from noise level

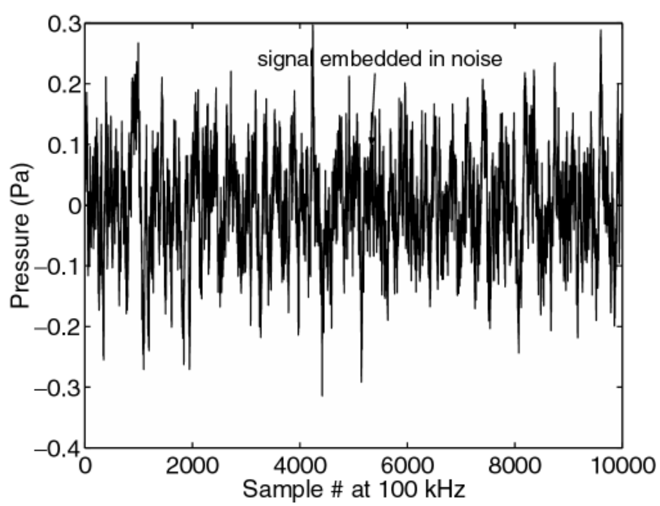


Trigger algorithm



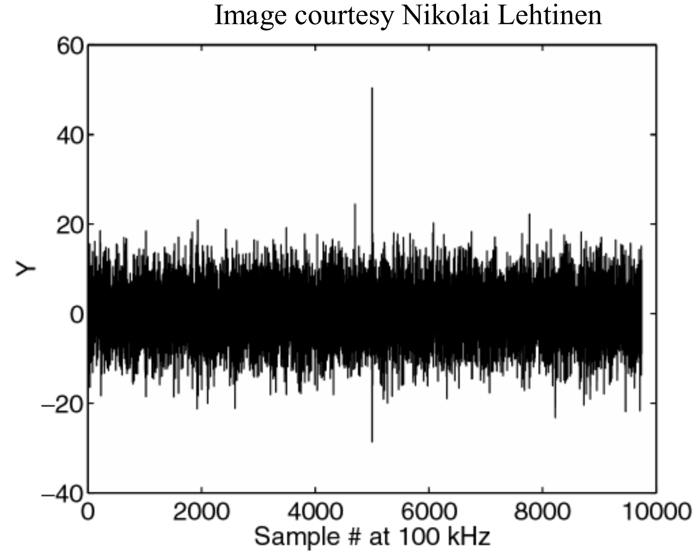
Digital filter response function

Image courtesy Nikolai Lehtinen



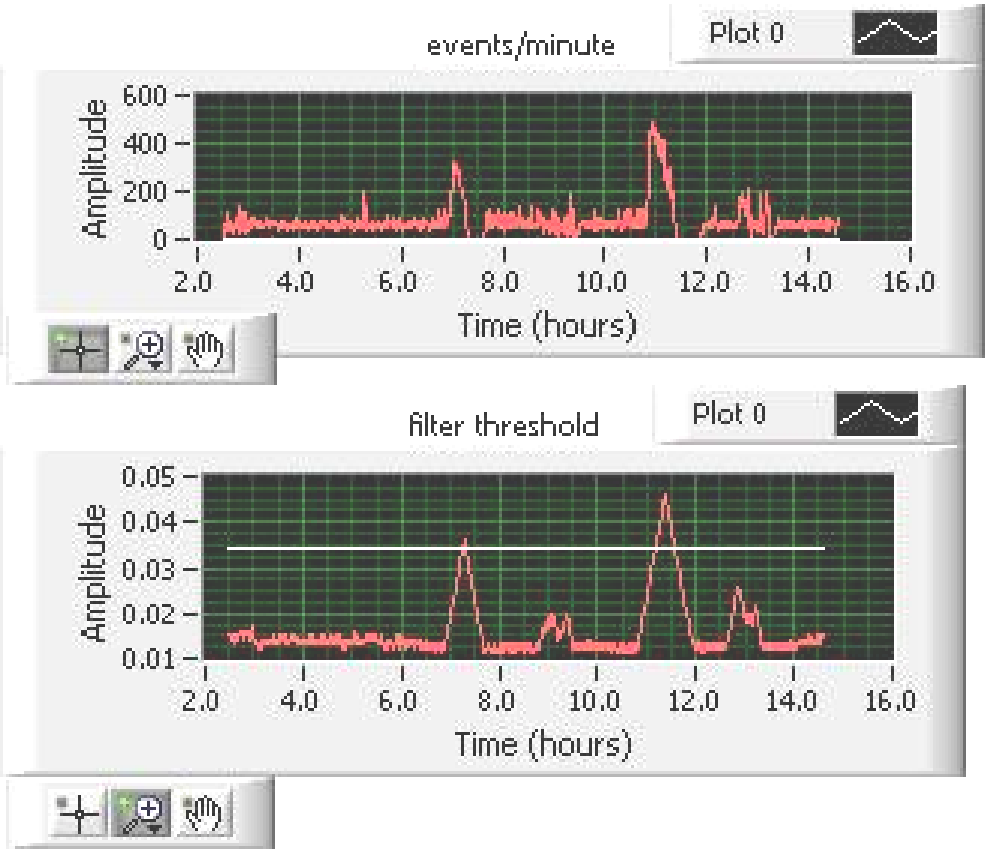
Simulated data

Image courtesy Nikolai Lehtinen

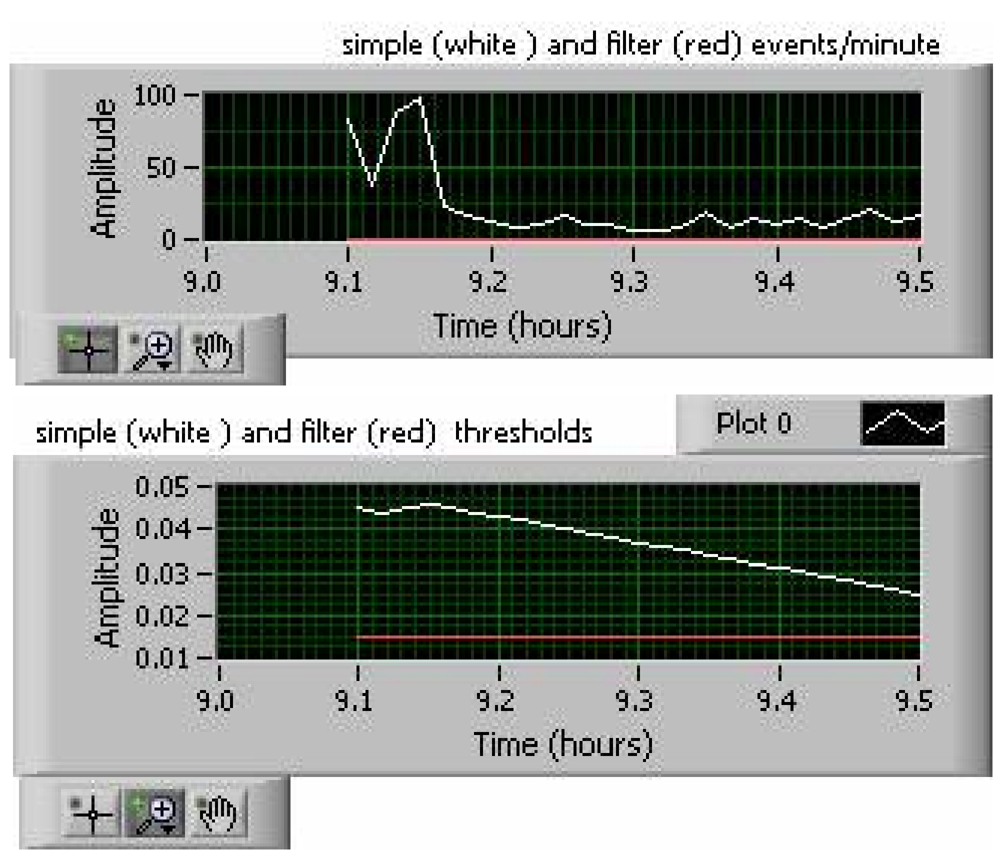


Filtered simulated data

Adaptive threshold



A typical run, from 2am to 2pm



The implosion calibration run

Data file format (one file/minute)

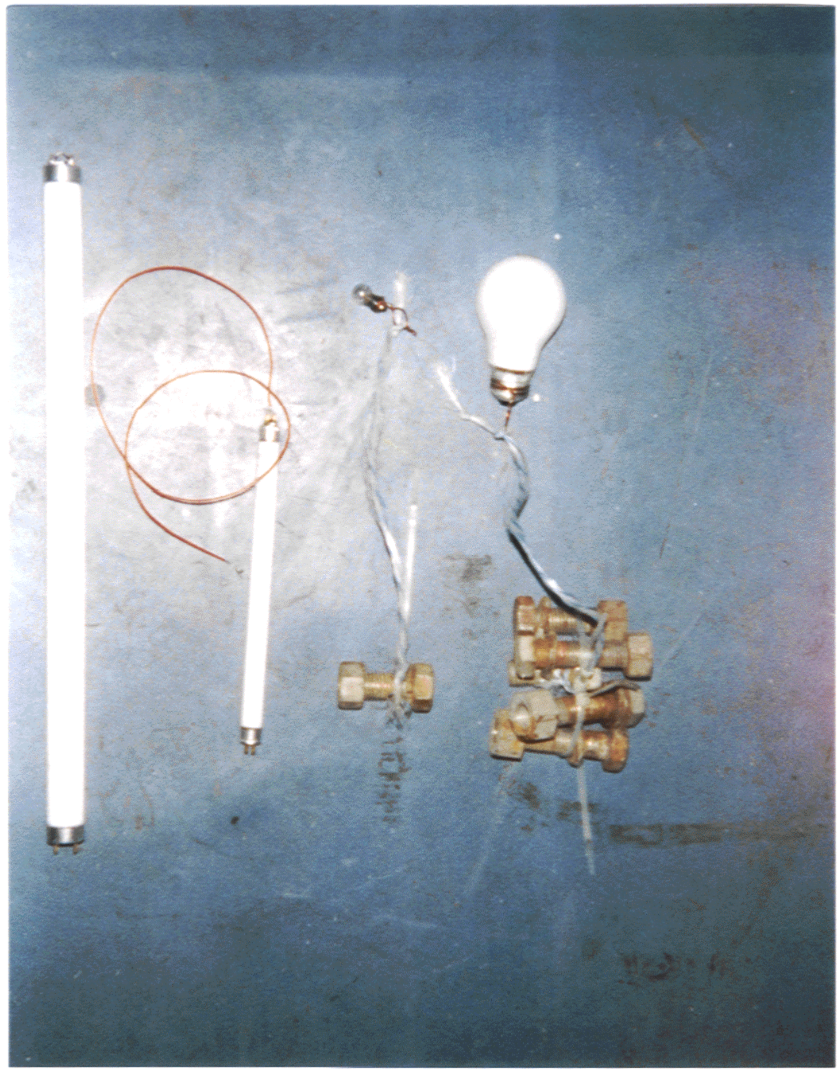
Data	Type	Size (bytes)
Minute Data		587838
thresholds (simple + filter)	2-element array of sgl	8
spectrum df	sgl	4
spectrum	2D array of sgl (512 x 7)	14344
trigger data (simple + filter):	2-element array of structs	42
on?	boolean	1
threshold	sgl	4
threshold step	sgl	4
target events/minute	I32	4
# events last minute	I32	4
overflows last minute	I32	4
raw data from first 0.l s	1D array of 20480 samples	573440
Event Data	60 evts * 5046 bytes =	302760
overflows since last event	I32	4
triggering index	I32	4
trigger type (simple or trigger)	boolean	1
triggering value	sgl	4
triggering channel	I8	1
time stamp	dbl	8
dt	sgl	4
raw data	2D array of sgl (179 x 7)	5020

TOTAL 890.598 KB * 60 minutes * 24 hours = 1.3 GB/ 24 hrs (after compression, fits on a CD-ROM)

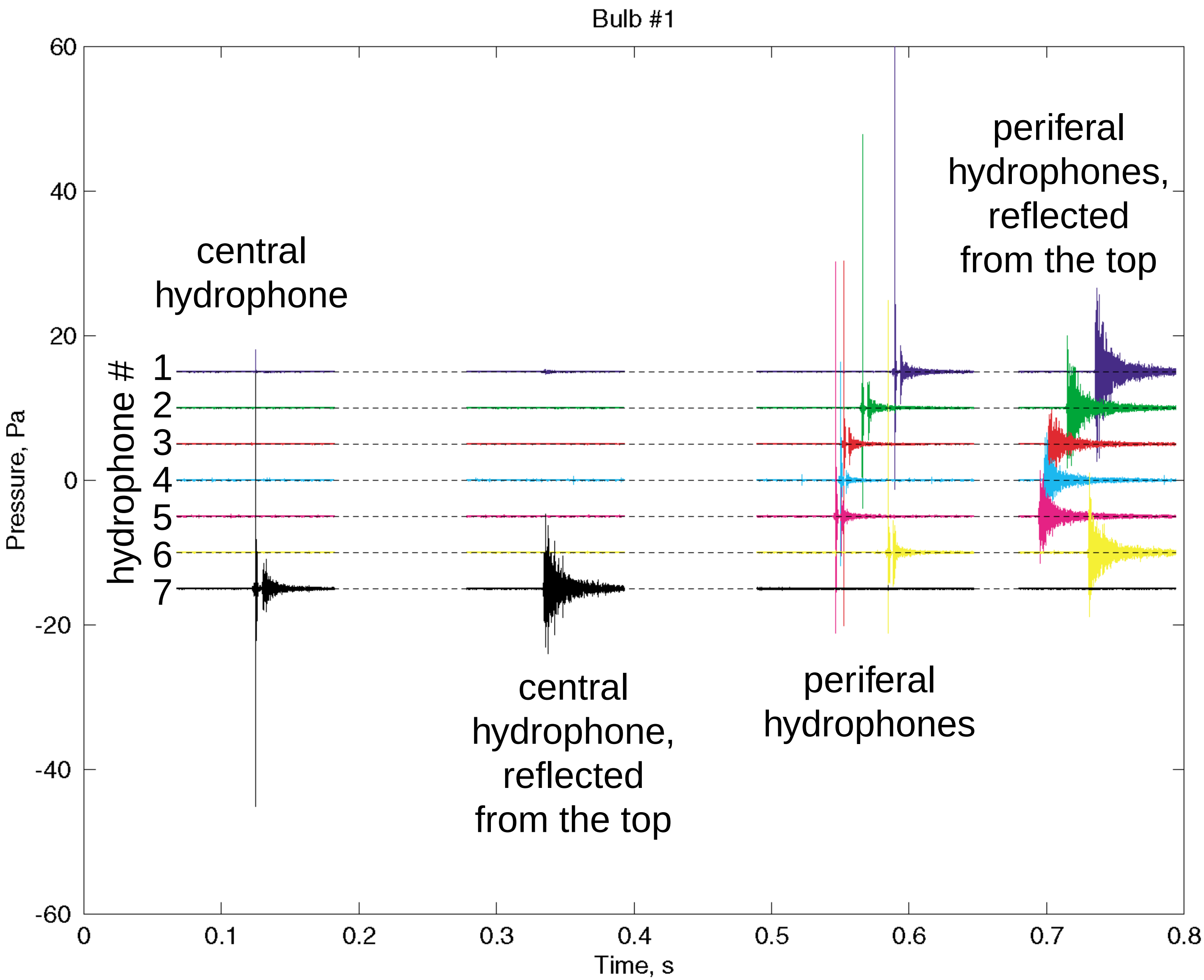
Current acquisition parameters

Hydrophones in use	1-7 (not 8)
Trigger type	filter
Target events/minute	60
Starting threshold	0.1
Threshold step	0.005
Capture duration / trigger	1 ms (179 samples)
Tau	10 μs
Response function samples	12
ADC limits	0.5 V
Sampling frequency	max: 1250 kHz / 7 channels = 179 kHz

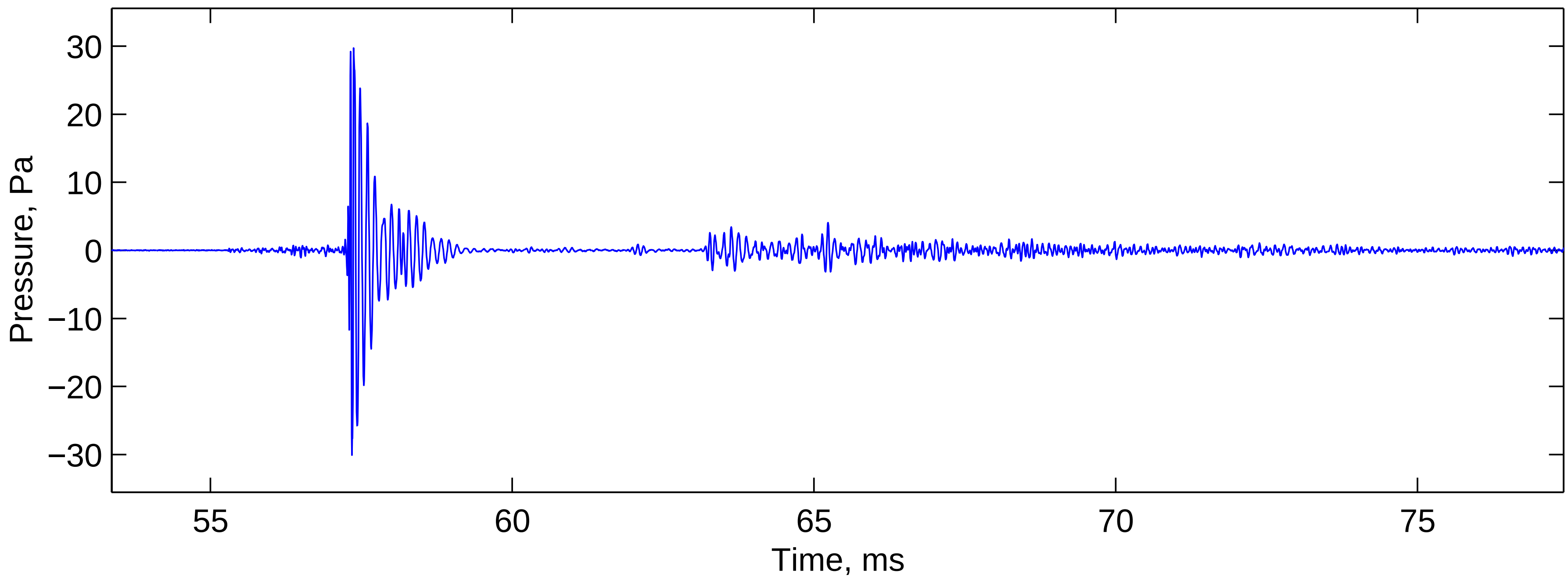
The calibration light bulbs

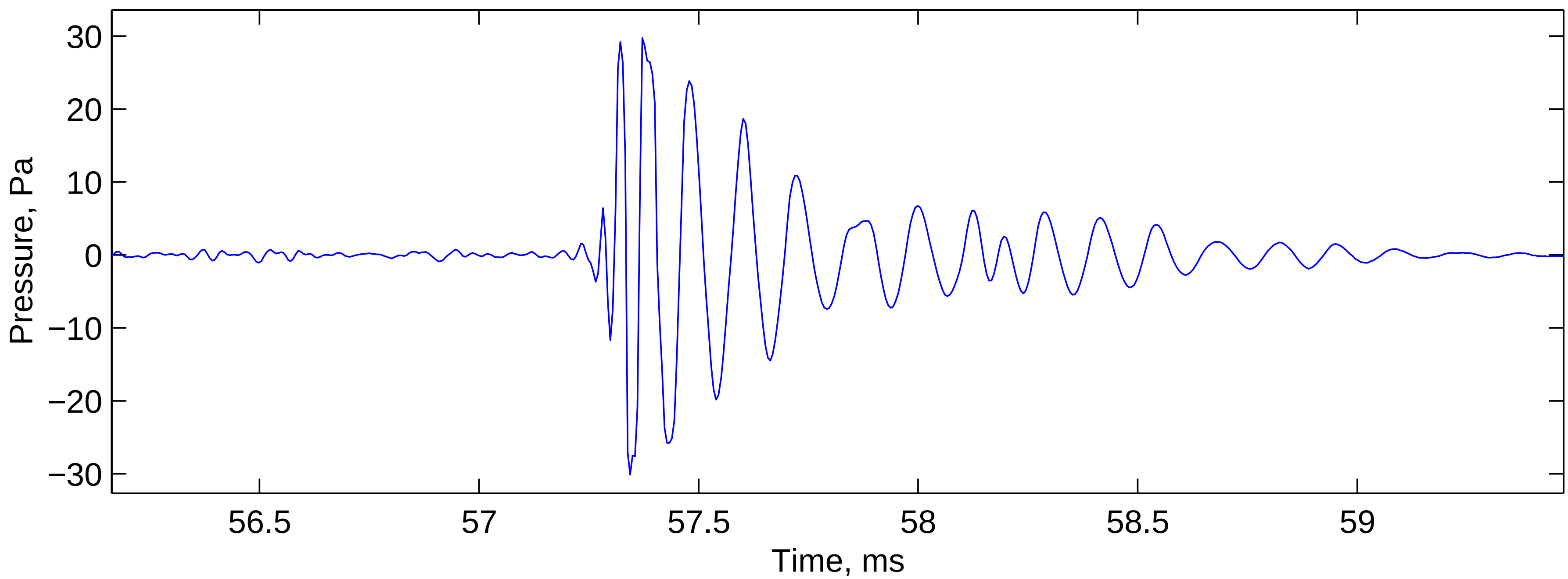


Lightbulb pressure data

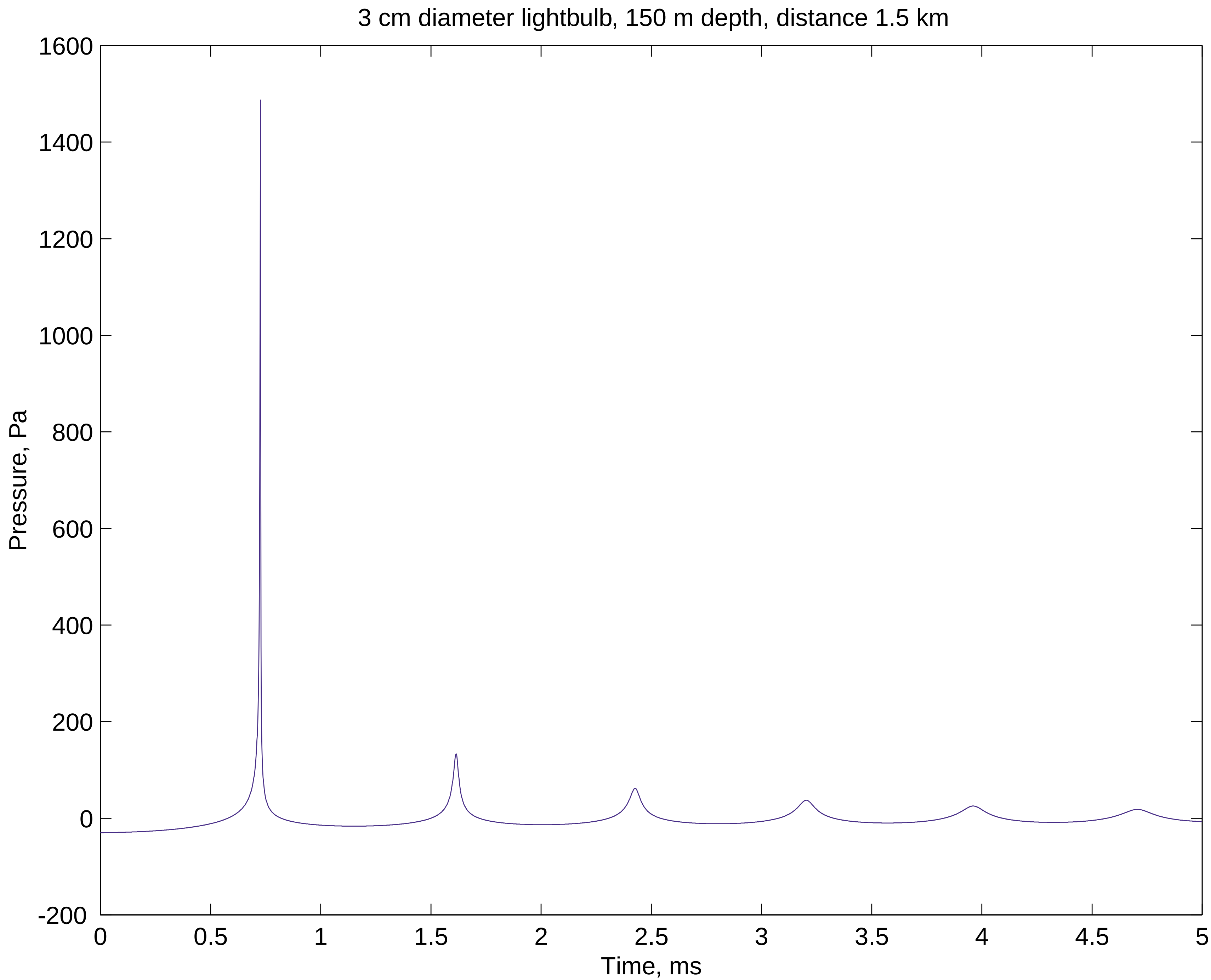


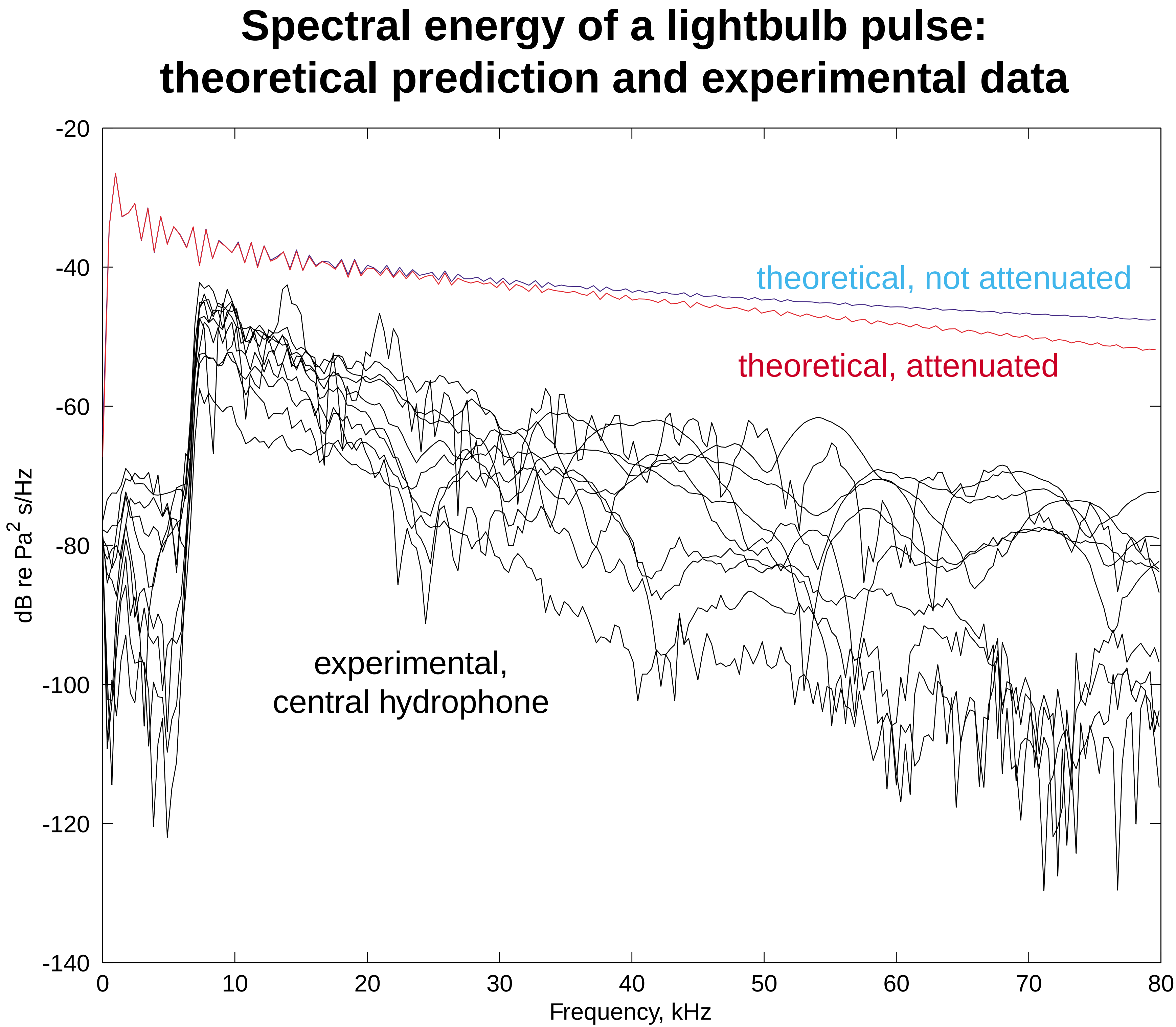
Close-up of the initial signal



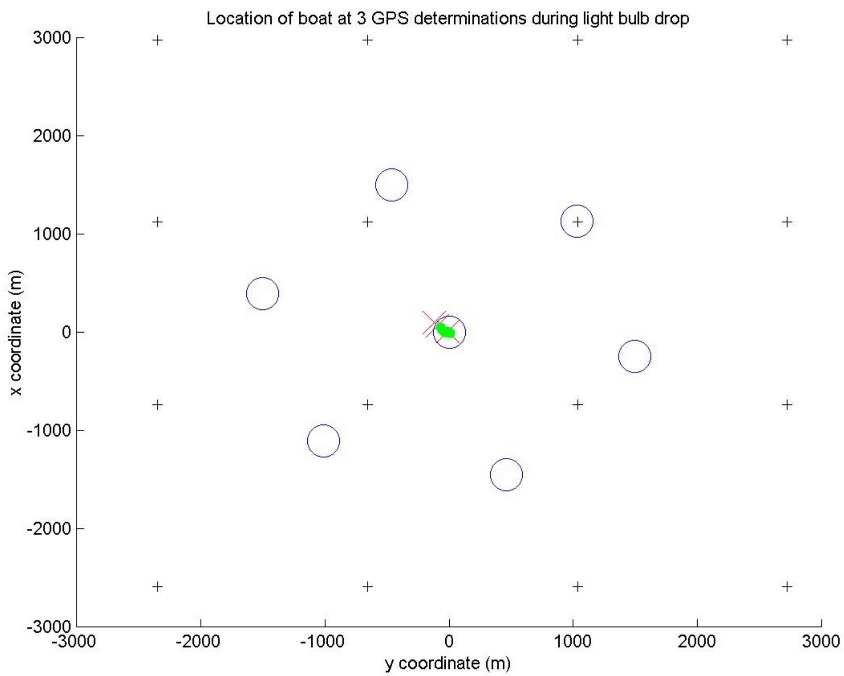


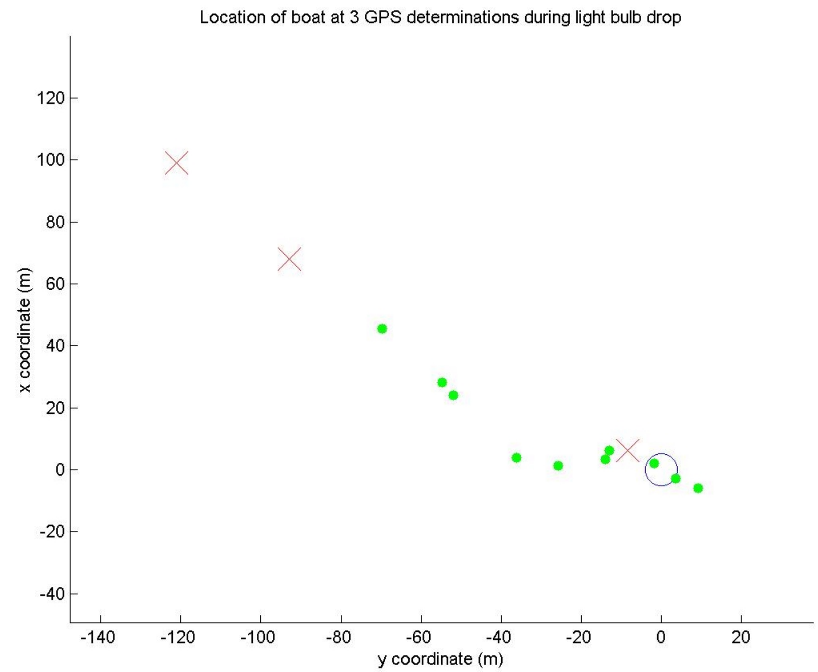
Theoretical calculation of a pulse from a lightbulb implosion




Spectral energy of a lightbulb pulse:
theoretical prediction and experimental data
theoretical, not attenuated
theoretical, attenuated
experimental,
central hydrophone
dB re Pa^2 s/Hz
Frequency, kHz
-20
-40
-60
-80
-100
-120
-140
0
10
20
30
40
50
60
70
80

Boat (GPS) and bulb (reconstructed) coordinates

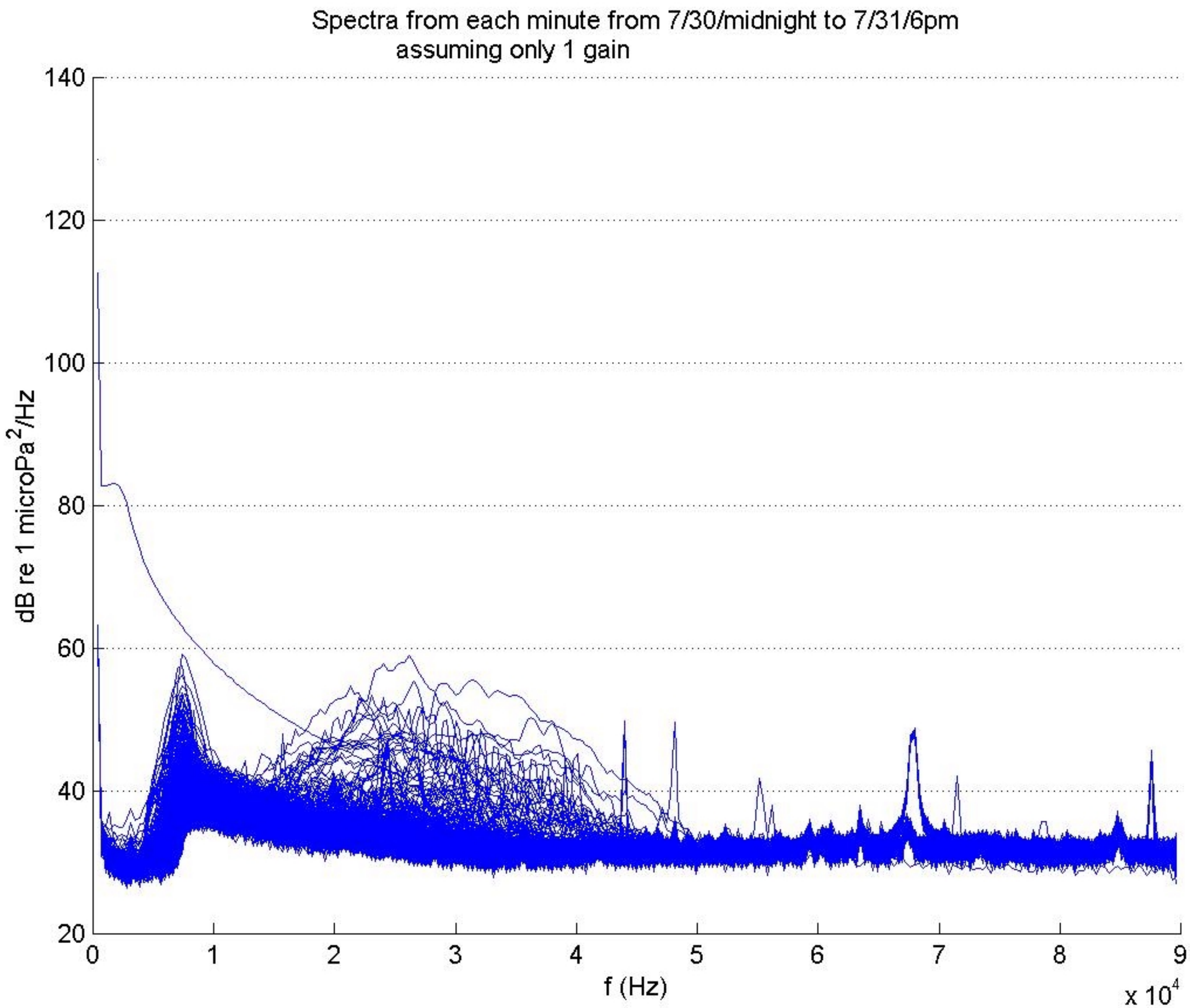




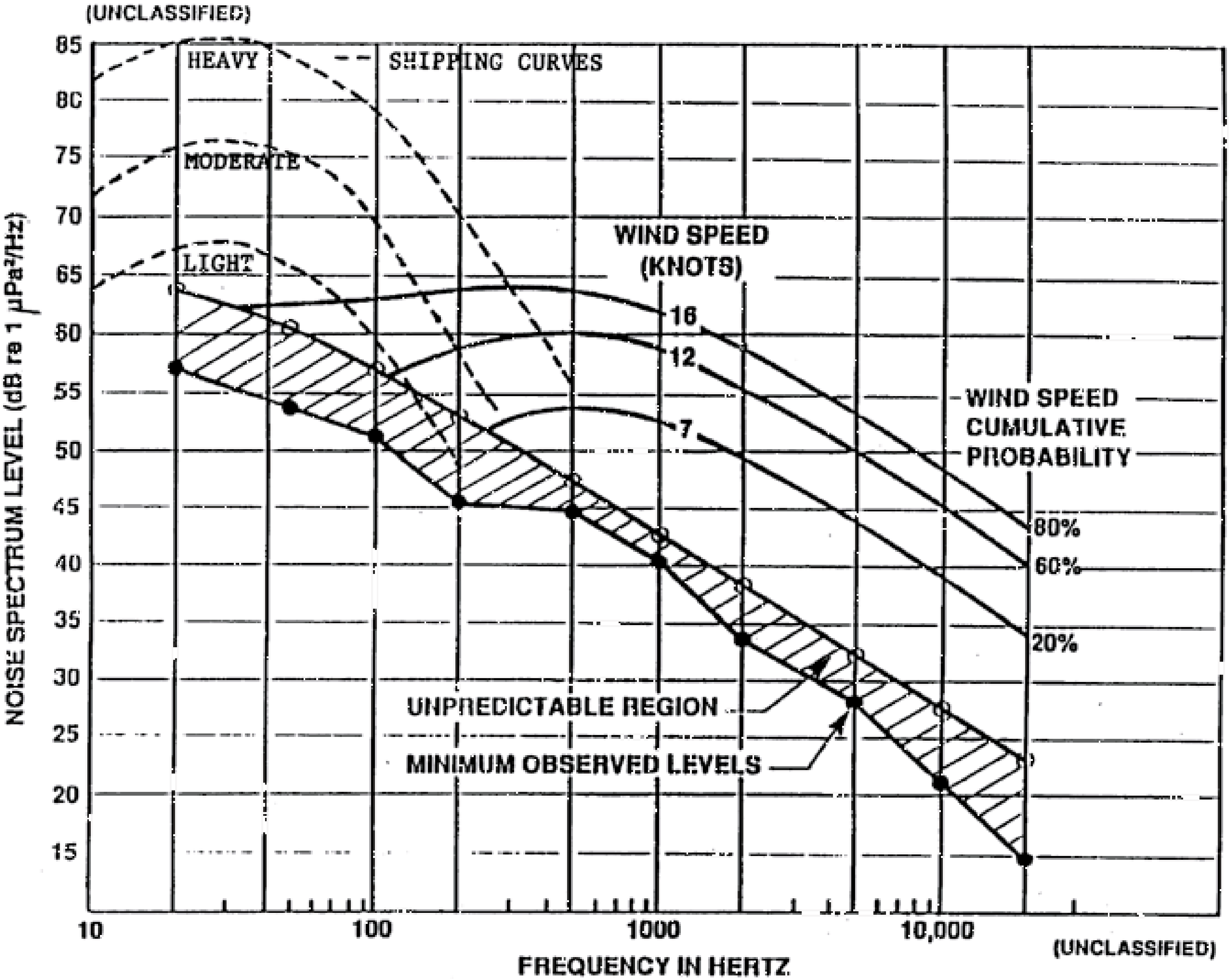
Reconstructed implosion depths

bulb	depth (m)	P (kPa)	E0 (J)
1	160	1563	234
2	107	1047	157
3	139	1360	204
4	166	1626	244
5	126	1237	186
6	101	990	148
7	86	838	126
8	135	1324	199
9	188	1842	276
10	290	2846	427

Spectra from every minute for two days

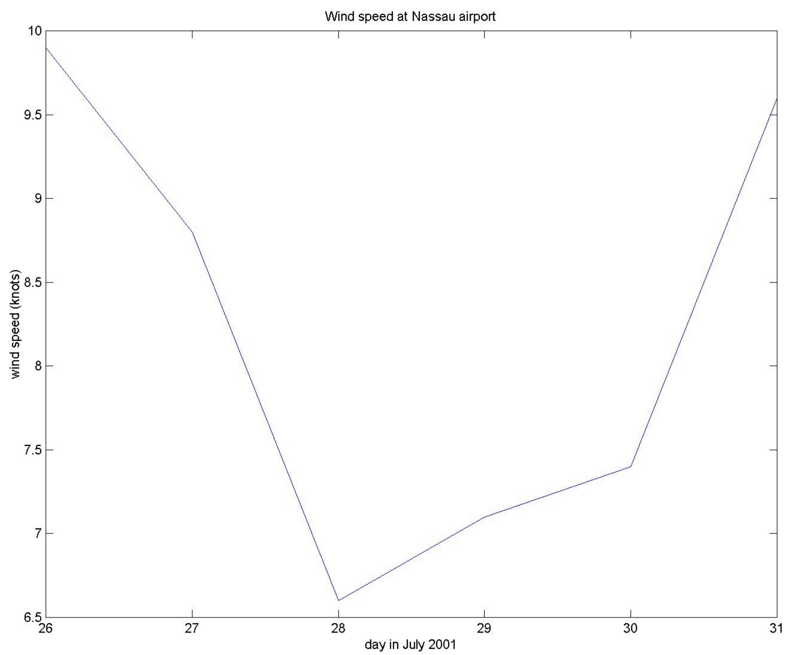


AMBIENT NOISE LEVELS AT AUTEC, TOTO, BAHAMAS

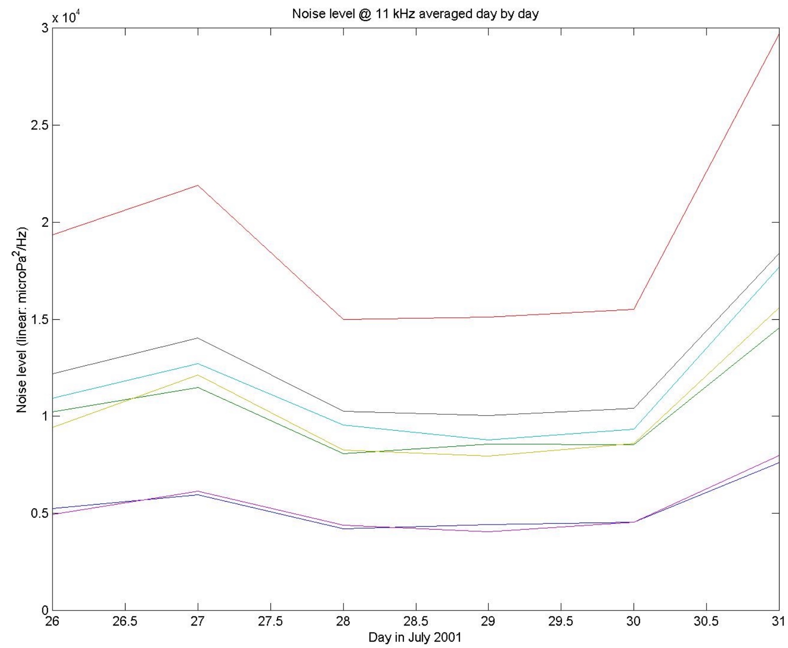


Wind and Noise

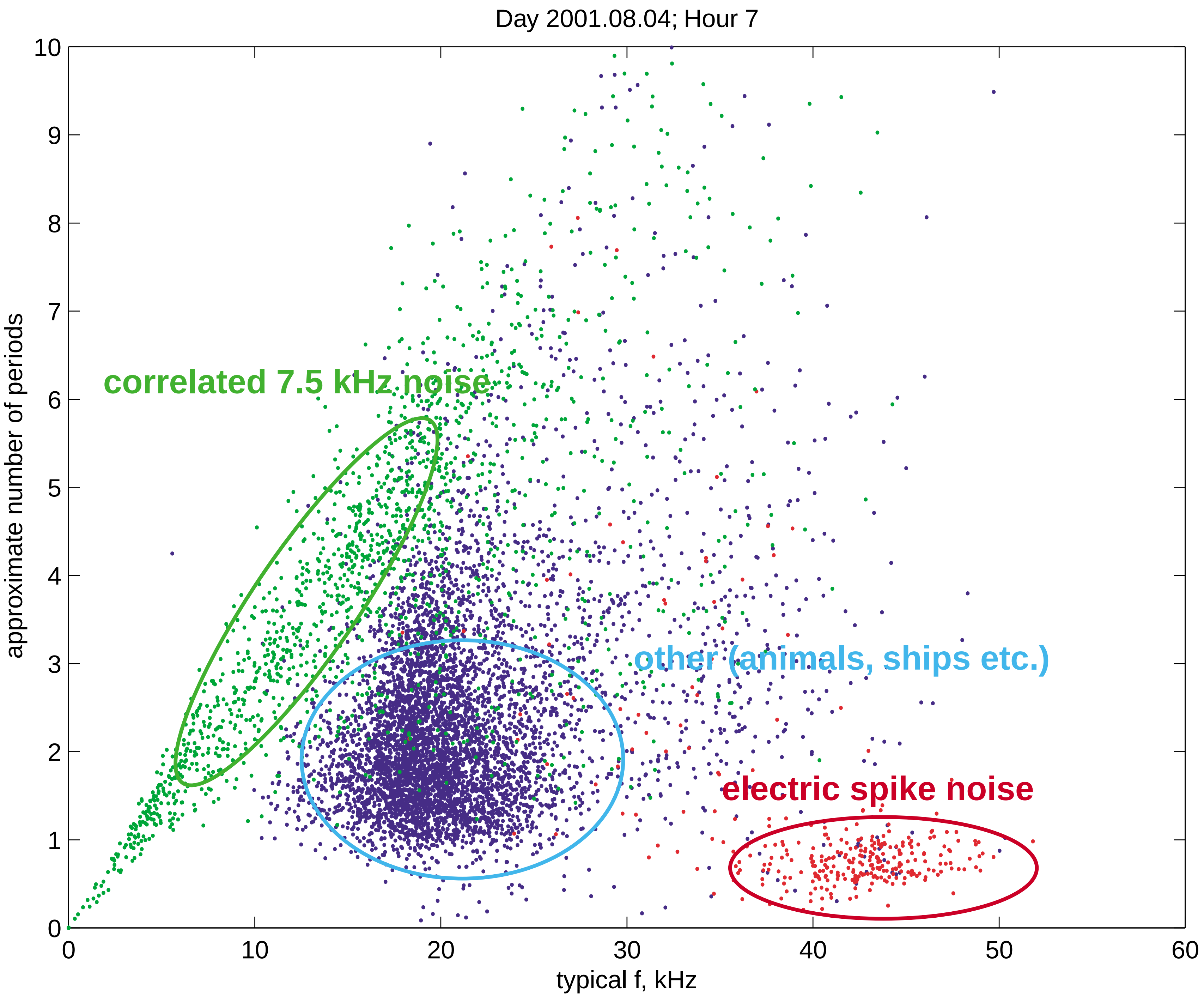
Wind speed at Nassau airport



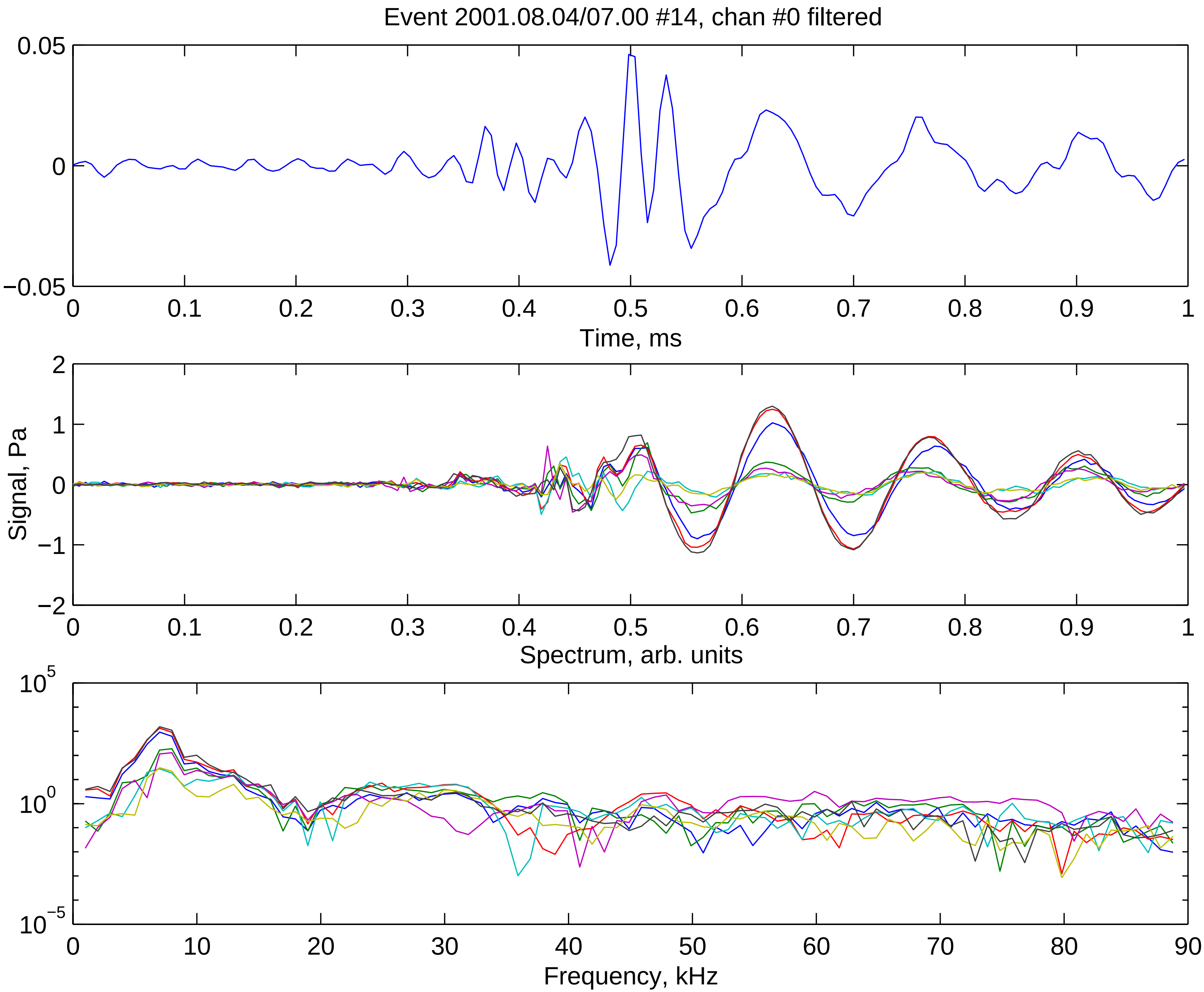
Noise at each phone



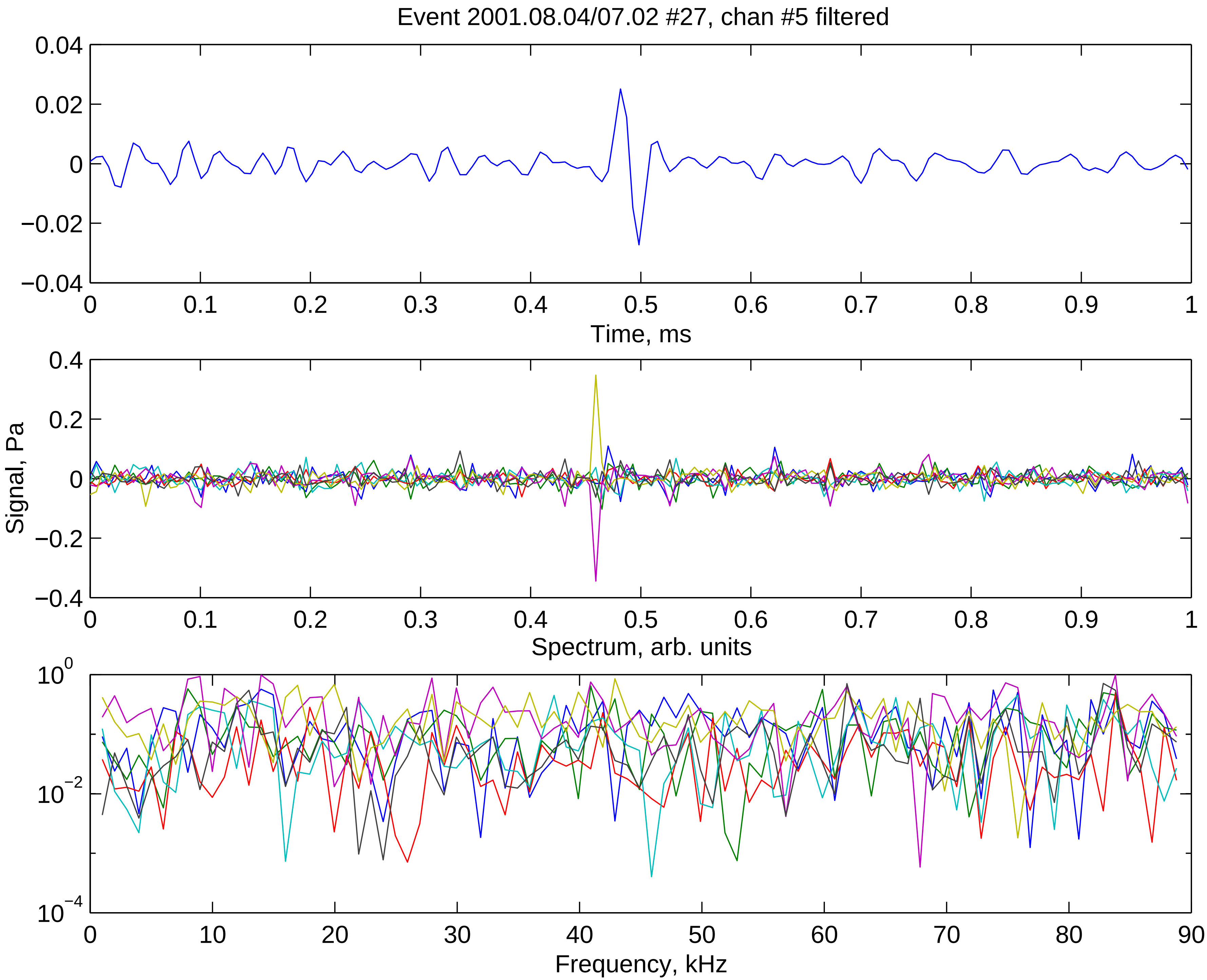
Basic classification of events



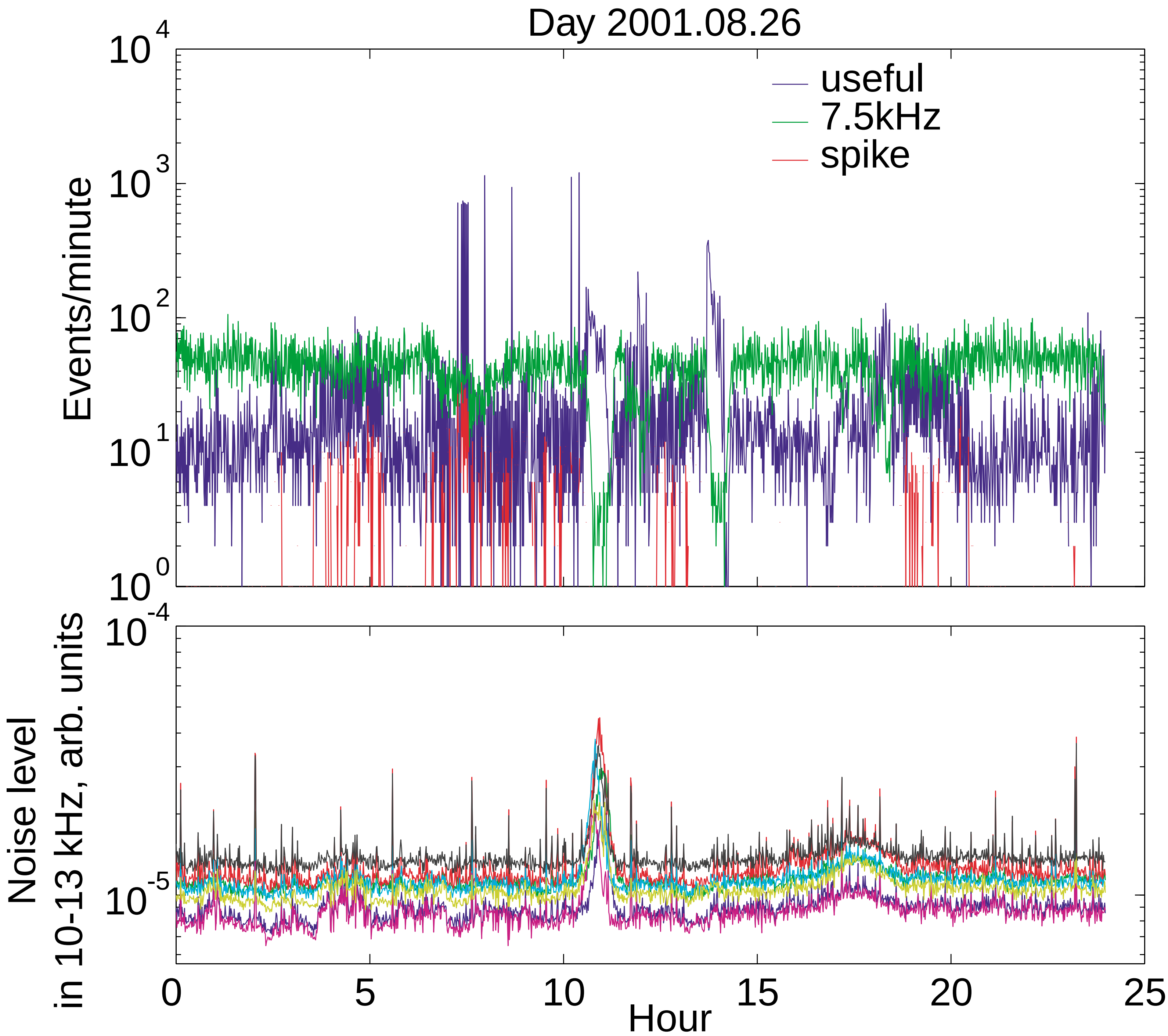
Correlated noise at 7.5 kHz



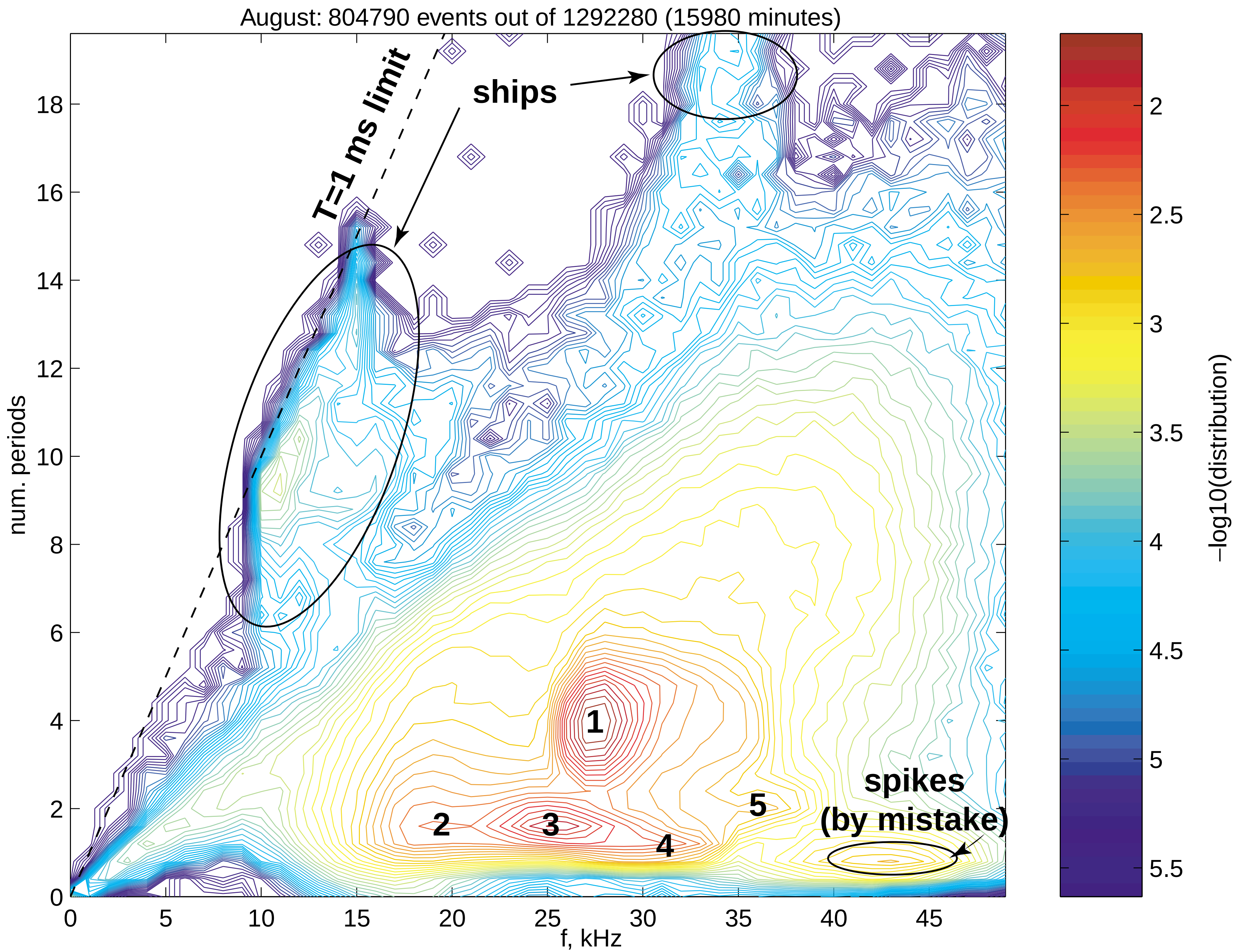
Electric spikes (generated in the DAQ card)



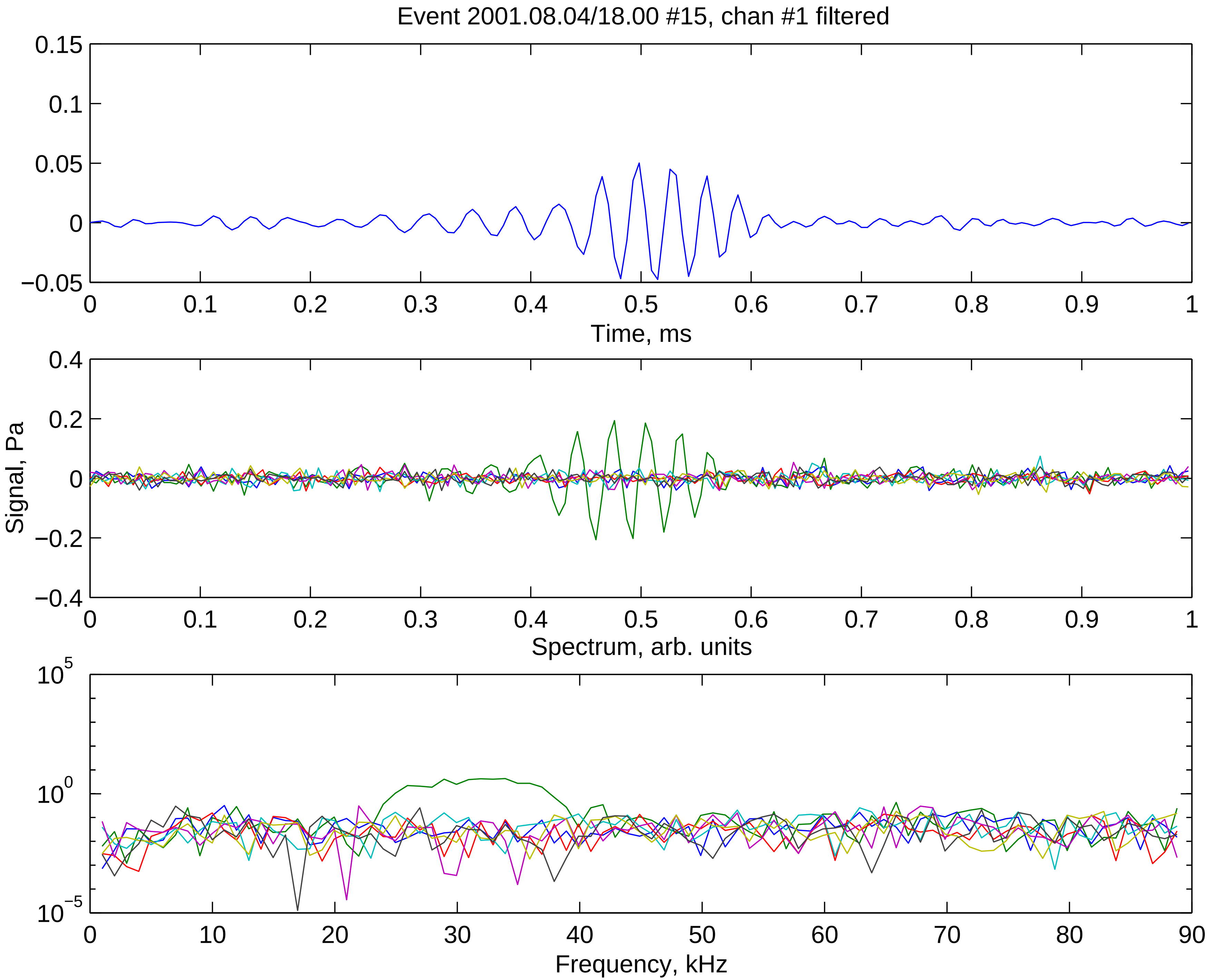
Relative content of acoustic ("useful") and non-acoustic events



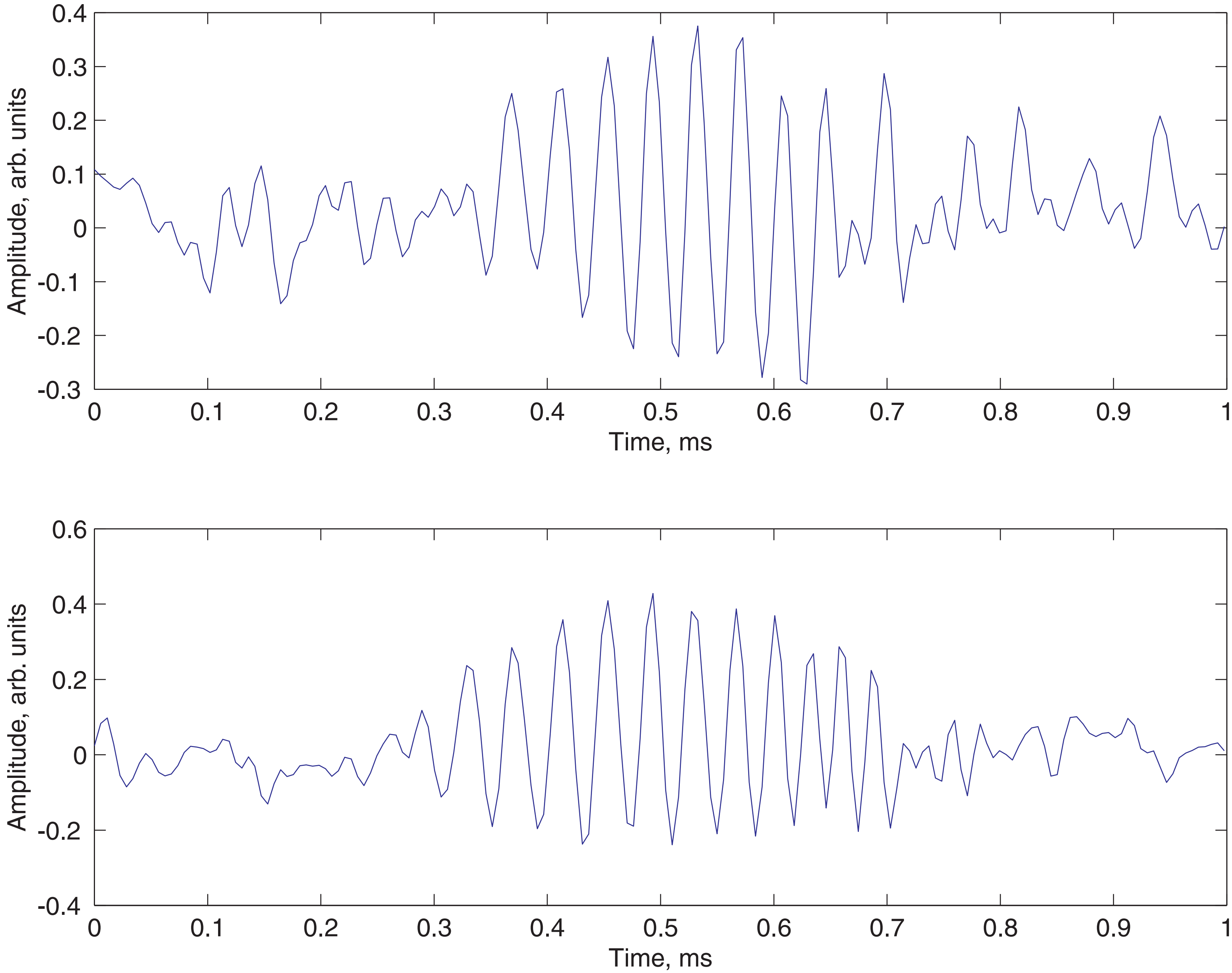
August: *frequency* vs *number of periods* distribution of "useful" events.



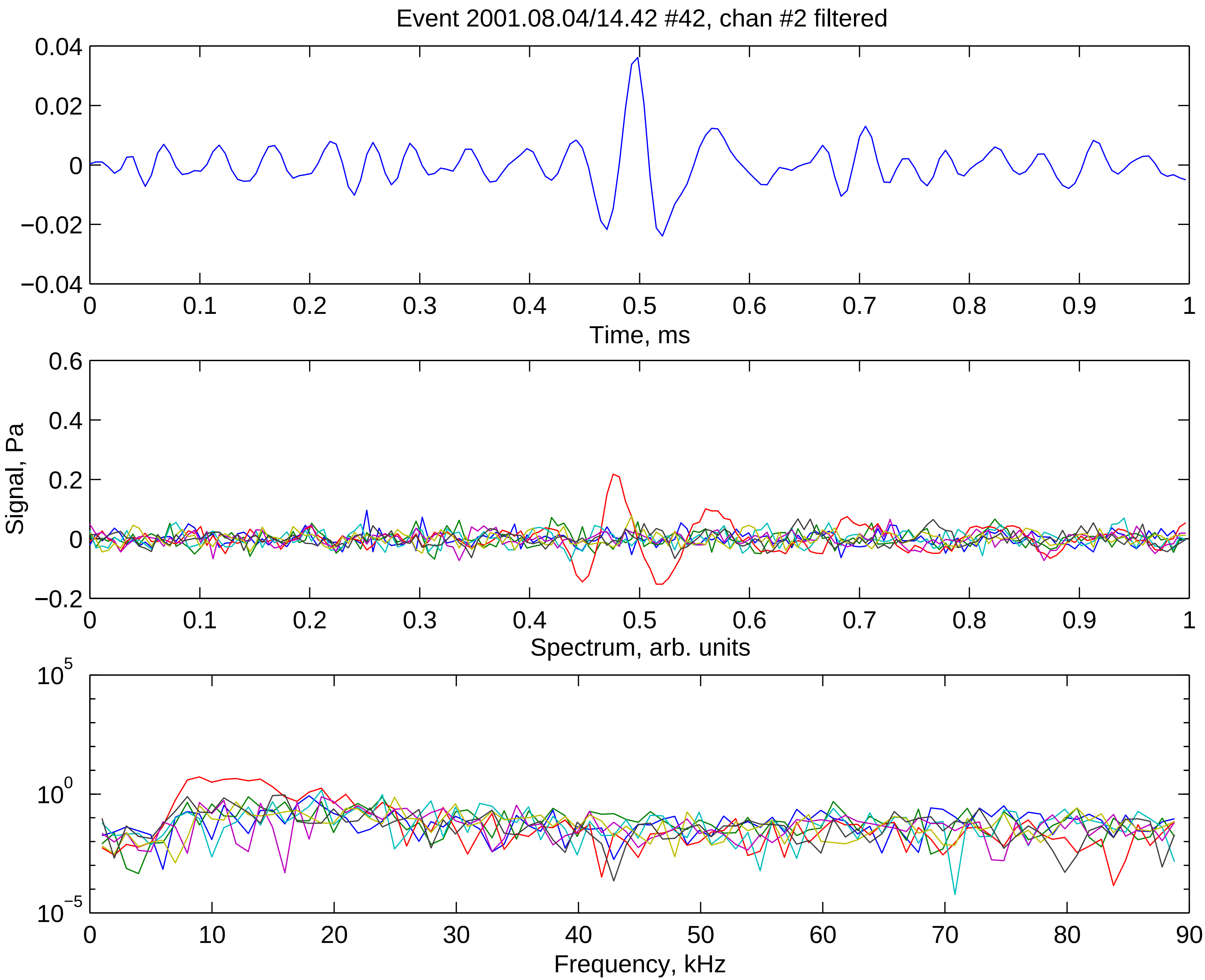
Example of event 1



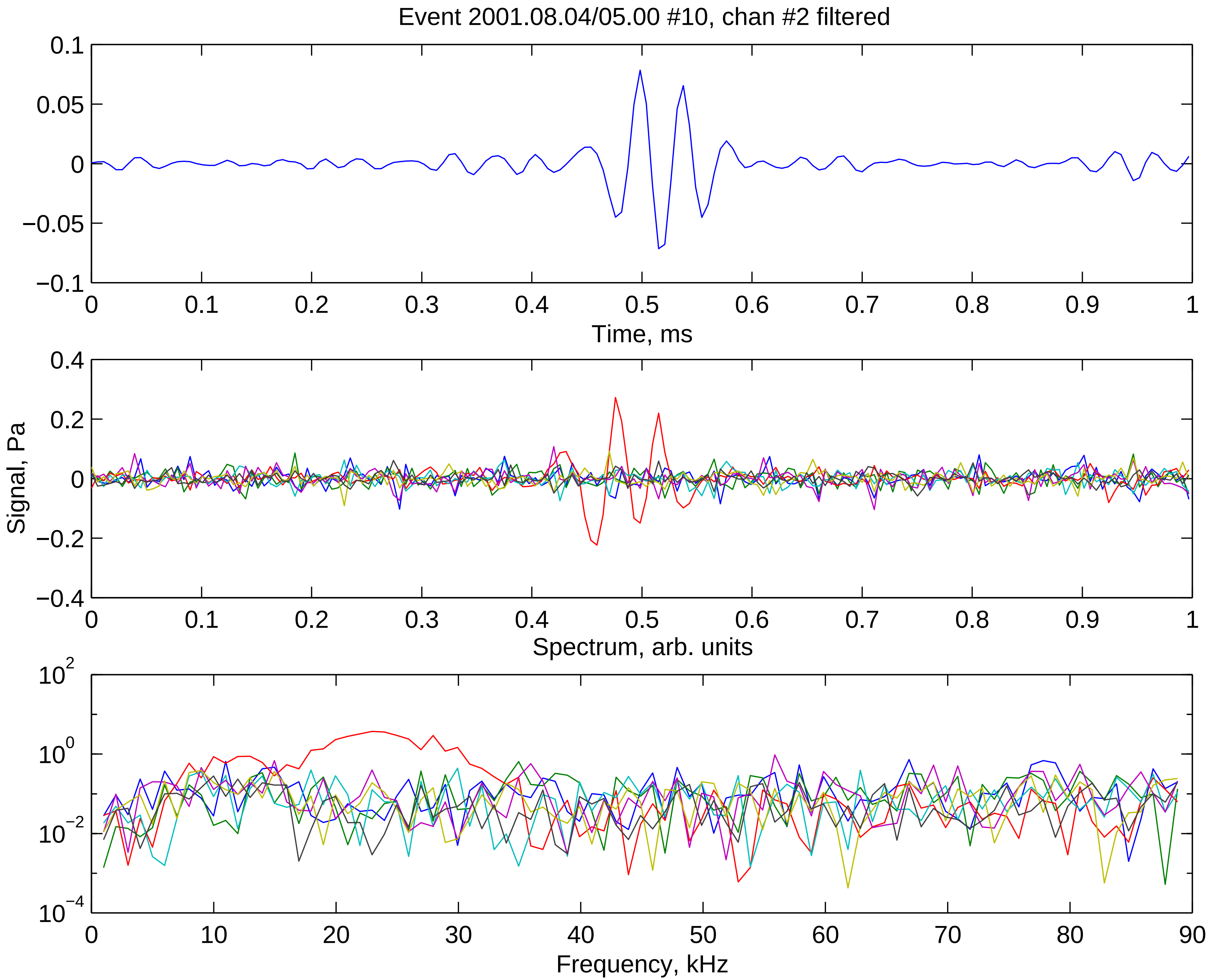
Examples of dolphin signals recorded by AUTEC personnel

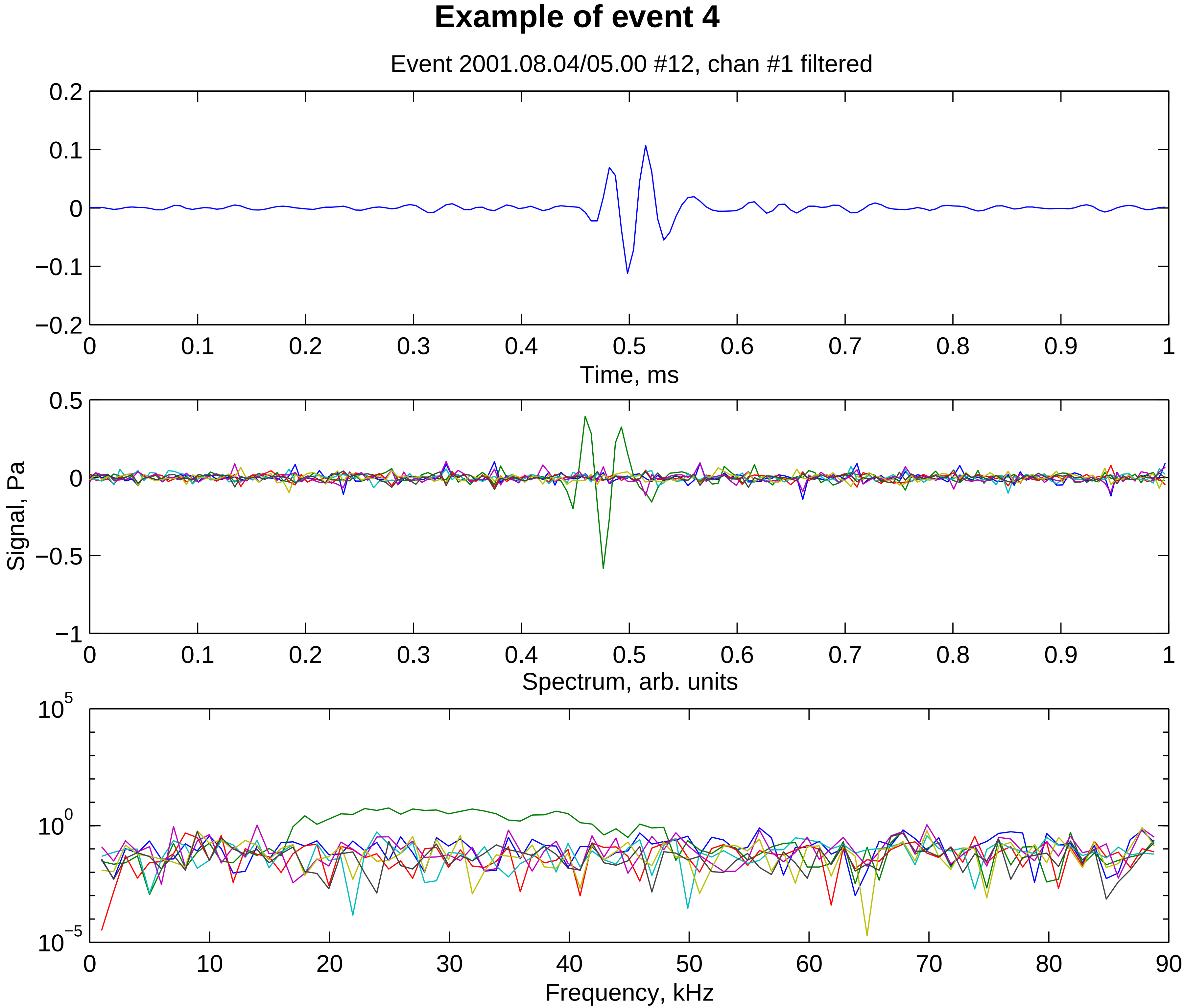


Example of event 2

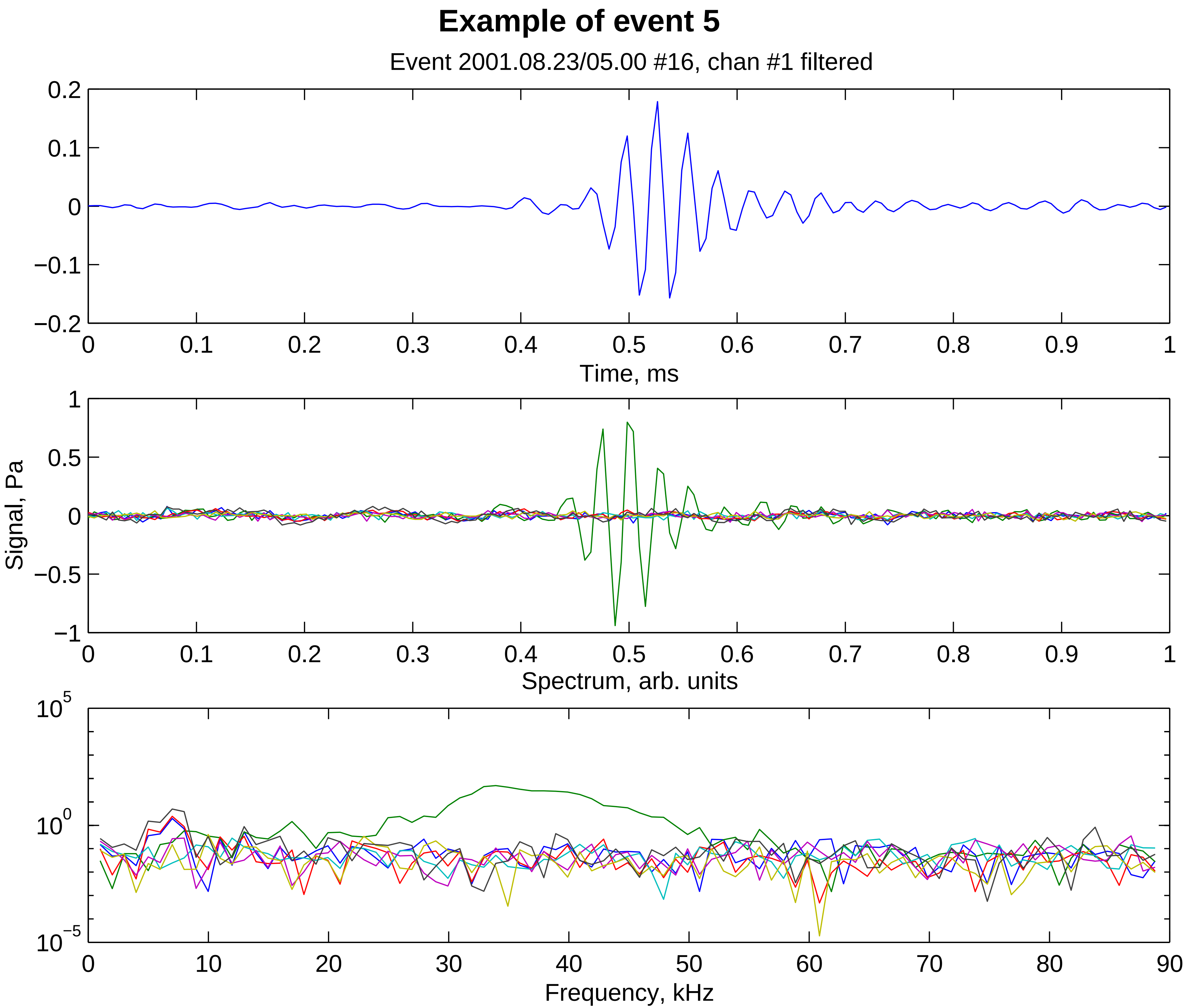


Example of event 3



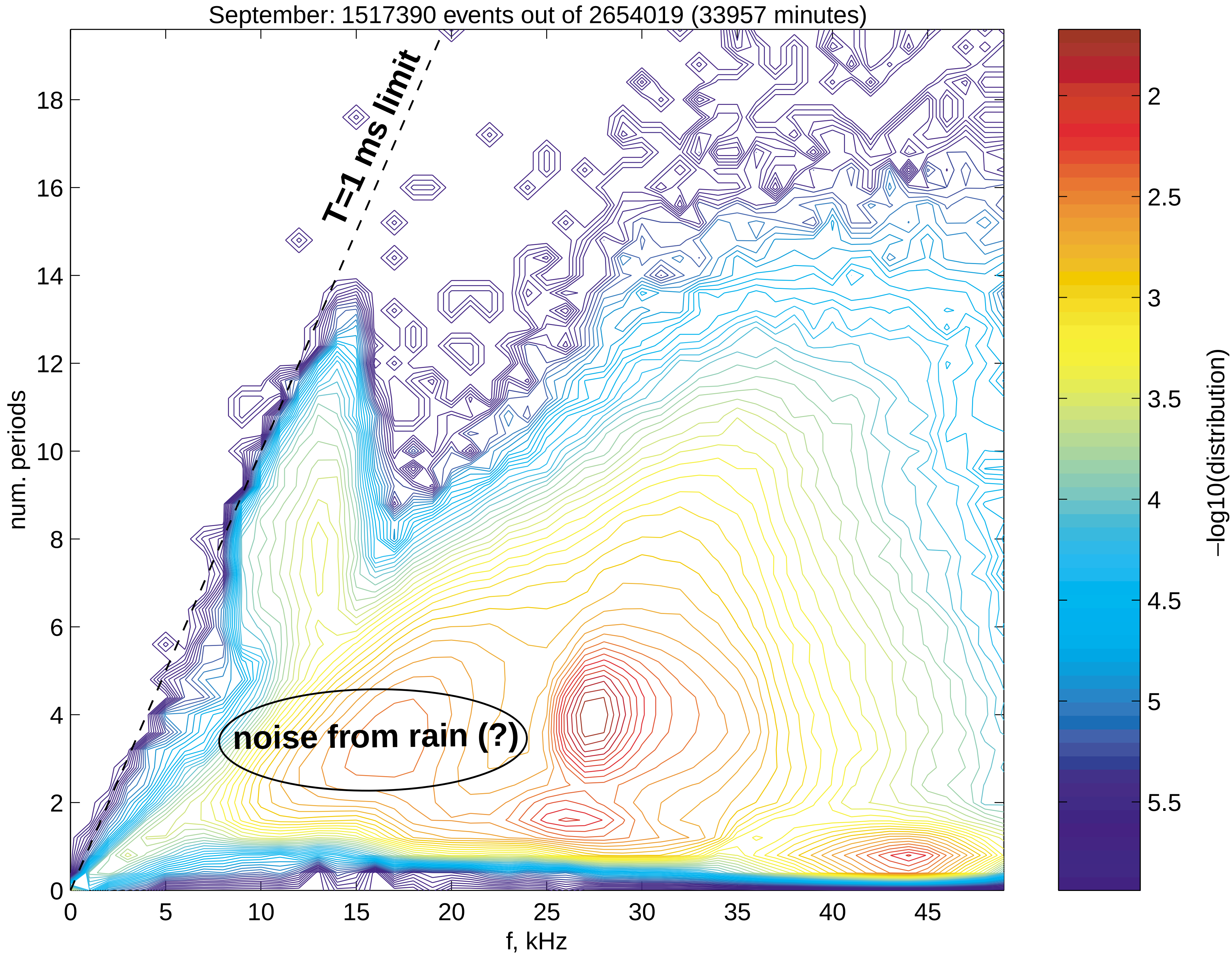


Example of event 4
Event 2001.08.04/05.00 #12, chan #1 filtered
0.2
0.1
0
−0.1
−0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time, ms
Signal, Pa
0.5
0
−0.5
−1
Spectrum, arb. units
10^5
10^0
10^{-5}
0
10
20
30
40
50
60
70
80
90
Frequency, kHz

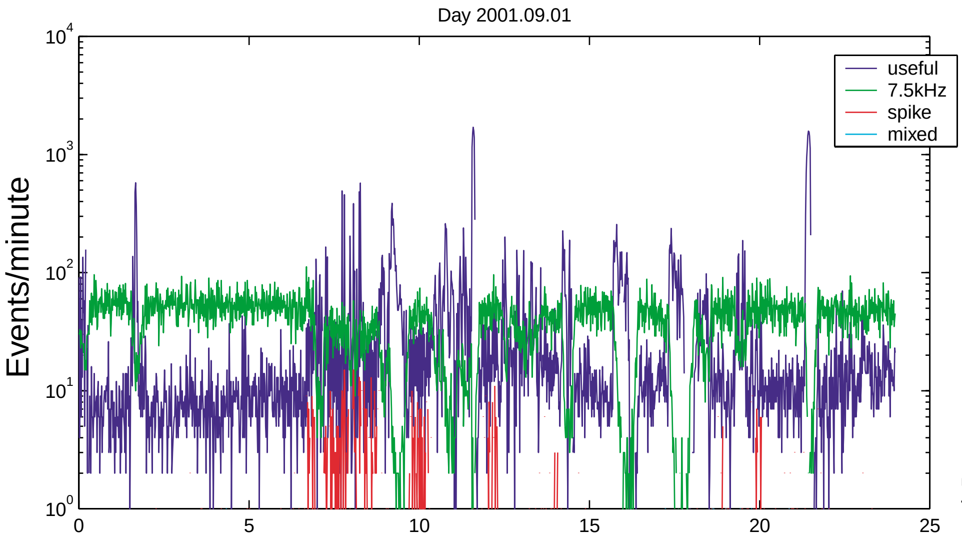


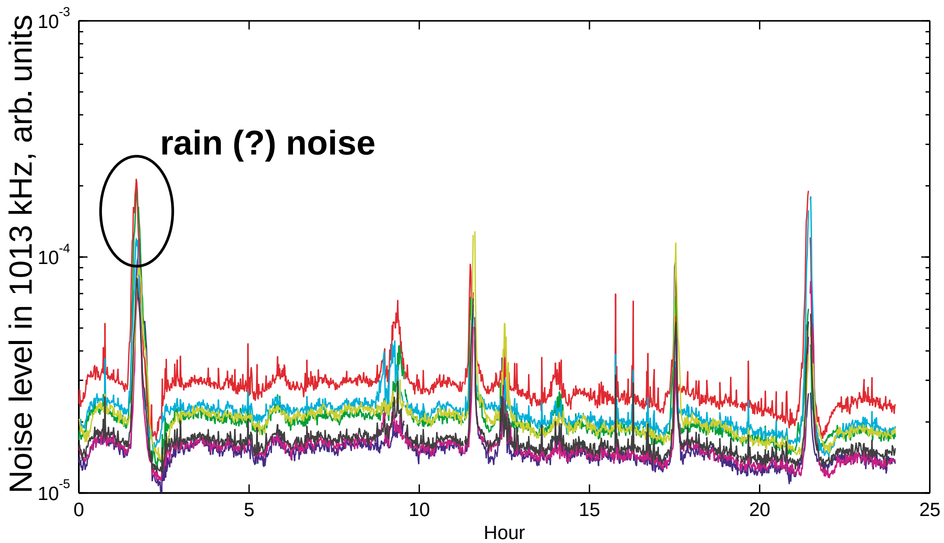
Example of event 5
Event 2001.08.23/05.00 #16, chan #1 filtered
Time, ms
Signal, Pa
Spectrum, arb. units
Frequency, kHz

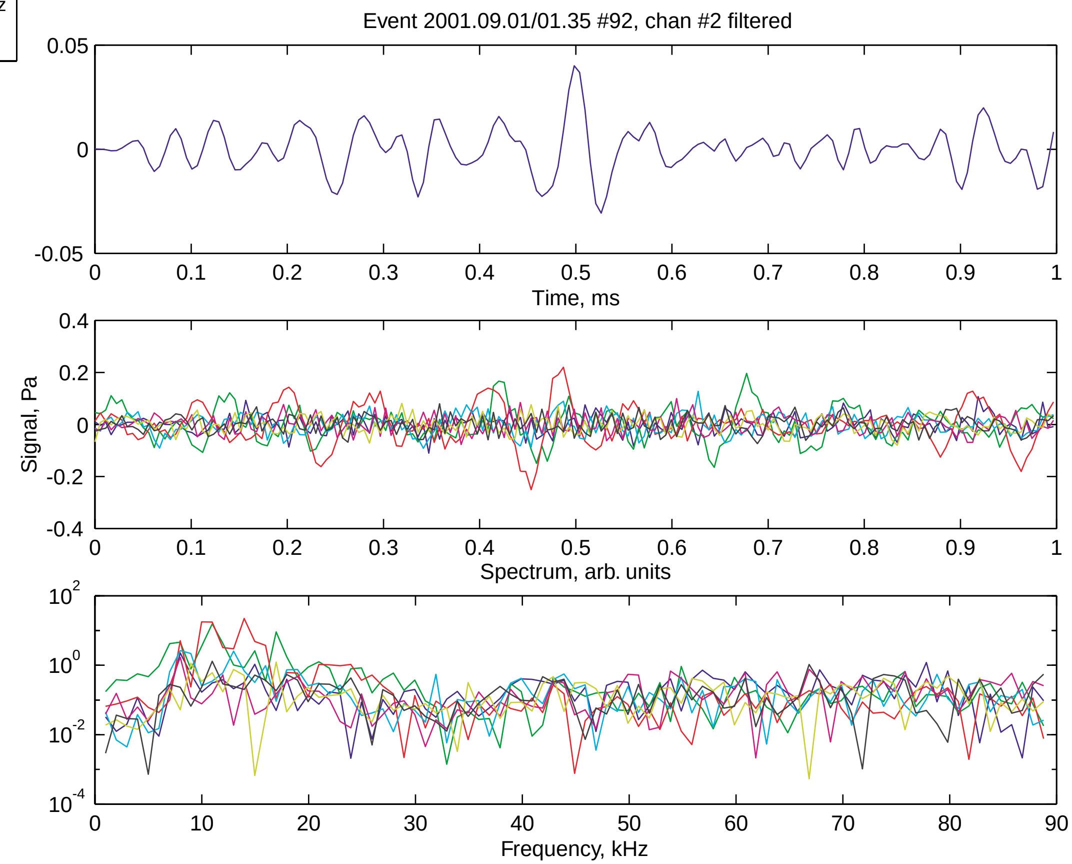
September: *frequency* vs *number of periods* distribution of "useful" events.



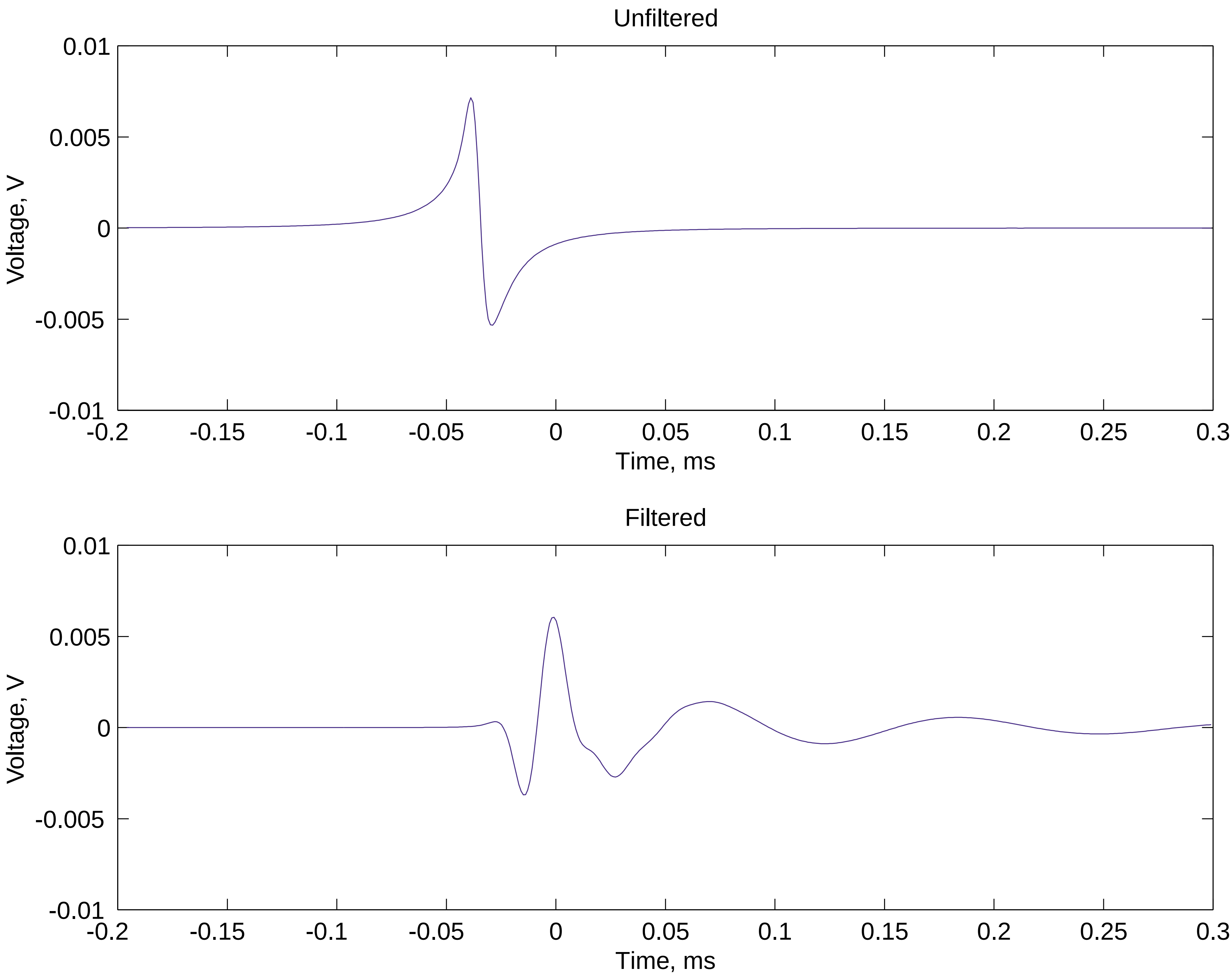
Rain (?) signals



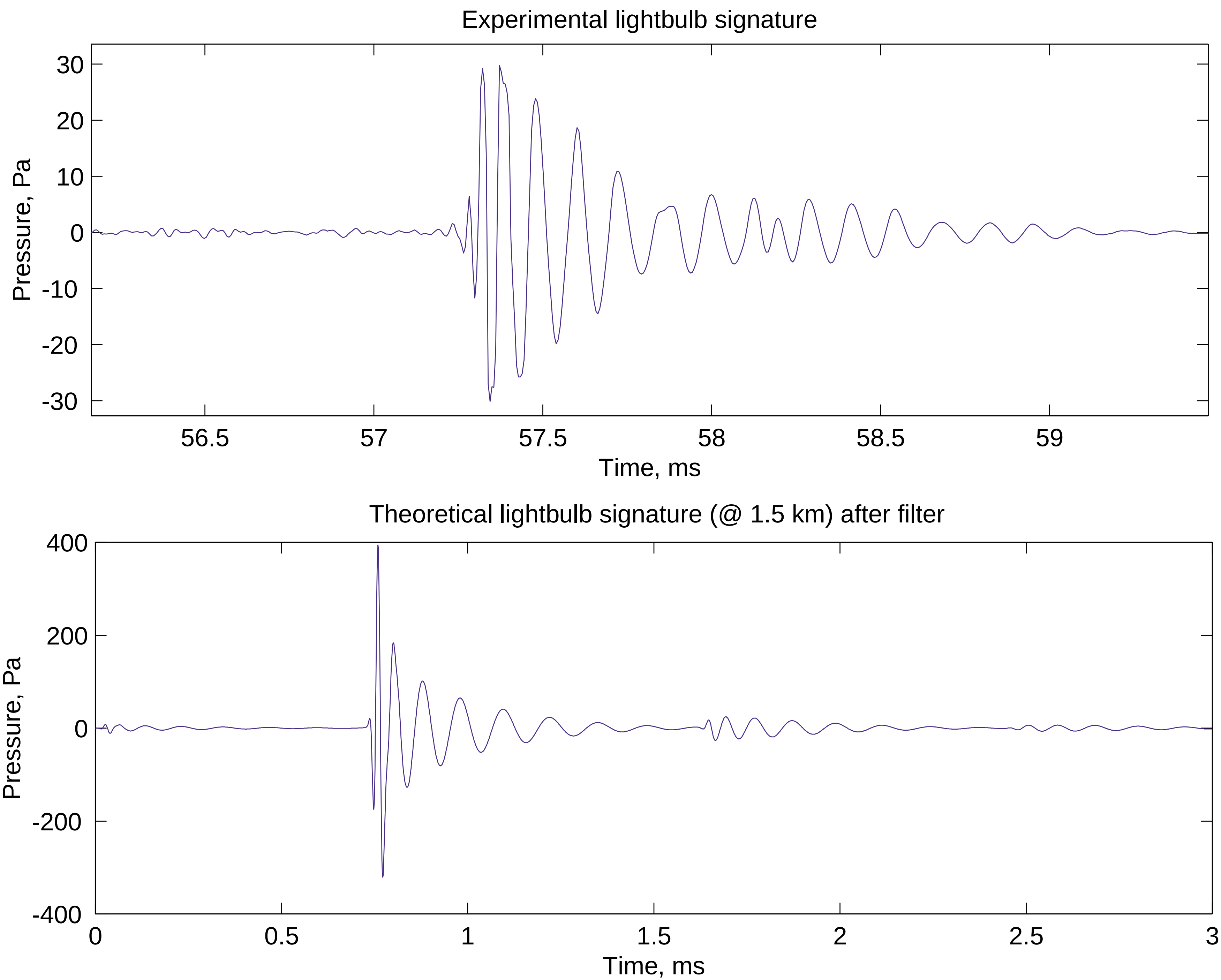




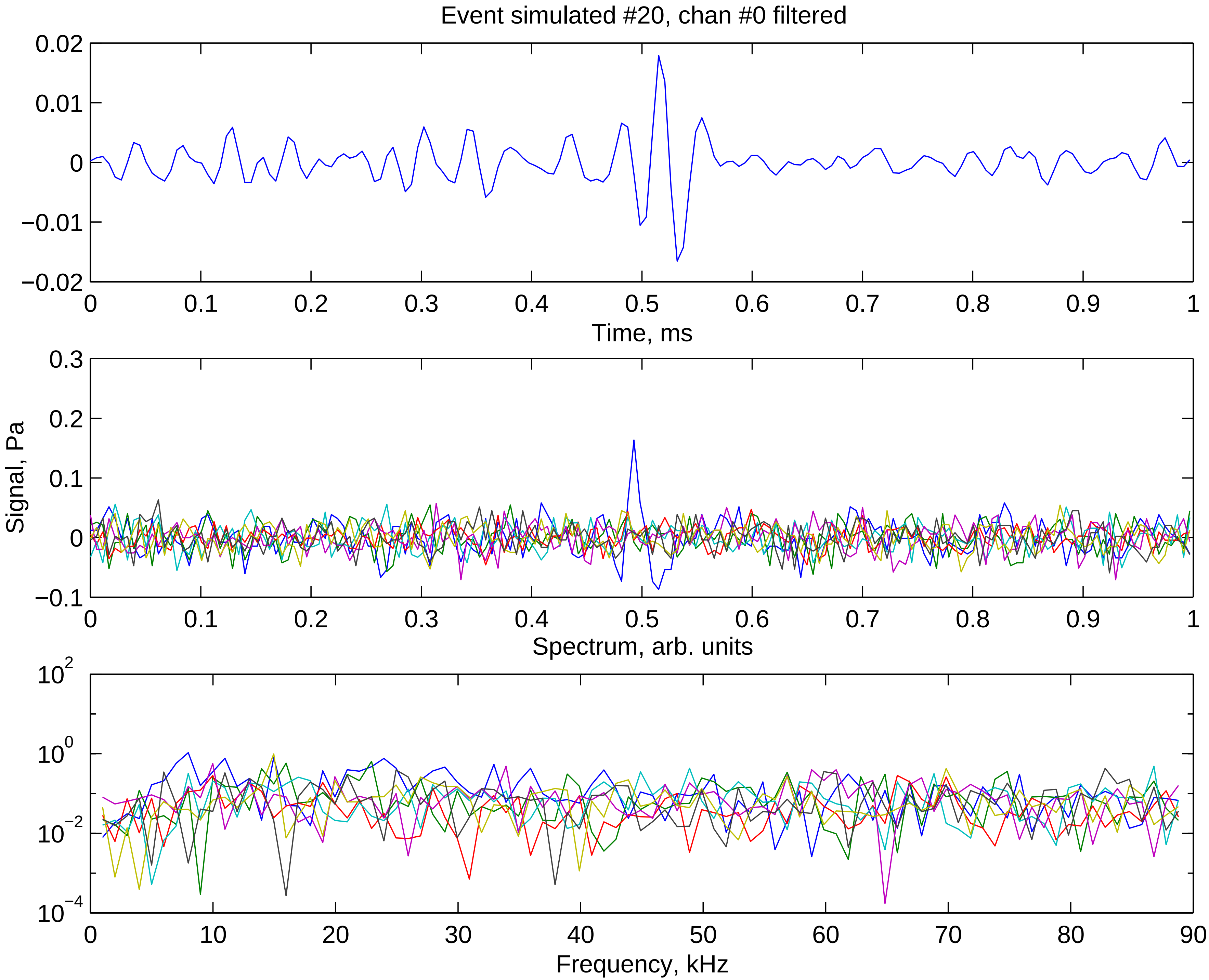
UHE neutrino signature after AUTEC hydrophone filter



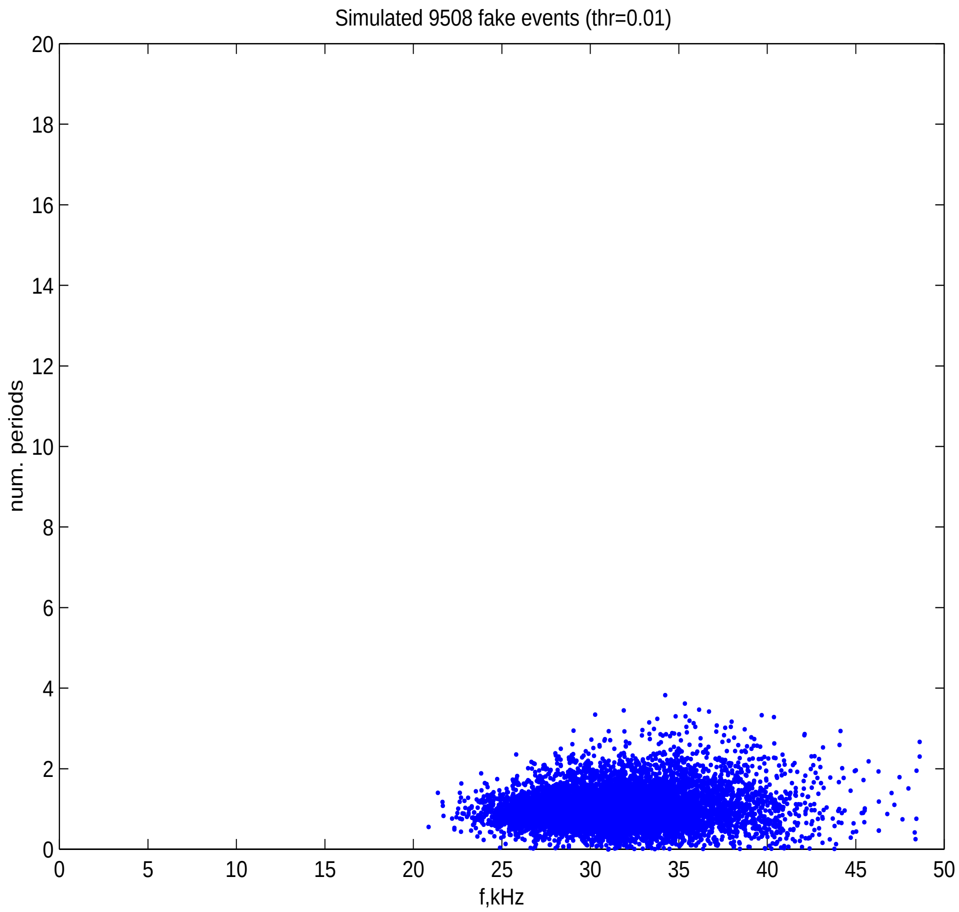
Theoretical lightbulb signature (@ 1.5 km) after filter

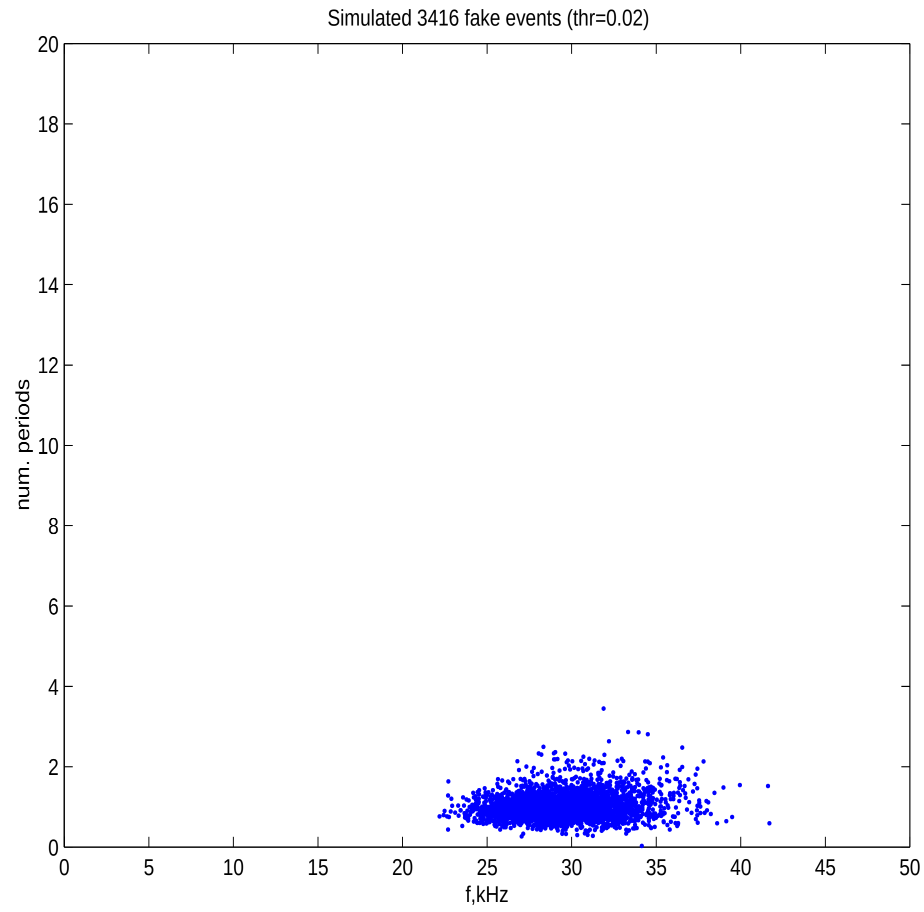


Simulated event

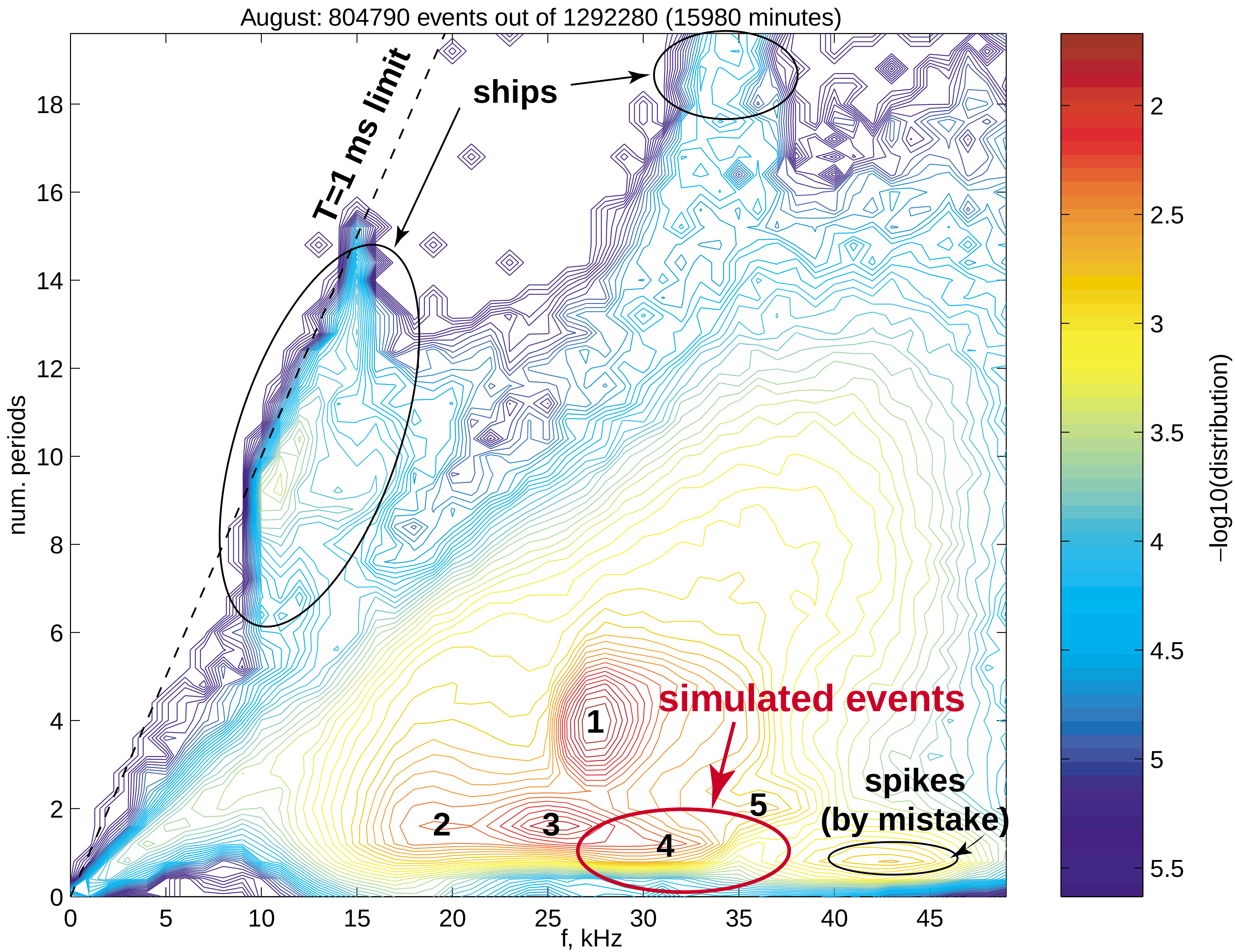


Frequency vs *number of periods* distribution of simulated events.





August: *frequency* vs *number of periods* distribution of "useful" events.



Conclusions and current work

- the fact that AUTEC uses high-pass 7.5 kHz filter makes neutrino detection more difficult because some of the energy of the signal is contained below this frequency,

- to distinguish between some type of noise (such as 7.5 kHz noise and spike noise) and neutrino signature, a second filter is needed beside the matched filter. It will be installed during the second field trip this winter.

- to distinguish between animal signals and neutrino signature, a more elaborate filter is needed, which will take into account the phase information and directionality of the pulse.