

Spatiotemporal patterns, triggers and anatomies of seismically detected rockfalls

Supplementary material

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Introduction

This supplementary material contains a documentation of all 49 detected rockfall events from the main article. The methods of data processing are explained in this main article. The supplementary material contains for all rockfall events the full set of timing, seismic processing setup and results as well as results of the trigger mechanism analysis.

For the rockfall depicted in figure 3 of the article this material contains the R code used to generate the location estimates as well as plots of the signal envelopes for each of the located pulses.

Furthermore, for all events with a preceding and posterior time window of in total about 15 minutes, power spectral density estimates (PSD) were plotted. The PSDs were calculated from the vertical component of the most representative seismic station (denoted in the title), with signals deconvolved and filtered between 1 and 80 Hz. The PSDs are overlain by the waveform of the seismic data (semi transparent white line) and the onset of the rockfall event is indicated by a black square at the bottom of the figure. All data were processed with the R-package ``eseis" version 0.3.1.

The raw seismic data (vertical components of all available stations) is provided as ASCII files with a buffer of 60 s before and 120 s after the raw picked event. The time stamp is given as POSIXct string. The files ``seismic stations 2014.txt" and ``seismic stations 2015.txt" contain information about station IDs, locations in UTM coordinates and sensor and logger types.

2 Tables

Table 1: Data table part 1. Rockfall event definitions, seismic STL-LTA-picking setup and localisation setup and metadata. ID is consecutive in time and links to 3 and the main article. Event start denotes rockfall initiation as detected from seismic data, given in UTC time. Duration_{picked} is the event duration based on the STA-LTA-picking routine (cf. main article). Duration_{manual} is the duration of a rockfall event from manual inspection of the seismic data. Variables f_{low} and f_{high} denote the filter frequency limits for localisation. Variables t_{pre} and t_{post} indicate additional time added to Event start and Duration_{manual} for localisation to cover variability of all included signals. $\text{SNR}_{station}$ is the signal-to-noise ratio threshold that needed to be passed to allow localisation of an event. SNR_1 to SNR_4 are the resulting signal-to-noise ratios of the prepared data for localisation. SNR_{mean} is the corresponding average signal-to-noise ratio.

ID	Event start	Duration_{picked} (s)	Duration_{manual} (s)	f_{low} (Hz)	f_{high} (Hz)	t_{pre} (s)	t_{post} (s)	$\text{SNR}_{station}$	SNR_1	SNR_2	SNR_3	SNR_4	SNR_{mean}
1	08-06-2014-02:52:12	0.7	8	10	20	1	1	5	20.1	19.6	8.5	6.7	13.7
2	08-06-2014-11:33:10	0.8	6	20	40	1	1	5	55.9	19.5	16.9	24.8	29.3
3	08-18-2014-03:15:11	1.6	5	7	20	1	1	5	27.5	13.1	13.4	4.7	14.7
4	08-19-2014-05:34:16	0.8	2	10	20	0	1	5	11.6	10.2	3.7	16.2	10.4
5	08-26-2014-10:13:46	0.6	3	10	20	1	1	5	22	0	14.2	10.8	11.7
6	08-29-2014-20:20:58	0.5	2	10	20	1	1	5	29.2	7	10.3	10.5	14.3
7	09-02-2014-05:39:14	1.2	1	5	40	1	1	5	28.7	32	6.1	10.3	19.3
8	09-25-2014-07:03:13	3	6	2.8	5.6	1	1	5	10.3	12.4	7.5	19.9	12.5
9	10-01-2014-09:23:05	5	10	1	35	1	1	5	21.2	34.7	10.4	13.5	19.9
10	10-02-2014-17:59:50	2.3	4	5	16	1	1	5	17	8.8	7.3	15.1	12.1
11	10-12-2014-22:45:50	1.9	1	10	23	1	1	5	26.5	8.6	8.9	12.1	14
12	10-15-2014-01:58:32	1.1	4	11	21	1	1	5	49.4	10.7	5.2	8.4	18.4
13	10-17-2014-00:09:25	6.8	8	4.7	15.2	1	1	5	11.1	7.8	5.5	8.8	8.3
14	10-20-2014-15:05:34	0.3	7	16	26	1	1	5	55.9	15.9	14	22	26.9
15	10-20-2014-19:11:09	0.1	5	10	20	1	1	5	35.8	10.7	12.1	13.9	18.1
16	10-22-2014-11:47:28	1.3	2	11	19.9	1	1	5	7.3	8.9	5.7	11.9	8.5
17	10-26-2014-20:08:45	0.8	2	7	13	1	1	5	11.4	6	8.9	14.2	10.1
18	03-19-2015-01:34:06	1.4	2	5	8	1	1	5	9.9	14	6.5	6.2	9.1
19	03-19-2015-06:20:04	1.2	2	5	15	2	2	5	30.5	41.7	33.3	25.3	32.7
20	03-19-2015-08:23:53	2.3	2	10	30	2	2	5	53.9	68	44.9	36.9	50.9
21	03-19-2015-14:58:02	2.3	2	5	15	2	2	5	52.3	53.8	34.1	18.7	39.7
22	03-20-2015-00:31:17	1	2	5	15	2	2	5	18.6	14.9	7.3	16.4	14.3
23	03-21-2015-18:25:47	1.3	2	10	20	2	2	5	12.1	25.8	5.6	13	14.1
24	03-21-2015-18:30:49	0.9	2	5	15	2	2	5	15.9	53.1	9.1	24	25.5
25	03-25-2015-19:01:54	0.5	2	10	20	2	2	5	22.9	31.1	4.9	22.9	20.4
26	03-27-2015-04:49:21	1	2	5	15	2	2	5	21.3	12.5	12	8	13.5
27	03-31-2015-05:53:25	2.1	3	10	30	2	2	5	21	11.1	12.6	12	14.2
28	03-31-2015-06:03:31	1.9	3	5	15	2	5	5	12.6	32.6	6.9	6.8	14.7
29	03-31-2015-18:59:27	1	1	10	30	1	2	5	9.3	50	9.2	21.4	22.5
30	04-06-2015-13:22:42	10.4	10	5	15	2	2	5	71.7	73.5	67.7	17.8	57.7
31	04-07-2015-10:12:44	1.6	2	10	20	2	2	5	22.3	49.2	29.3	17.9	29.7
32	04-07-2015-14:01:54	0.9	1	5	15	2	2	5	24.4	31.8	15.8	10.7	20.7
33	04-08-2015-01:54:39	2.2	2	5	15	8	9	5	54.7	62.3	63.9	34.1	53.8
34	04-08-2015-20:31:14	1.7	2	5	15	2	2	5	9.5	12.7	11.9	7.2	10.3
35	04-09-2015-00:25:57	1.2	2	10	30	4	8	5	51.3	66	7.7	23	37
36	04-17-2015-08:32:20	4	4	10	20	2	2	5	14	10.2	9.7	6	10
37	04-17-2015-11:16:25	3.2	4	5	15	2	2	5	50.2	40	19.6	17.6	31.8
38	04-18-2015-01:21:03	1	1	3	5	3	1	5	13	9.8	11.9	22.2	14.2
39	04-18-2015-03:17:35	1.2	1	5	15	2	2	5	32.9	25.5	13.6	9.7	20.4
40	04-18-2015-11:54:39	2.4	3	10	30	2	2	5	20.7	13.8	6.5	19.6	15.1
41	04-18-2015-16:05:14	0.7	1	6	15	2	0	6	5.8	14.2	7.3	8.8	9
42	04-21-2015-06:48:50	2	3	20	40	6	15	5	15.3	18.1	17.4	10.9	15.4
43	04-24-2015-17:04:35	1.7	2	10	20	2	2	5	16.5	52.2	33.3	10.1	28
44	04-27-2015-06:23:42	1.5	2	4	15	2	5	4	17.4	6.3	60.7	8.2	23.1
45	05-07-2015-06:57:21	1.5	2	10	30	2	2	5	11.4	41.1	50.2	7.8	27.6
46	05-08-2015-07:41:44	1	1	10	20	2	2	5	19.8	39.9	14	19.1	23.2
47	05-10-2015-18:07:26	5	5	10	30	2	2	5	28.1	36.4	6.2	19.4	22.5
48	05-13-2015-17:38:30	2.7	3	5	15	2	2	5	26.7	10.1	7.5	7.4	12.9
49	05-29-2015-15:05:52	2.1	4	10	20	2	4	5	10.3	20.3	12.6	18.8	15.5

Table 2: Data table part 2. Rockfall event localisation results, rockfall-associated seismic signals and trigger characteristics. ID corresponds to 1. X_{seis} , Y_{seis} and Z_{seis} are the cartesian coordinates of the pixel with the highest seismic source location probability density P_{max} . Z_{tls} (m asl.) and V_{tls} (m³) are the rockfall detachment height and volume based on the lidar study by Dietze et al. (2017). Type denotes rockfall evolutionary type (cf. main article). $Event_{pre}$ and $Event_{post}$ indicate the time lag to previous and posterioir seismic signals that could be attributed to rockfall activity. Location is a desriptive classification of the impact area of the rockmass based on the location estimates and fall times. P_{cum} is the cumulative precipitation amount prior to a rockfall event. Lag_P (h) is the time lag between a rainfall event and a subsequent rockfall. Lag_{FT} (h) is the time lag between a freeze-thaw or thaw-freeze event and the subsequent rockfall. Lag_{quake} (h) is the time lag between a picked earthquake and a subsequent rockfall. Note that for the latter only data from 2015 was screened.

ID	X_{seis} (m)	Y_{seis} (m)	Z_{seis} (m asl.)	Z_{tls} (m asl.)	V_{tls} (m ³)	Type	$Event_{pre}$ (s)	$Event_{post}$ (s)	Location	P_{cum} (mm)	Lag_P (h)	Lag_{FT} (h)	Lag_{quake} (h)
1	415495	5156621	1096	NA	NA	A	NA	NA	cliff	6.2	26.9	NA	NA
2	416035	5158531	1085	NA	NA	A	NA	0.9	cliff	6.2	35.6	NA	NA
3	415485	5156861	1240	NA	NA	A	NA	NA	cliff	1.2	34.3	NA	NA
4	415855	5157551	1088	NA	NA	A	NA	1.5	cliff	6	0.6	NA	NA
5	416025	5158561	1064	NA	NA	A	3.7	1.6	cliff	36.2	0.2	NA	NA
6	416015	5158471	1089	NA	NA	A	1.6	1.6	cliff	4	0.3	NA	NA
7	415465	5156501	1119	NA	NA	A	3.9	NA	cliff	8.8	22.7	NA	NA
8	416015	5157781	918	1005	0.891 ± 0.038	A	NA	10.3	cliff	2.2	6.1	NA	NA
9	416115	5158701	916	984	2.338 ± 0.085	B	NA	NA	cliff	3.2	19.4	NA	NA
10	415975	5158271	1186	1108	0.416 ± 0.021	A	NA	NA	cliff	3.2	52.0	NA	NA
11	415485	5156561	1089	1064	0.201 ± 0.005	A	NA	NA	cliff	1	167.8	NA	NA
12	415505	5156541	1036	1018	0.063 ± 0.006	A	NA	NA	cliff	0.2	2.0	NA	NA
13	416065	5158811	1127	1218	0.192 ± 0.010	B	NA	NA	cliff	1.6	7.2	NA	NA
14	415505	5156871	1198	1104	0.175 ± 0.011	A	NA	NA	cliff	3.4	79.1	NA	NA
15	415515	5156841	1177	954	0.201 ± 0.005	A	NA	4.3	cliff	3.4	83.2	NA	NA
16	415635	5156991	1016	955	0.053 ± 0.004	A	NA	NA	cliff	4.2	0.8	12.8	NA
17	416015	5157891	919	994	0.258 ± 0.014	A	NA	1.8	cliff	4	25.1	68.1	NA
18	415885	5158261	1442	NA	NA	A	3.4	4.7	cliff	0.2	335.6	89.6	NA
19	415795	5157441	1293	NA	NA	A	1.4	NA	cliff	0.2	340.3	94.3	2.6
20	416045	5158751	1252	NA	NA	A	5.4	NA	cliff	0.2	342.4	96.4	4.7
21	415605	5157571	1533	NA	NA	A	NA	NA	top	0.2	349.0	103.0	11.3
22	416015	5158481	1112	NA	NA	A	NA	2.5	cliff	0.2	358.5	112.5	0.5
23	415935	5158181	1328	NA	NA	A	NA	1.2	cliff	3	0.4	2.4	12.3
24	415835	5157511	1300	NA	NA	A	NA	NA	cliff	3	0.5	2.5	12.4
25	415955	5157971	1240	NA	NA	A	NA	2.1	cliff	1.8	0.0	1.0	5.3
26	416065	5158871	1300	NA	NA	A	NA	1.8	cliff	4	0.8	34.8	1.9
27	415485	5157301	1635	NA	NA	B	NA	NA	top	22.2	1.9	70.9	0.4
28	415865	5157641	1148	NA	NA	B	NA	NA	cliff	22.2	2.1	71.1	0.6
29	415955	5158231	1219	NA	NA	A	0.5	NA	cliff	0.6	1.0	84.0	0.5
30	415795	5157451	1318	NA	NA	A	1.5	1.2	cliff	0.2	24.4	52.4	0.1
31	415985	5158061	1169	NA	NA	A	NA	5.4	cliff	0.2	45.2	73.2	9.1
32	415805	5157451	1293	NA	NA	A	NA	8.4	cliff	0.2	49.0	3.0	12.9
33	415965	5158271	1208	NA	NA	A	3.6	NA	cliff	0.2	60.9	9.9	24.8
34	415485	5156431	986	NA	NA	A	NA	21	base	0.2	79.5	14.5	4.6
35	415935	5158201	1354	NA	NA	A	3.1	12.4	cliff	0.2	83.4	18.4	8.5
36	416015	5158591	1237	NA	NA	B	NA	NA	cliff	0.2	283.5	218.5	3.7
37	416015	5158541	1266	NA	NA	A	1.2	8.4	cliff	1	2.3	221.3	0.8
38	416055	5157991	866	NA	NA	B	NA	NA	base	5.6	0.4	235.4	3.5
39	416015	5158641	1218	NA	NA	A	NA	NA	cliff	8.2	0.3	237.3	0.0
40	416005	5158021	1094	NA	NA	B	NA	NA	cliff	0.2	6.9	245.9	2.1
41	415645	5157451	1453	NA	NA	A	NA	0.1	top	0.2	3.1	250.1	2.4
42	416135	5159011	1229	NA	NA	B	NA	NA	cliff	0.2	65.8	50.8	0.3
43	415555	5157161	1553	NA	NA	A	NA	3.4	top	0.2	148.1	133.1	1.5
44	415935	5158191	1332	NA	NA	B	NA	NA	cliff	0.4	30.4	194.4	0.2
45	415615	5156941	1006	NA	NA	A	0.8	3.2	base	6.4	23.0	193.0	0.3
46	416205	5159341	879	NA	NA	A	NA	NA	base	6.4	47.7	217.7	1.8
47	415965	5157731	970	NA	NA	B	NA	NA	base	0.4	25.1	276.1	1.0
48	416005	5158021	1094	NA	NA	B	NA	NA	cliff	0.4	96.6	347.6	0.8
49	415945	5157941	1221	NA	NA	A	NA	NA	cliff	2	60.1	179.1	35.4

3 Photo panels

Table 3: Data table part 3. Additional information from descriptive seismic analysis. IDs correspond to previous two tables.

ID	Comment
1	no other signals visible
2	helicopter passing by during event and 10 to 7 minutes before
3	small earthquake about 7 minutes before
4	rain drop impacts throughout all stations
5	rain drop impacts throughout all stations, helicopter passing by 35 minutes before
6	rain drop impacts predominantly at upper stations
7	helicopter passing by 10 to 3 minutes before, unknown source about 2 minutes before event, more prominent at Gate of China
8	explosion preceeding event by 6 minutes
9	train passage about 5 minutes before and 1 minute after event
10	train passage about 12 minutes before and one minute after event
11	no other signals visible
12	slight rain event 10 to 5 minutes before
13	no other signals visible
14	helicopter passing by a few minutes before and after the event
15	no other signals visible
16	unidentifiable broadband (10 to 80 Hz) signal pulses before and after the event
17	no other signals visible
18	two weak signals (20-80 Hz) visible some minutes before event
19	train passage about 6 minutes before and 2 minutes after event
20	helicopter passing by about 10 to 5 minutes before event
21	rain noise about 4 minutes before event
22	no other signals visible
23	High frequent (30-80 Hz) short pulse (only visible at that closest station) about 2 minutes before event
24	Preceding rockfall (ID 23) visible 5 minutes before
25	rain drop impacts throughout all stations
26	Weak 10-80 Hz signal period about 4 minutes before event
27	Air-traveled signal about three minutes before event
28	Significant blasting signals 15 to 3 minutes before event
29	rain drop impacts throughout all stations
30	Earthquake about 3 minutes before
31	Train passage about 5 minutes before, remobilisation of debris 2 minutes after rockfall (only visible at Funny Rain)
32	no other signals visible
33	only minor local short pulses of energy visible
34	no other signals visible
35	rockfall outside monitored area about 20 minutes before
36	helicopter passed 10 minutes before, raindrop impacts all the time, constant signal around 40 Hz 6-1 minutes before
37	helicopter passage about 10 minutes before, low frequent activity at Funny Rain one minute before
38	rain drop impacts at all cliff top stations
39	rain drop impacts at all cliff top stations
40	rain drop impacts at all cliff top stations
41	rain drop impacts at all cliff top stations, increasing signal content around 5 Hz
42	abundant avalanche-like signals also before but only visible at Funny Rain
43	short pulses about 20 s before, only visible at Sweaty Herbs and Gate of China
44	no other signals visible
45	helicopter passage about 8 minutes before
46	helicopter passage 5 minutes before and after event
47	low frequent pulse about 30 s before
48	multiple pulses of anthropogenic origin, rockfall is short pulse with sharp onset
49	no other signals visible


```

## clip time vector
t_i <- time_clip(time = t,
                 limits = c(p$start[i],
                           p$start[i] + p$duration[i]))

## detrend signals
s_i <- signal_detrend(data = s_i)

## calculate spectra
s_s_i <- signal_spectrum(data = s_i,
                        dt = 1/200, method = "multitaper")

## filter signals
s_f_i <- signal_filter(data = s_i,
                      dt = 1 / 200,
                      f = c(p$f_low[i],
                           p$f_high[i]))

## calculate signal envelopes
s_e_i <- signal_envelope(data = s_i)

## assign result to output object
s_s[[i]] <- s_s_i

s_e[[i]] <- s_e_i

t_e[[i]] <- t_i
}

## generate spectra plots
jpeg(filename = "spectra.jpg",
     width = 4000,
     height = 1000,
     res = 300)

par(mfcol = c(1, 5),
    mar = c(5.5, 4.5, 3, 1))

for(i in 1:length(s_s)) {

  plot_spectrum(data = s_s[[i]]$LAU01,
               main = paste("Spectrum | phase", i))
}

dev.off()

## generate envelope plots
jpeg(filename = "envelopes.jpg",
     width = 5000,
     height = 4000,
     res = 300)

par(mfcol = c(4, 5),
    mar = c(5.5, 4.5, 3, 1))

for(i in 1:length(s_e)) {

  for(j in 1:length(s)) {

    plot(x = t_e[[i]],
         y = (s_e[[i]][[j]] * 10^6)^2,
         xlab = "Time",
         ylab = expression(mu*m^2/s^2),
         main = paste("Envelope", station$ID[j], " | phase", i),
         type = "l")
  }
}

dev.off()

```

Case event II characterisation

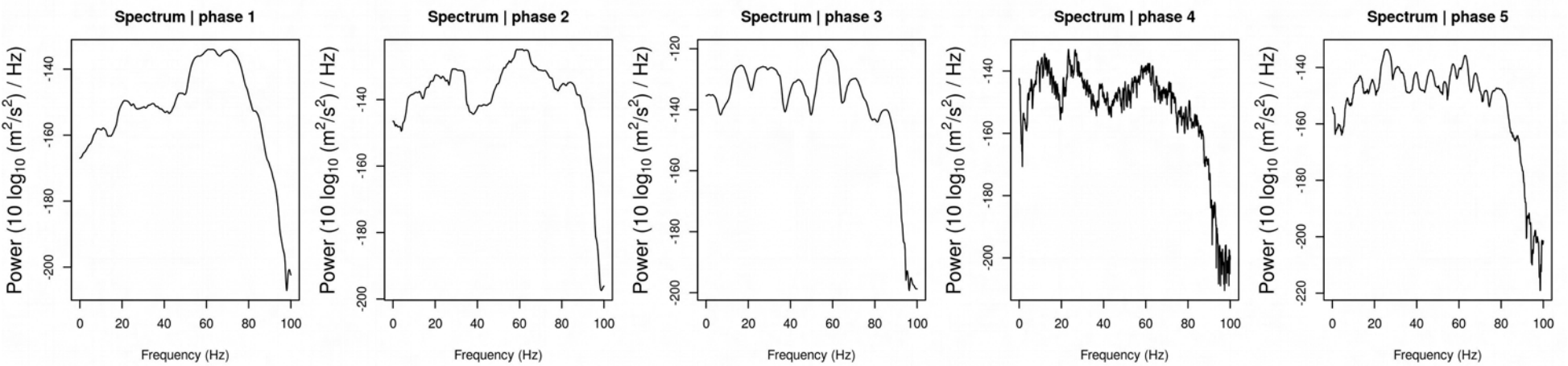


Figure 1. Spectra for the five recorded seismic pulses of the rockfall case event II (figure 3 from the main article) as recorded by station “Basejumpers Mess”.

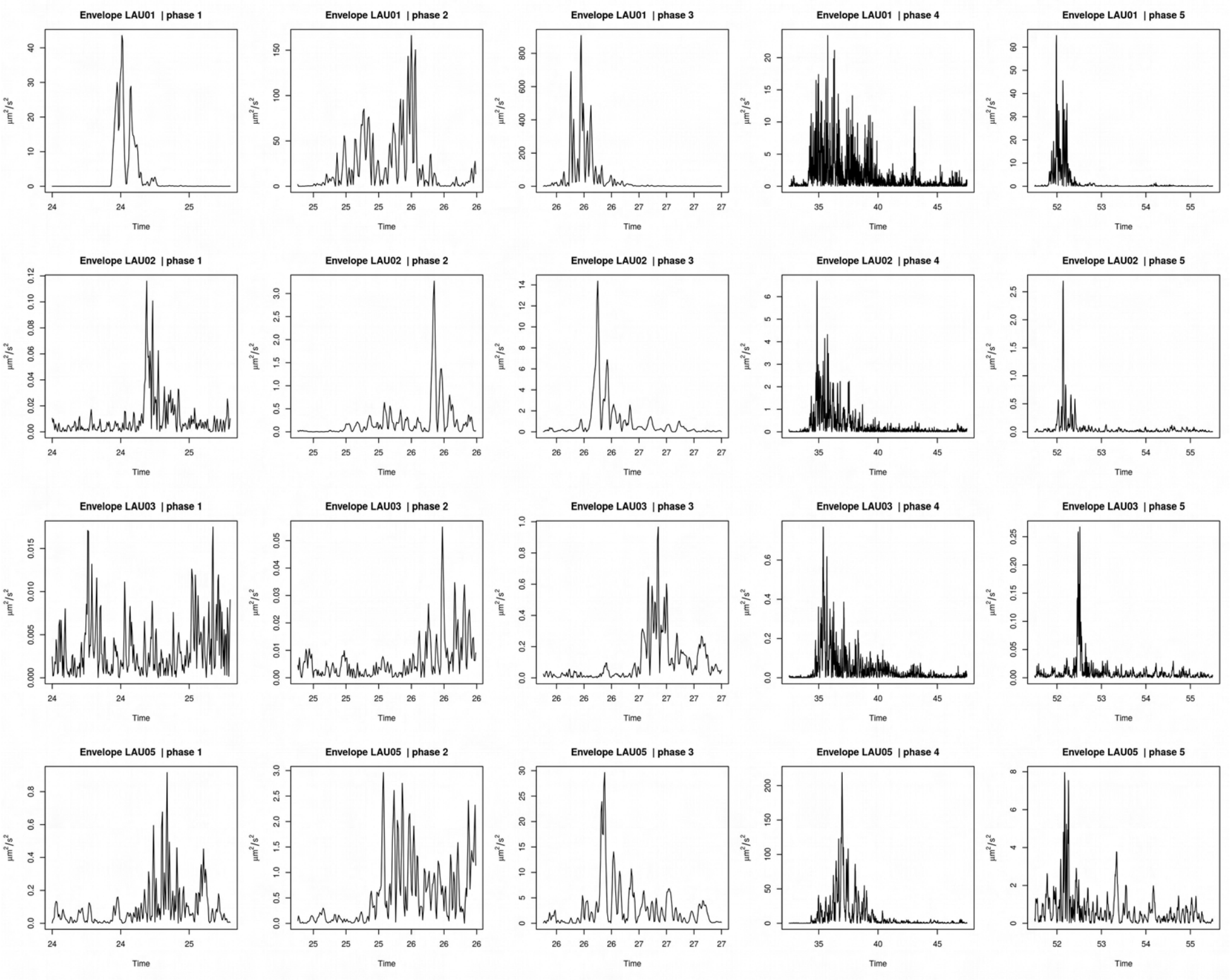
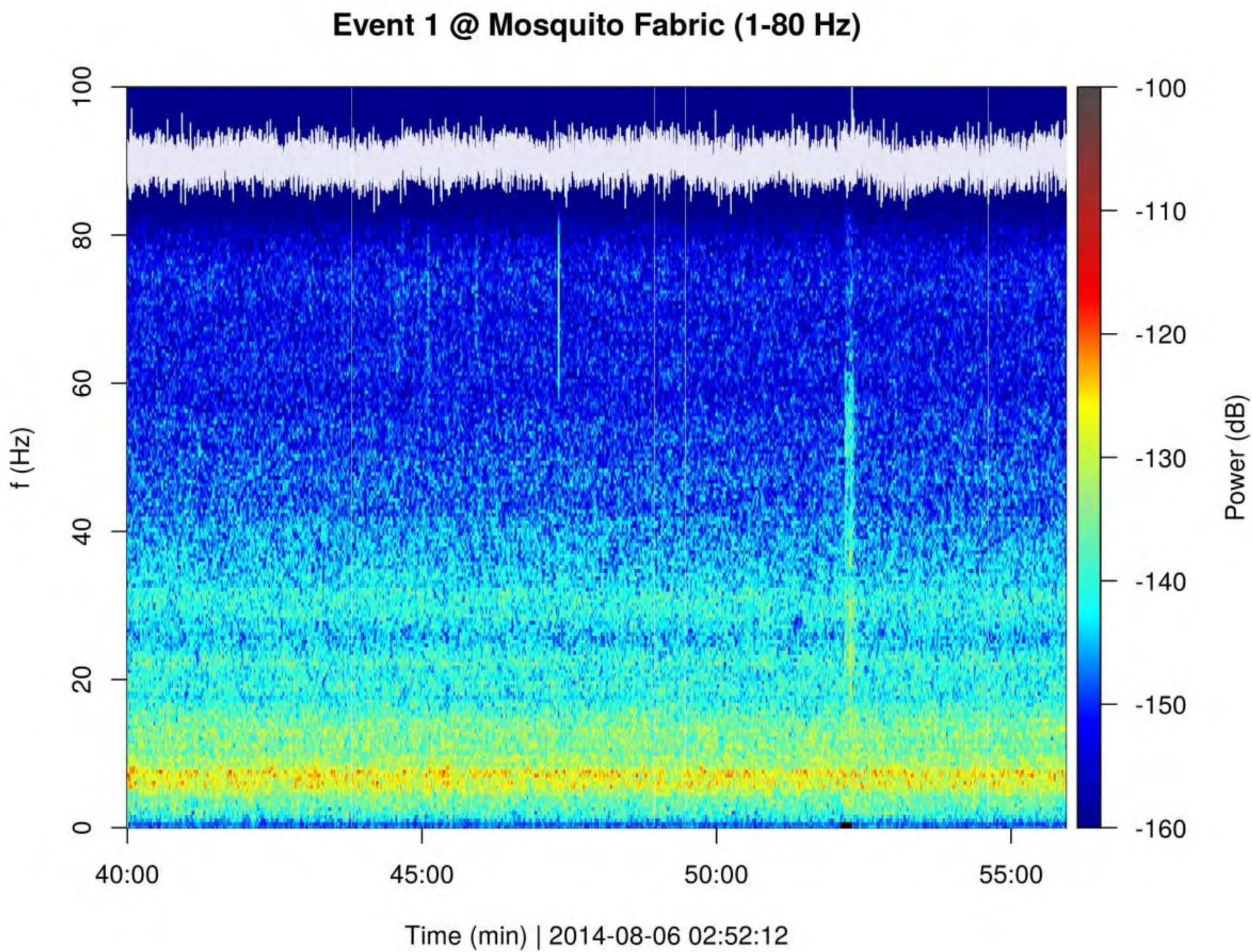


Figure 2. Envelopes of the five recorded seismic pulses of the rockfall case event II (figure 3 from the main article) as recorded by each of the four seismic stations: LAU01 – Basejumpers Mess, LAU02 – Gate of China, LAU03 – Sweaty Herbs, LAU05 Funny Rain.

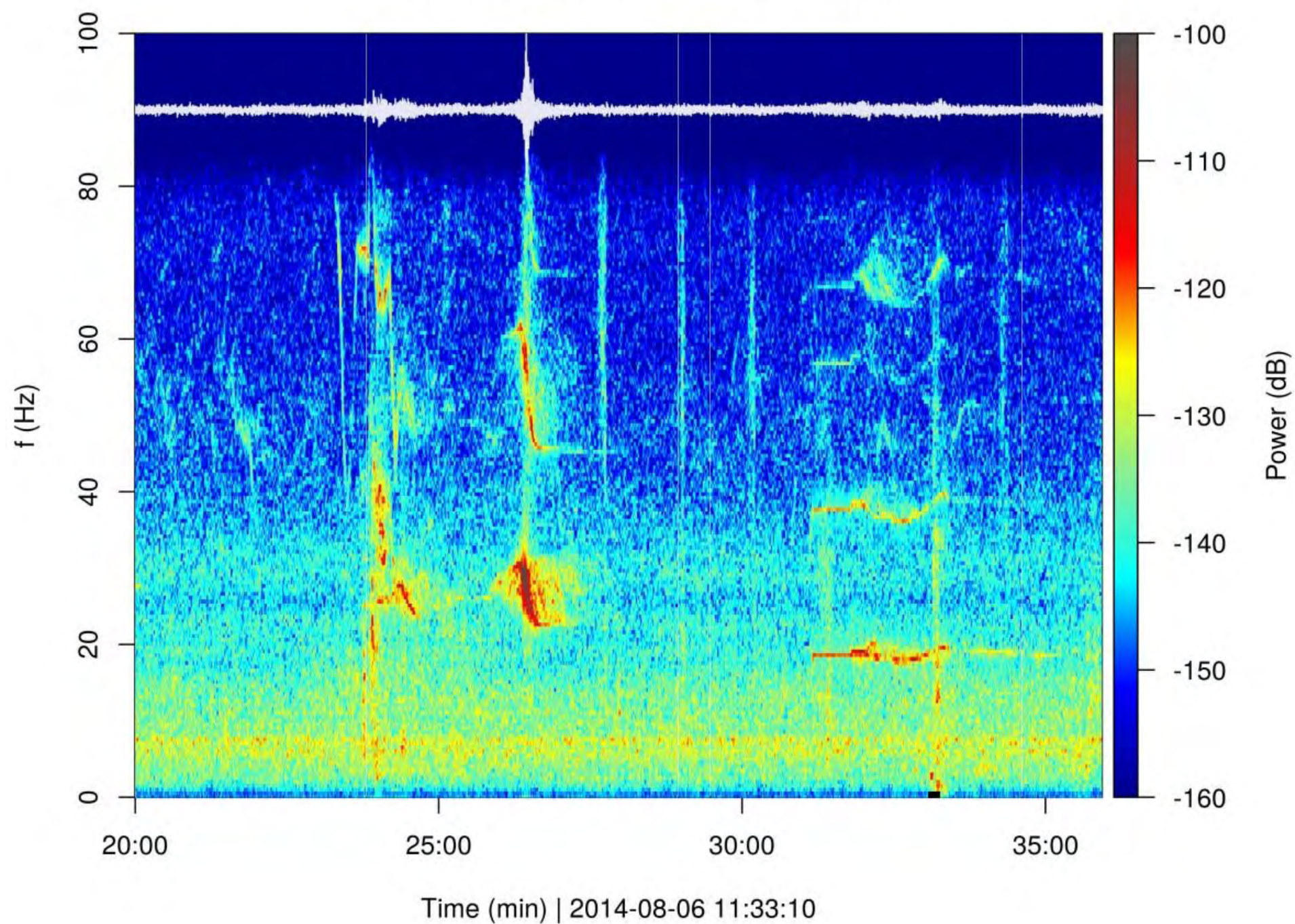
Photo documentation of the cliff during different seasons



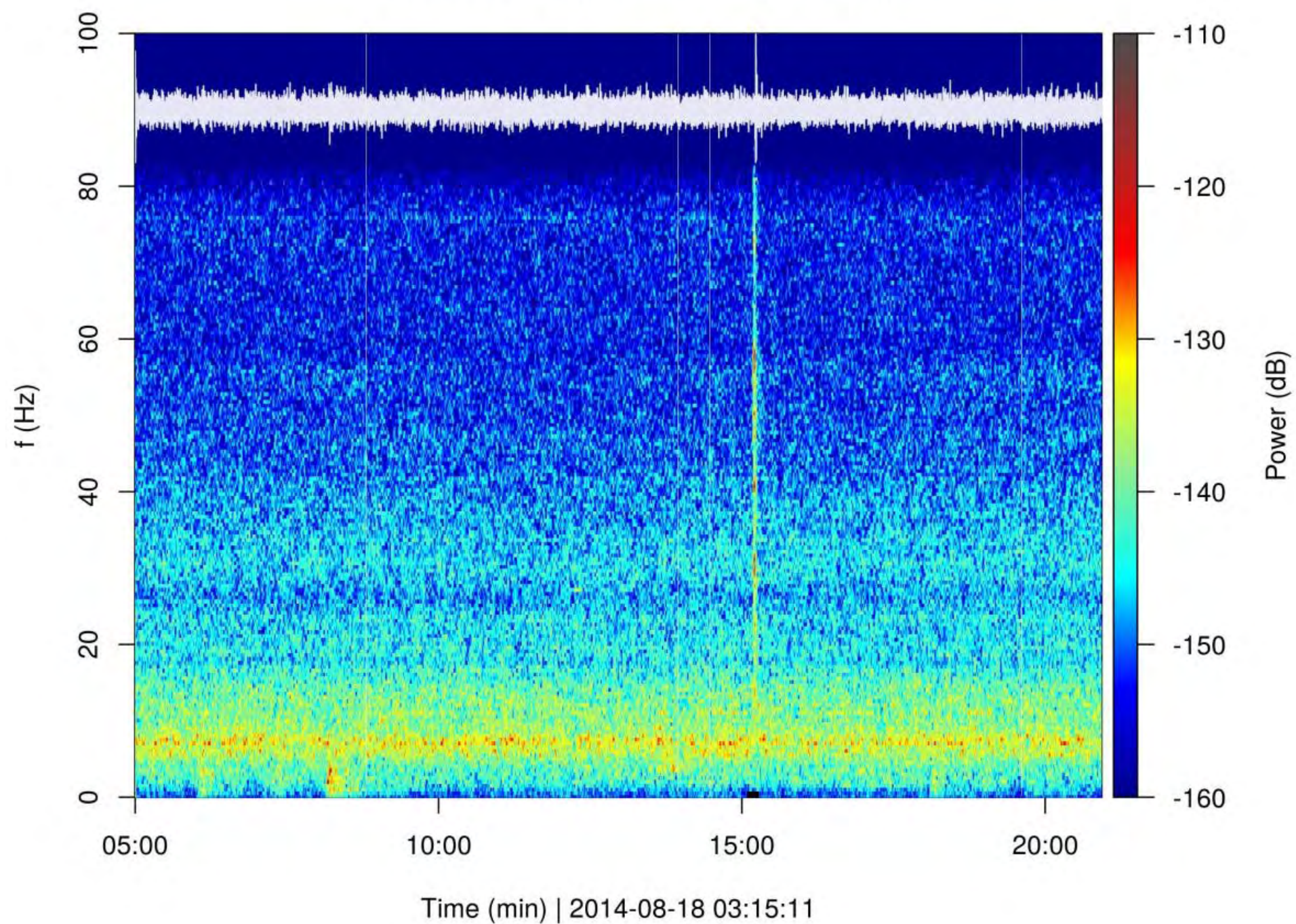
Spectrograms of each detected and located rockfall event



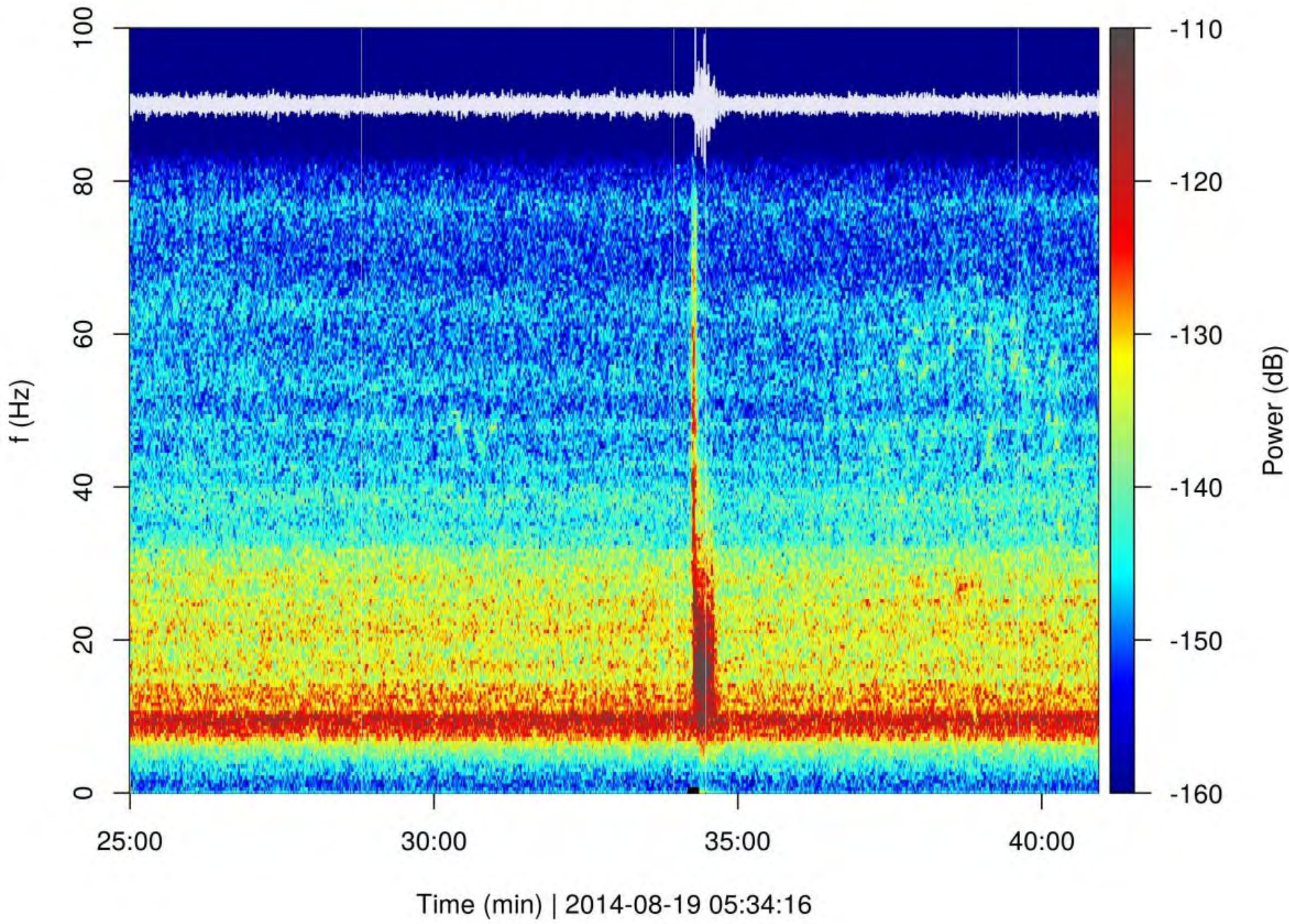
Event 2 @ Mosquito Fabric (1-80 Hz)



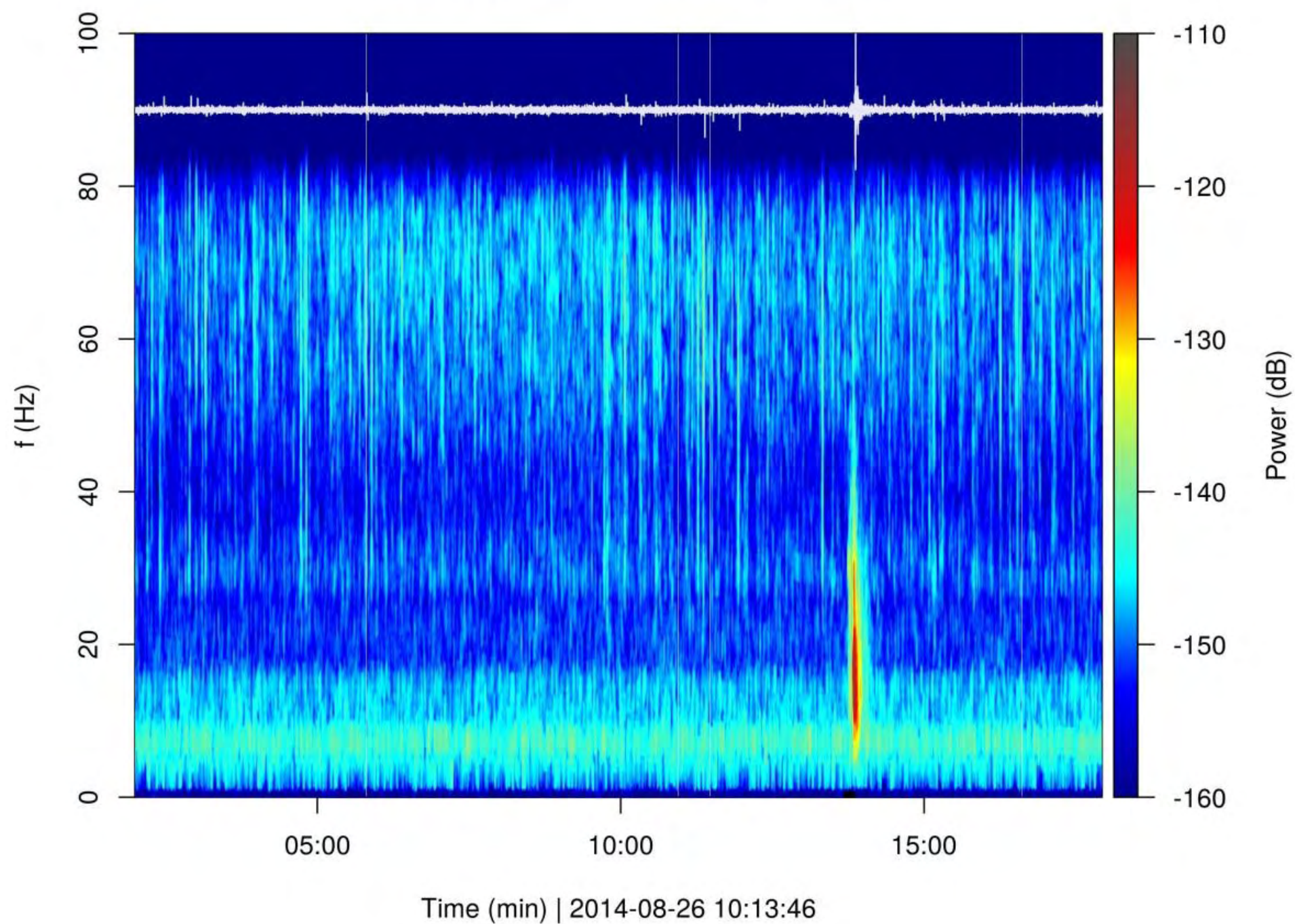
Event 3 @ Mosquito Fabric (1-80 Hz)



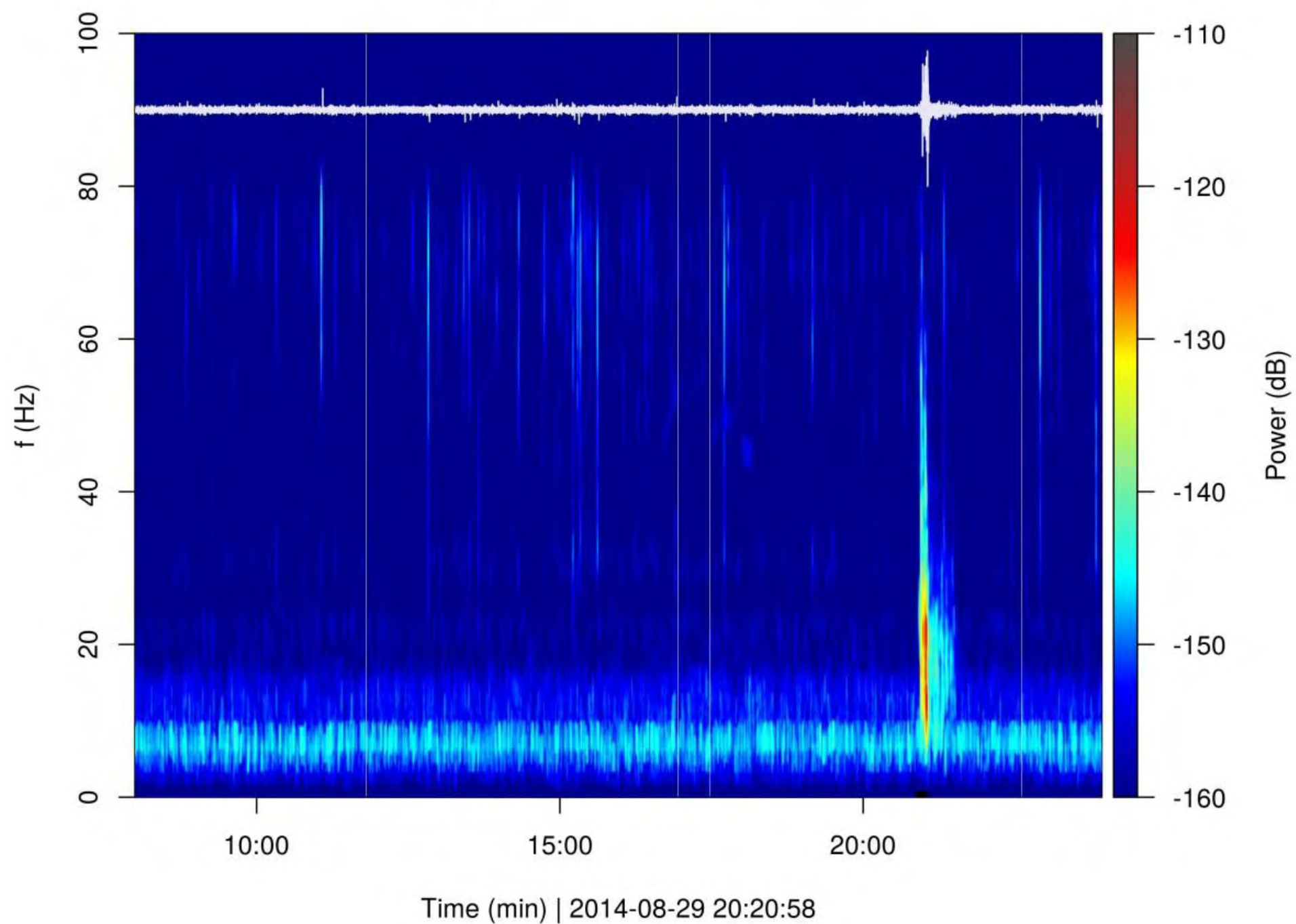
Event 4 @ Funny Rain (1-80 Hz)



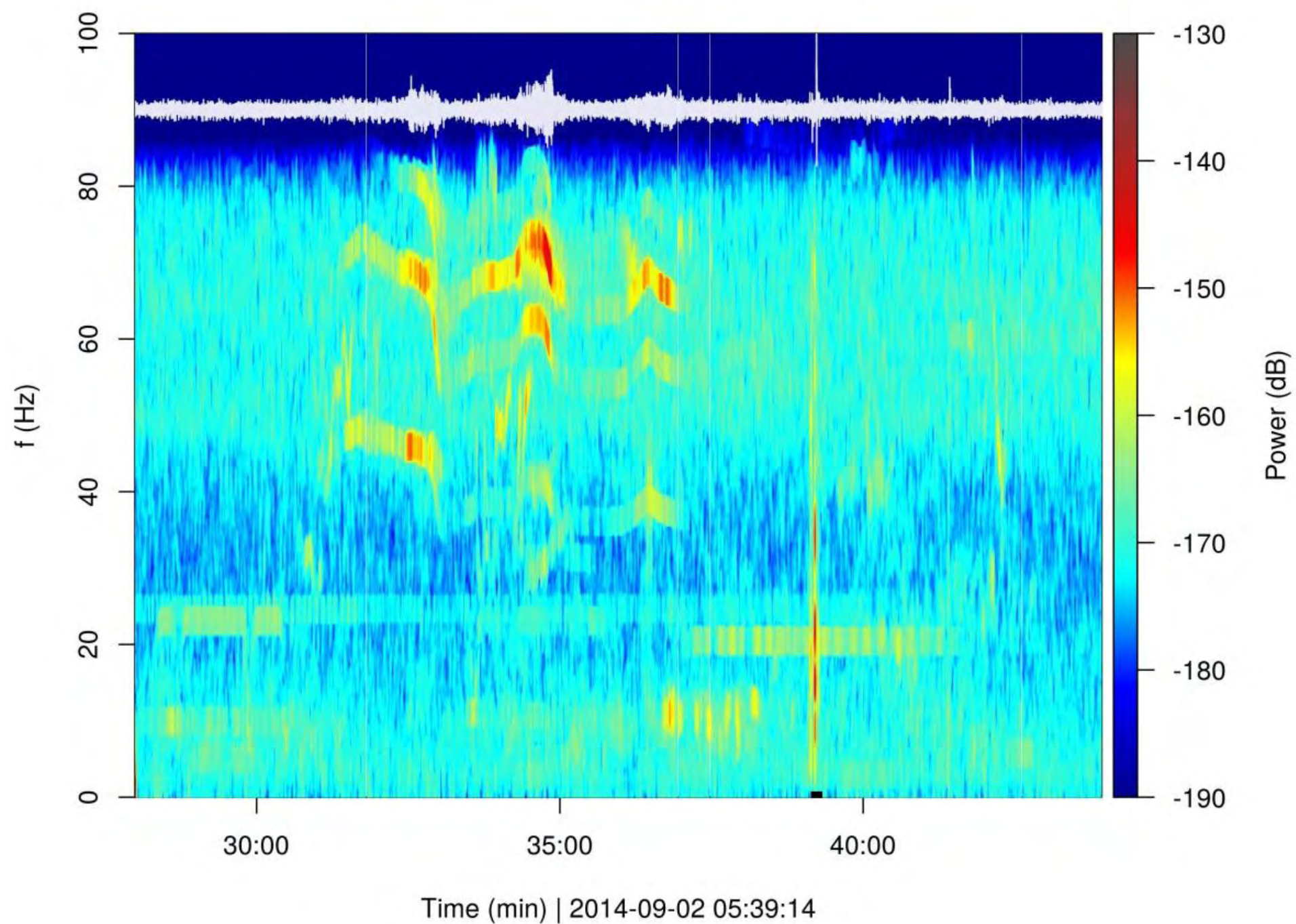
Event 5 @ Mosquito Fabric (1-80 Hz)



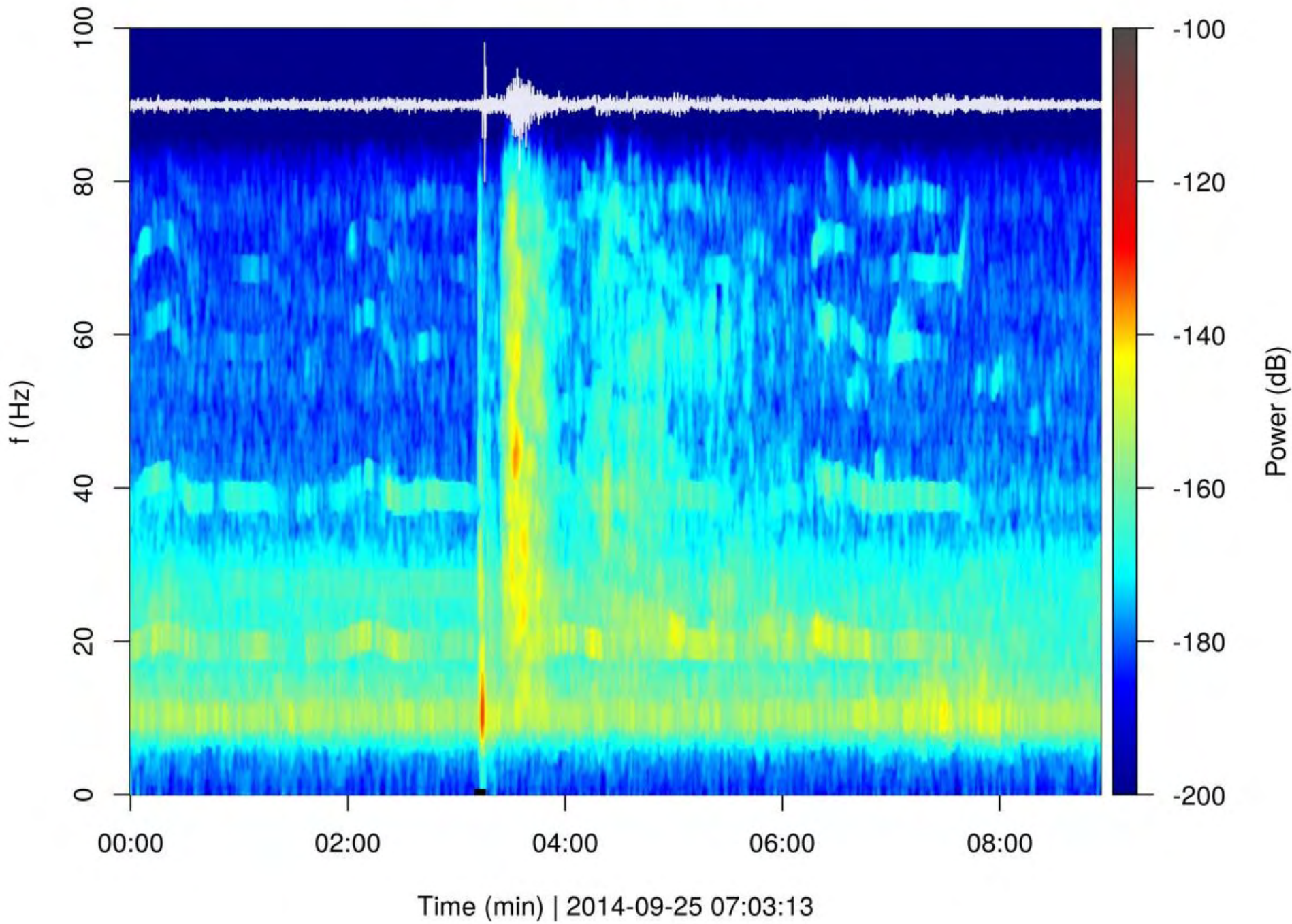
Event 6 @ Mosquito Fabric (1-80 Hz)



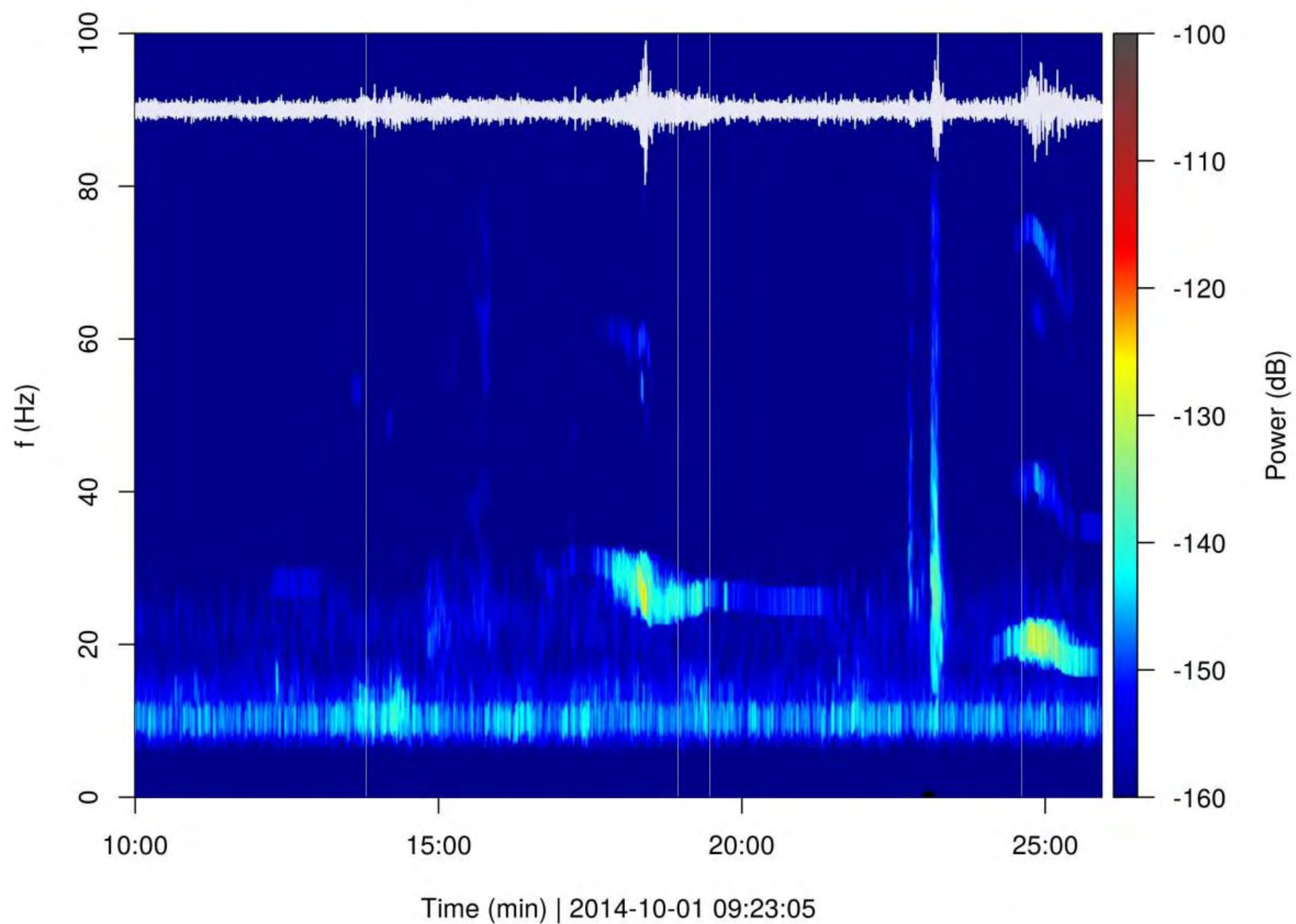
Event 7 @ Sweaty Herbs (1-80 Hz)



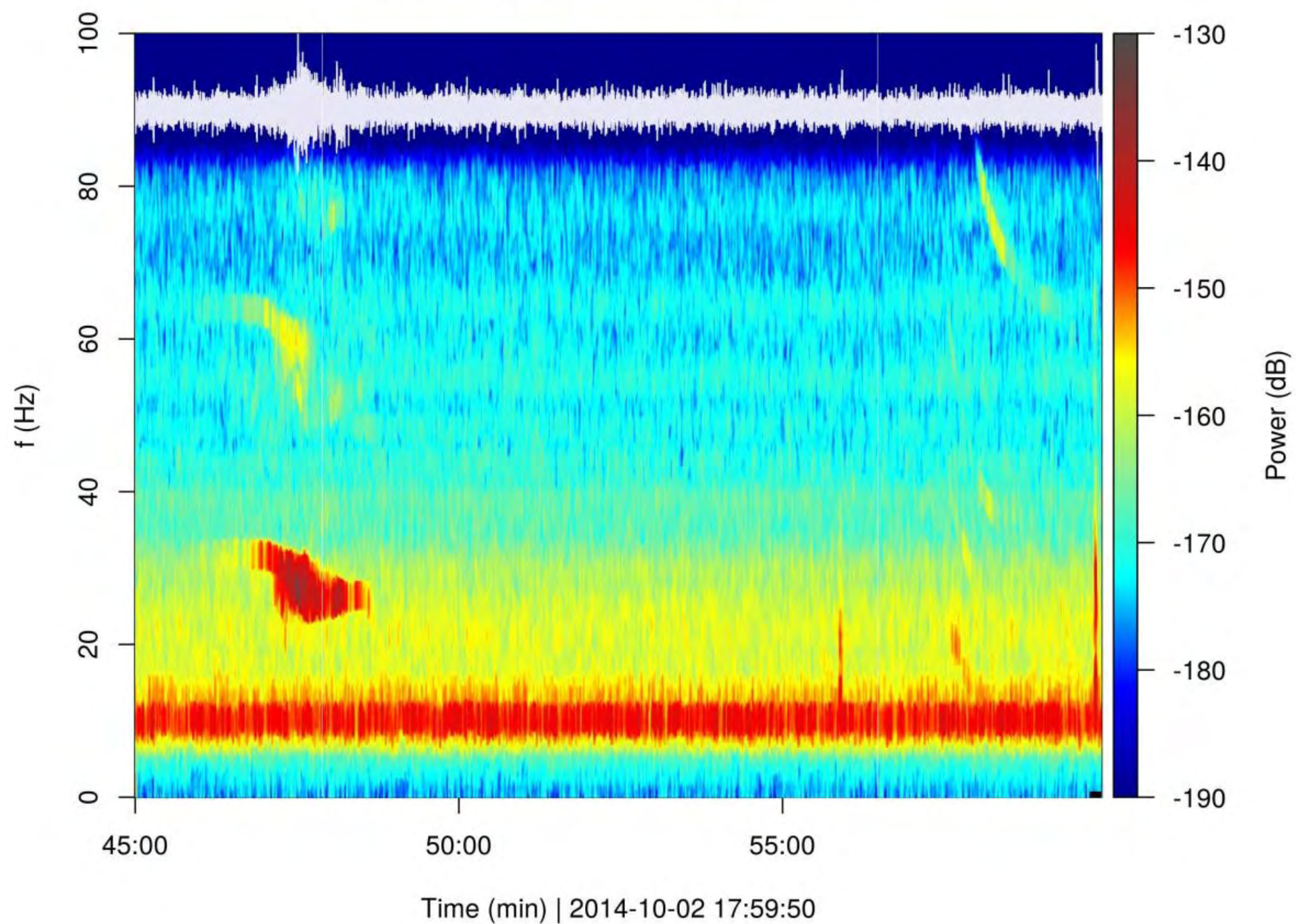
Event 8 @ Funny Rain (1-80 Hz)



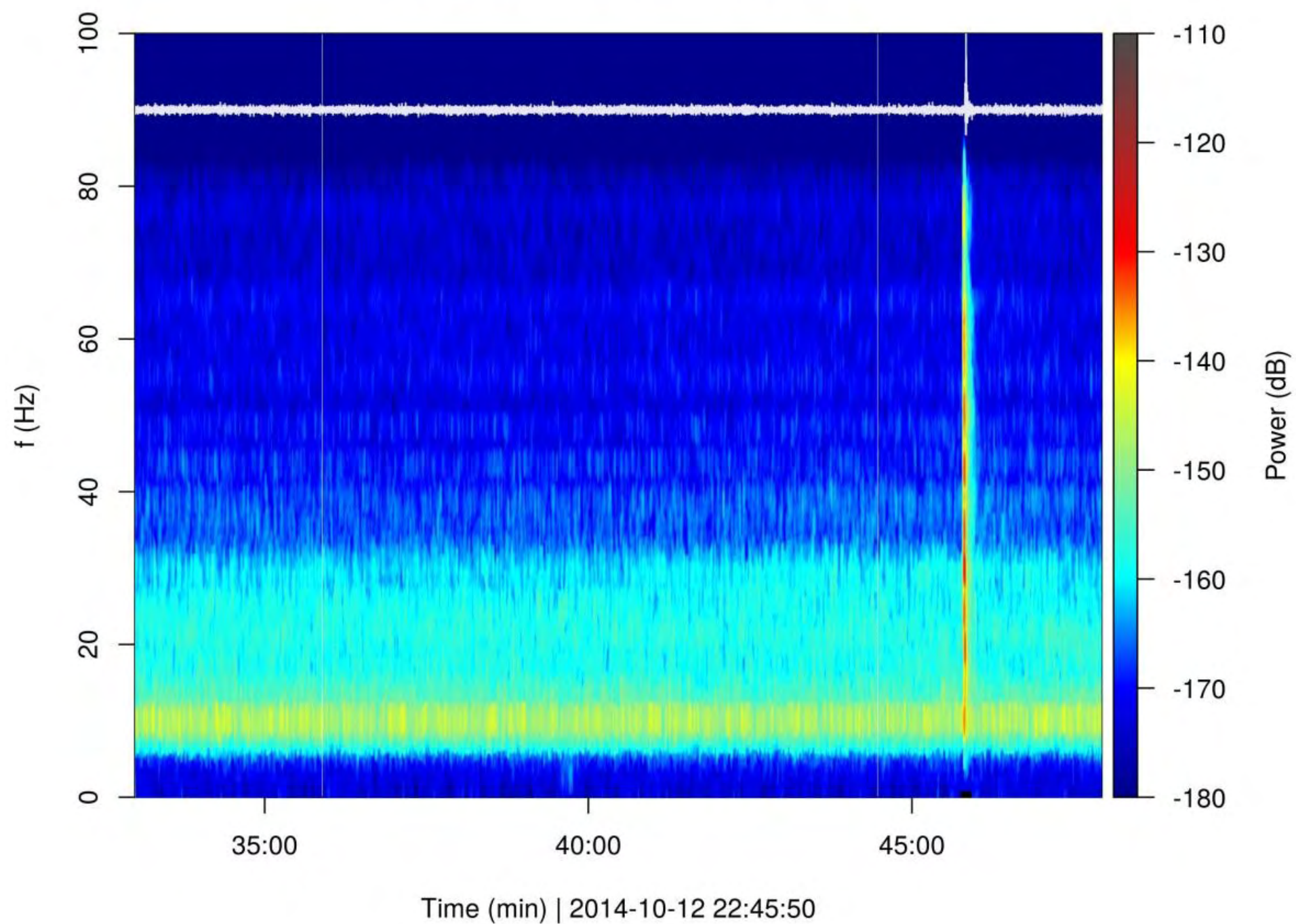
Event 9 @ Mosque Fabric (1-80 Hz)



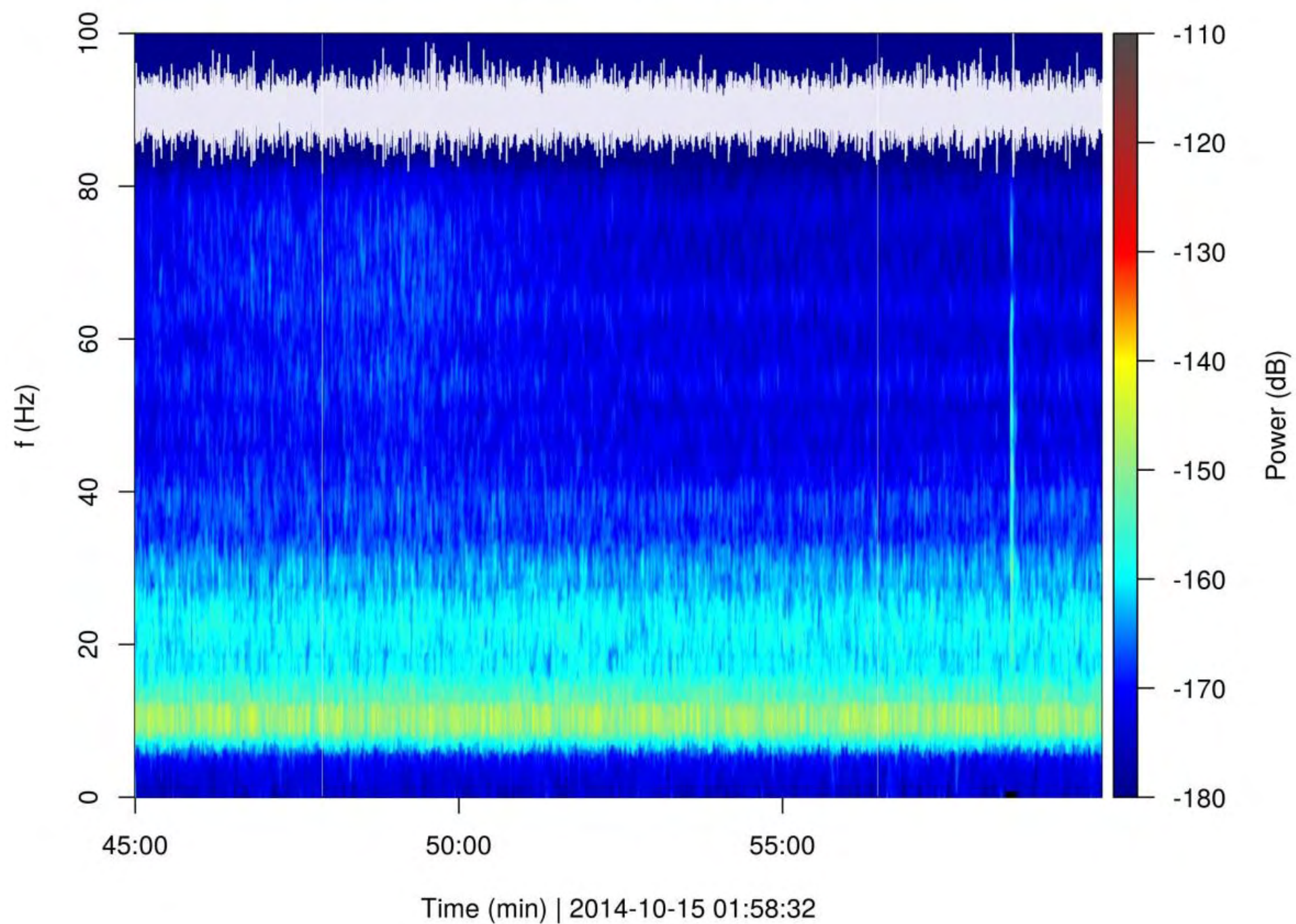
Event 10 @ Funny Rain (1-80 Hz)



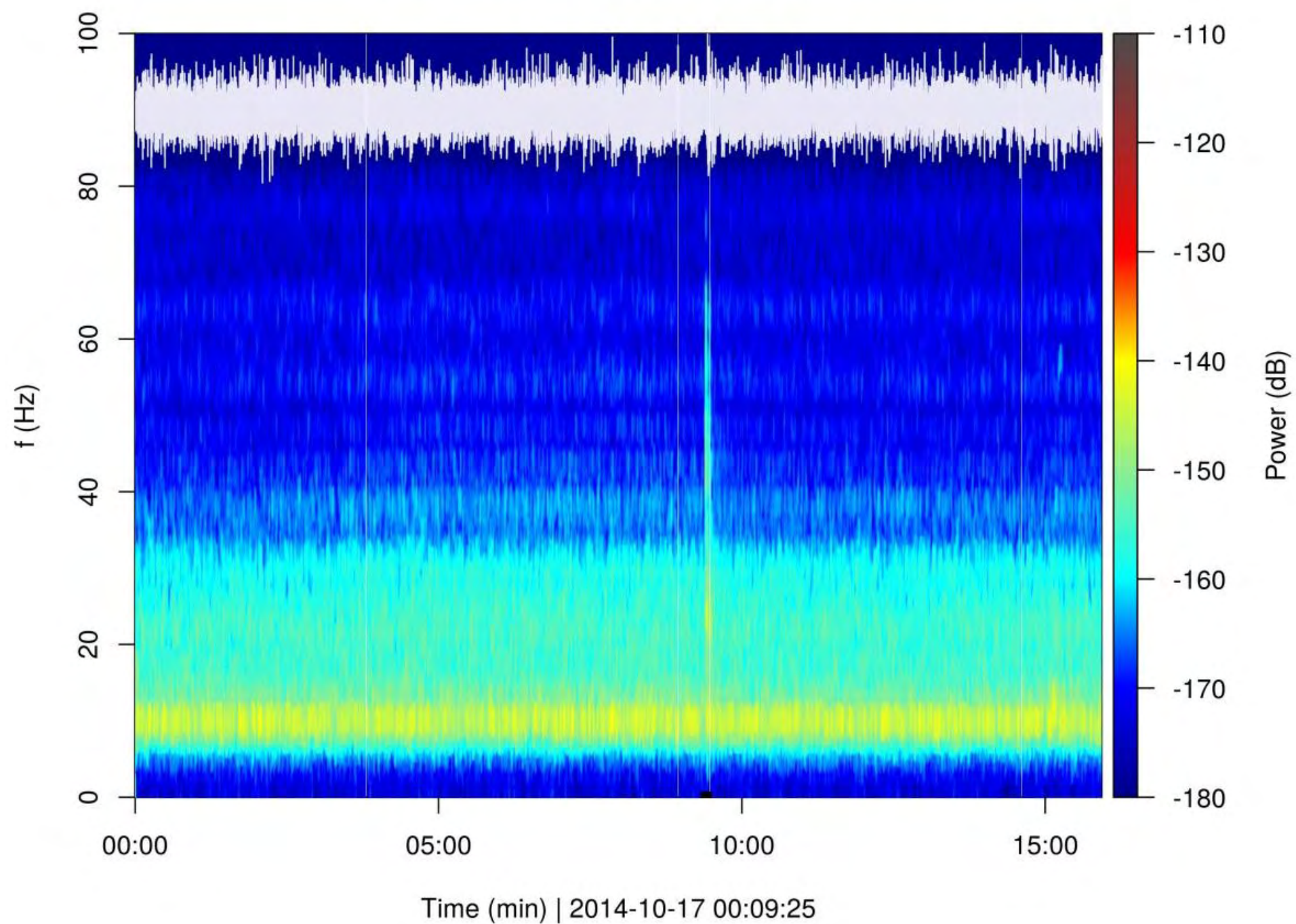
Event 11 @ Funny Rain (1-80 Hz)



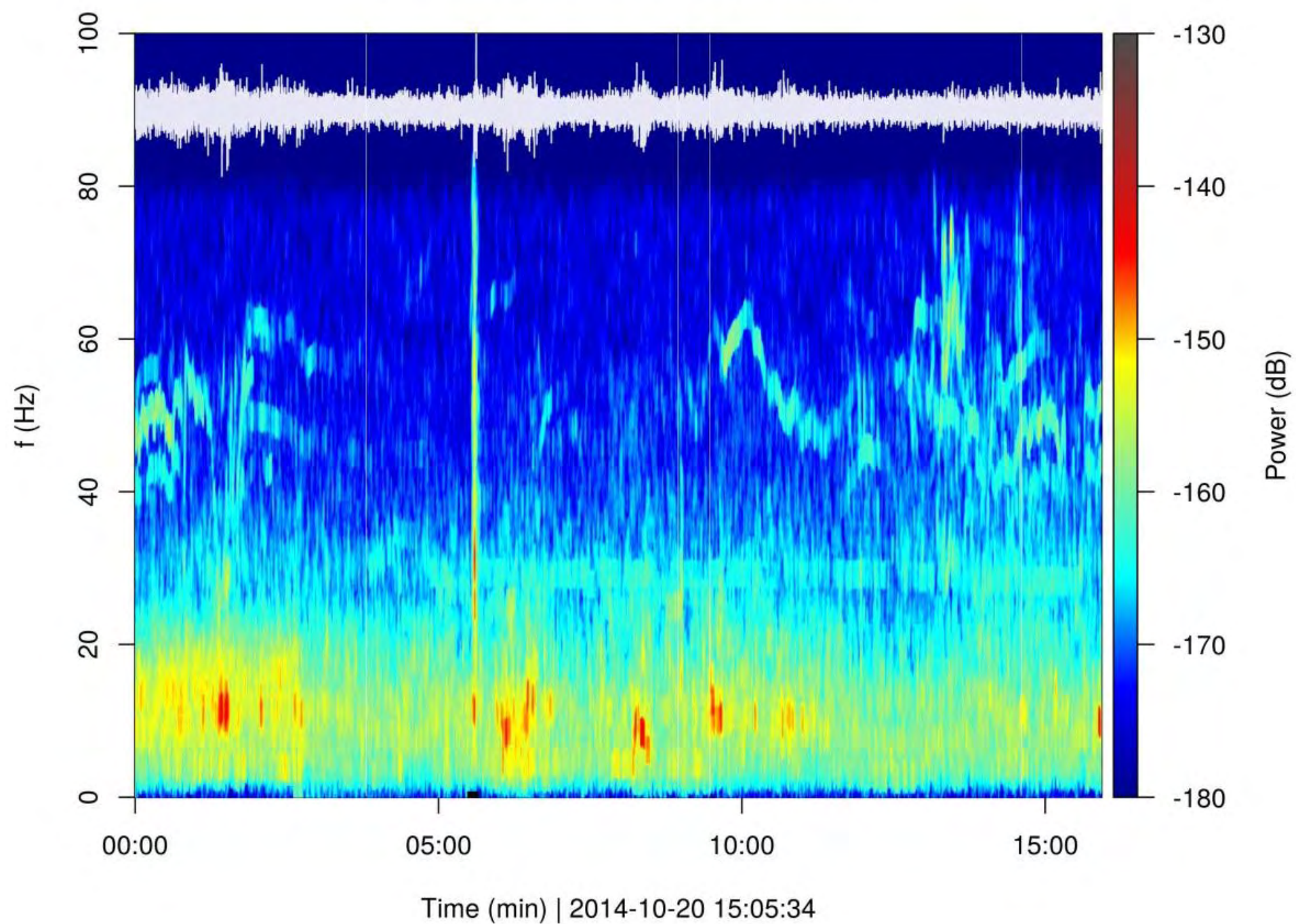
Event 12 @ Funny Rain (1-80 Hz)



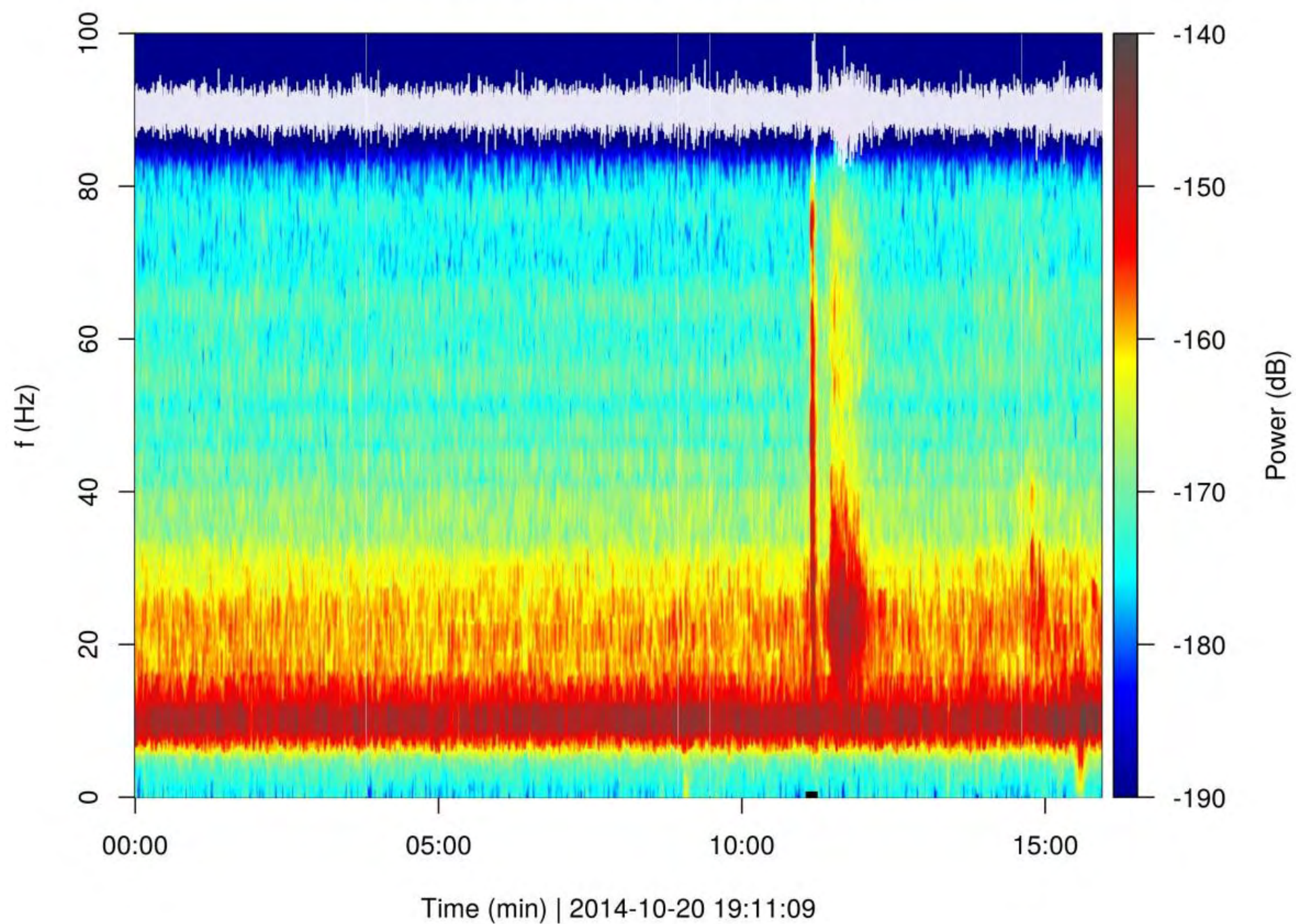
Event 13 @ Funny Rain (1-80 Hz)



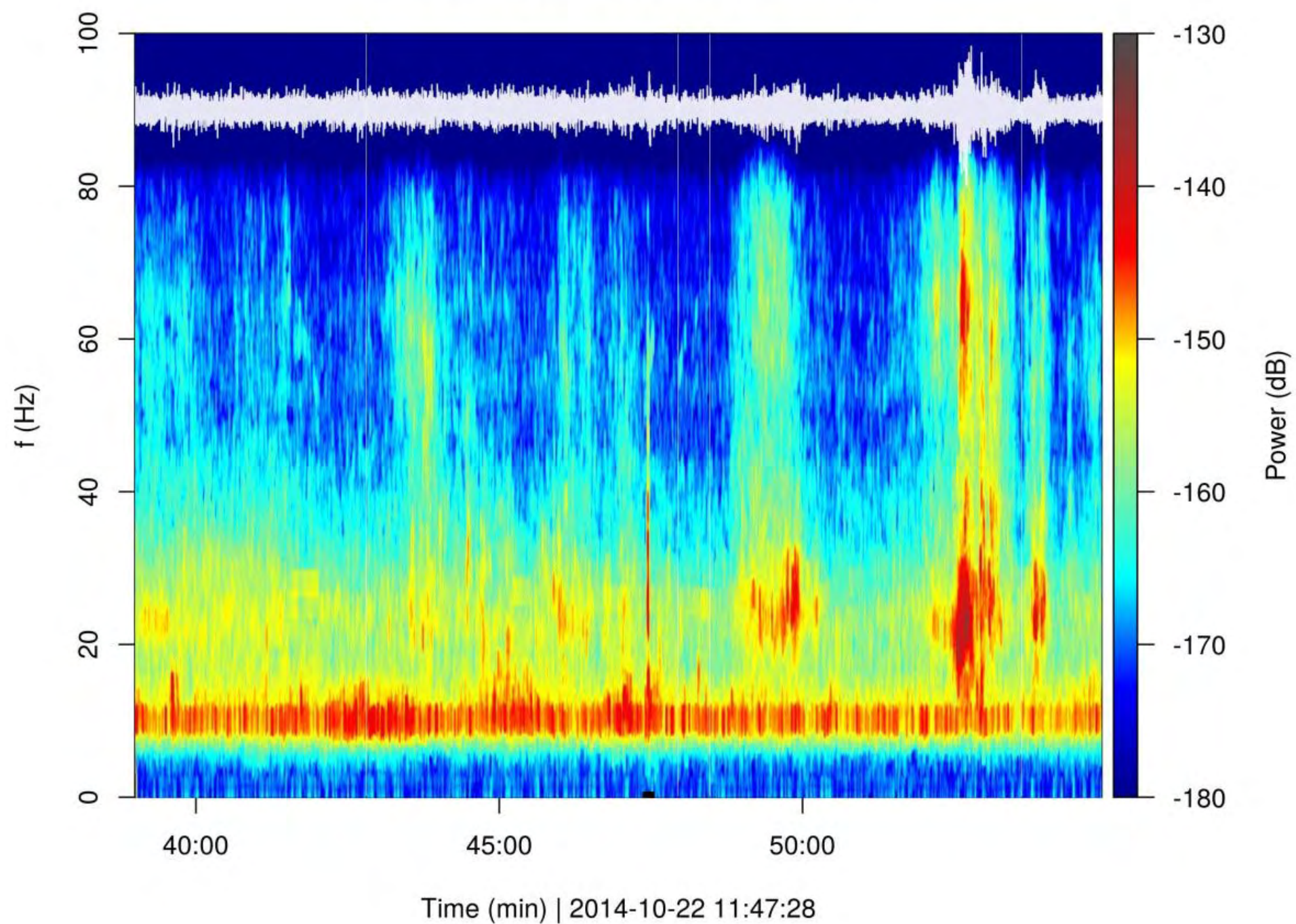
Event 14 @ Funny Rain (1-80 Hz)



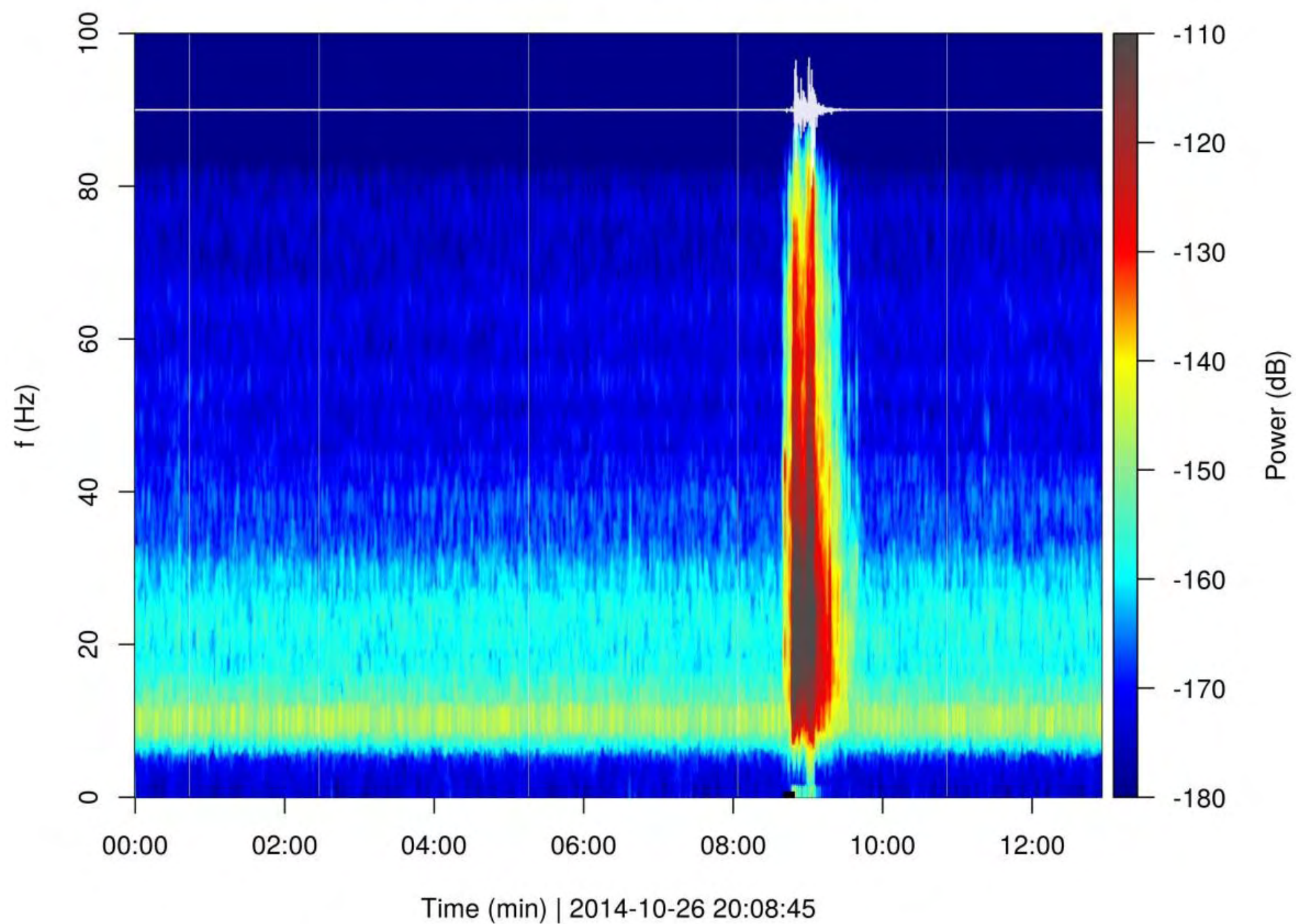
Event 15 @ Funny Rain (1-80 Hz)



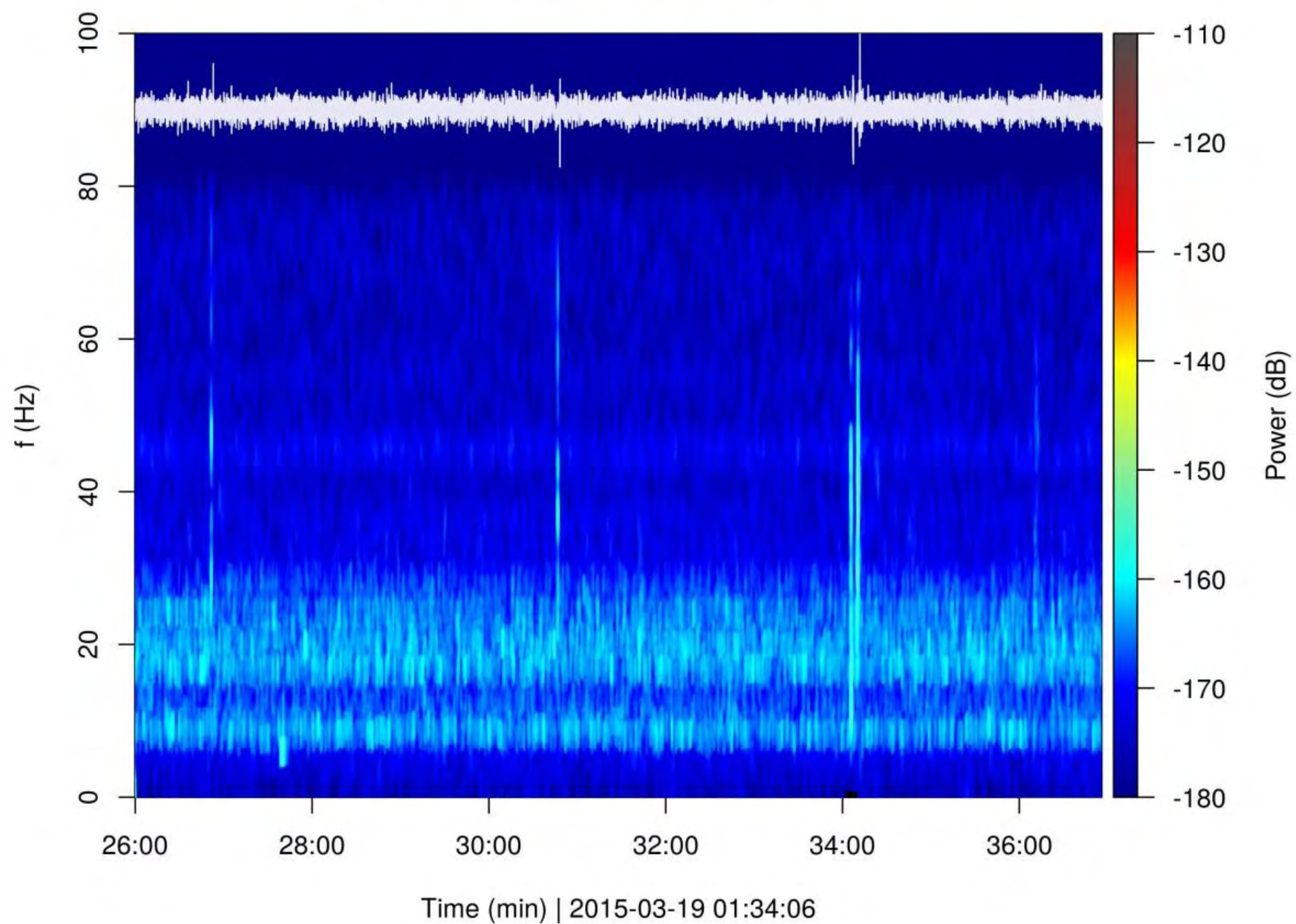
Event 16 @ Funny Rain (1-80 Hz)



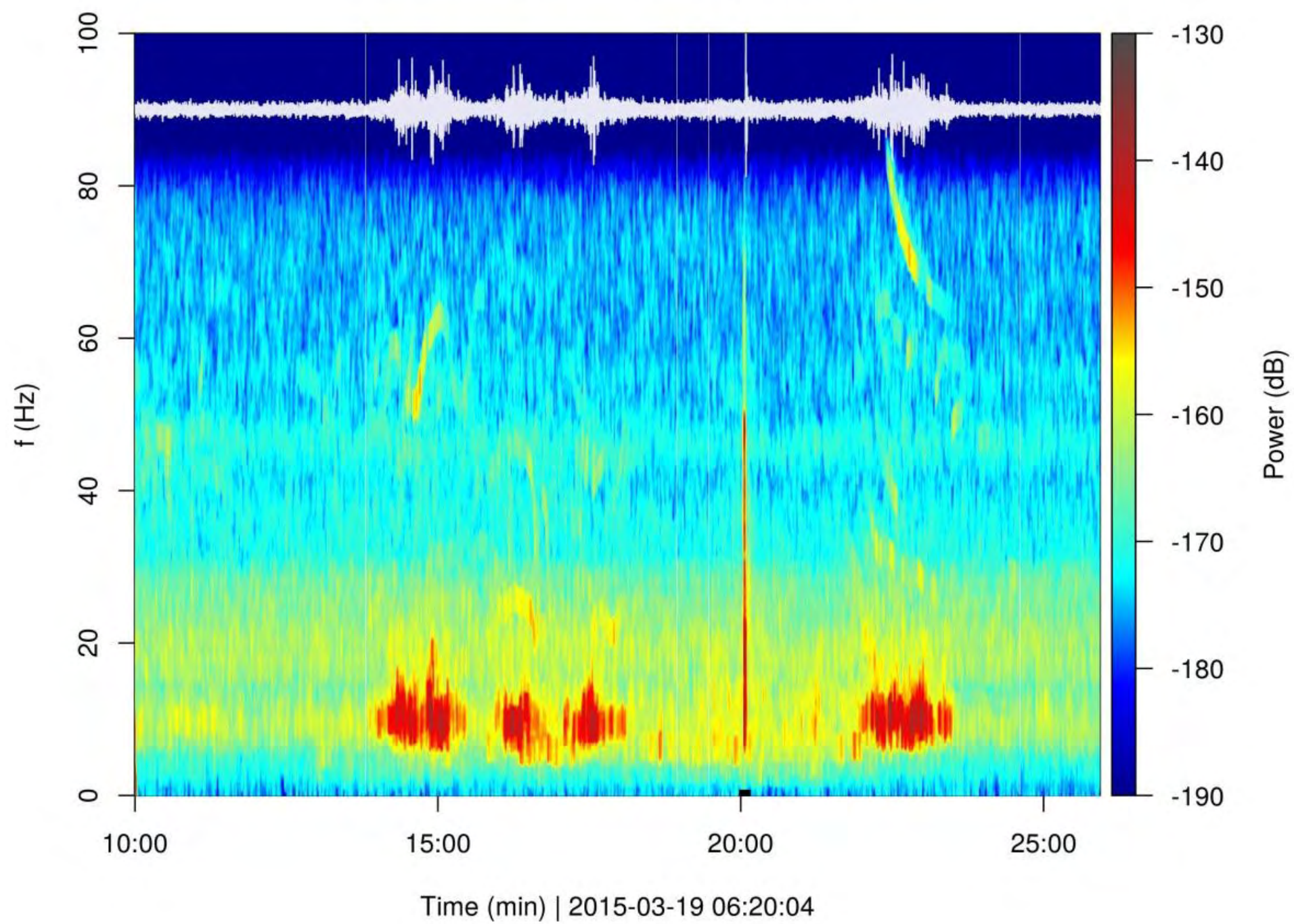
Event 17 @ Funny Rain (1-80 Hz)



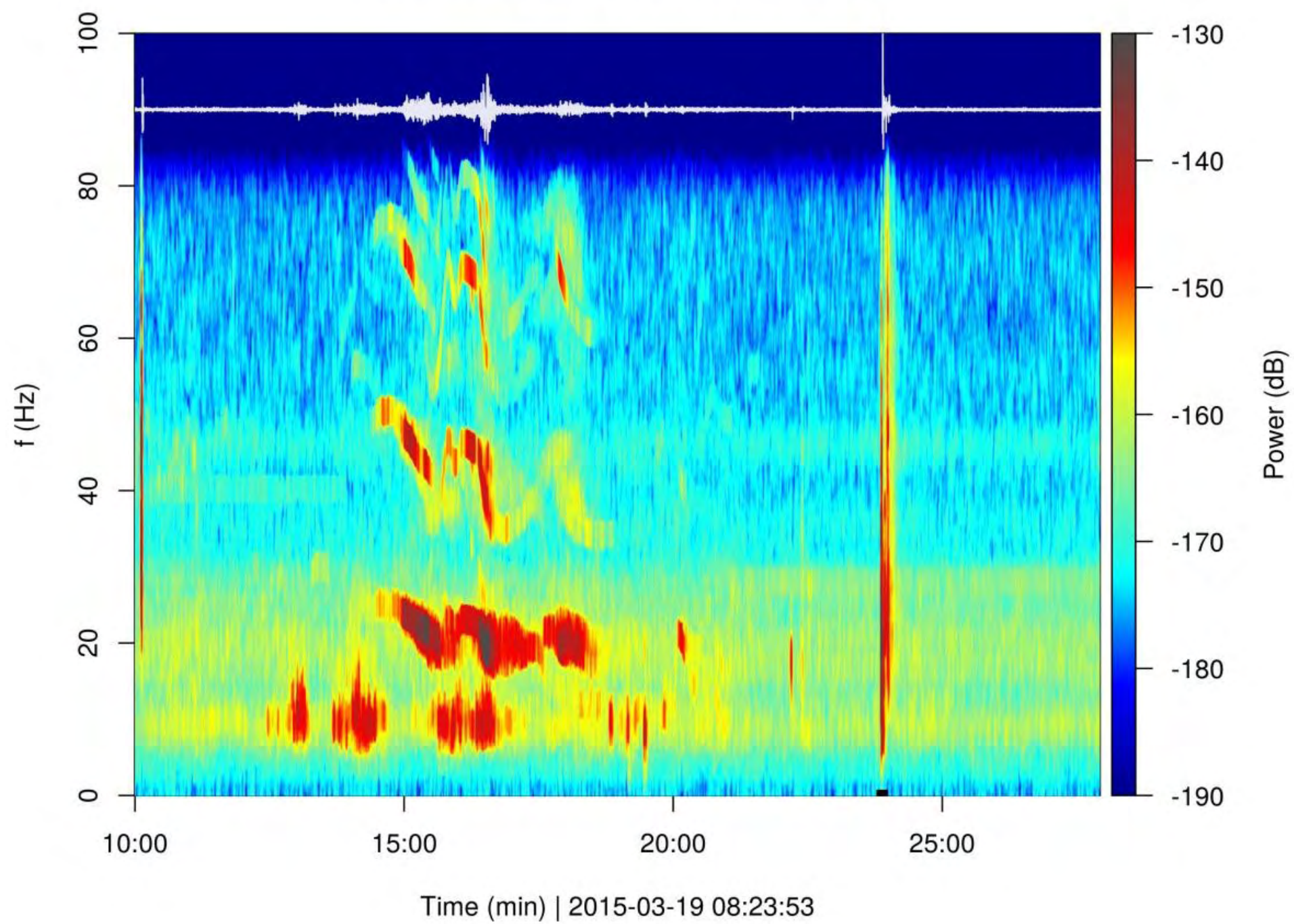
Event 18 @ Funny Rain (1-80 Hz)



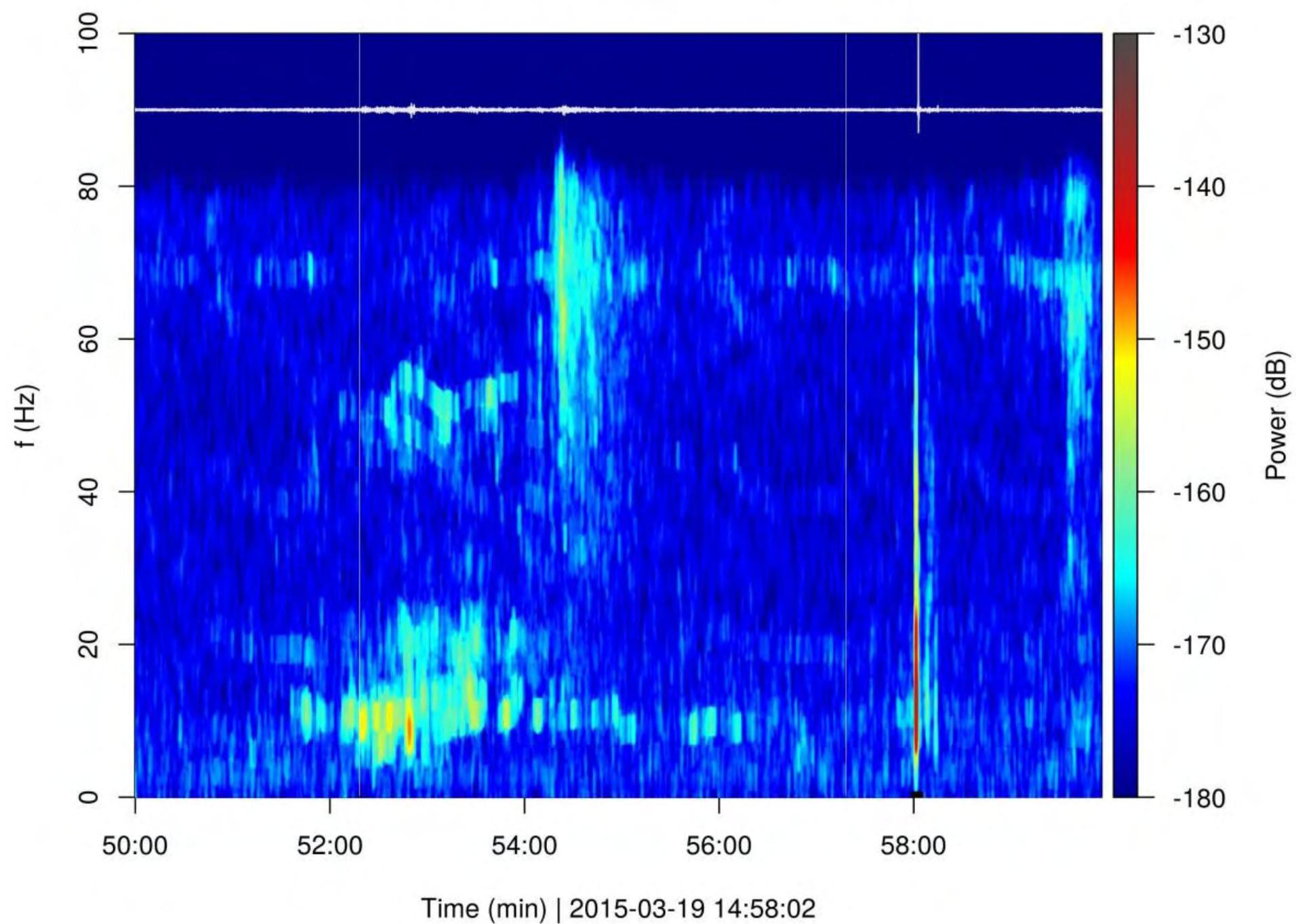
Event 19 @ Funny Rain (1-80 Hz)



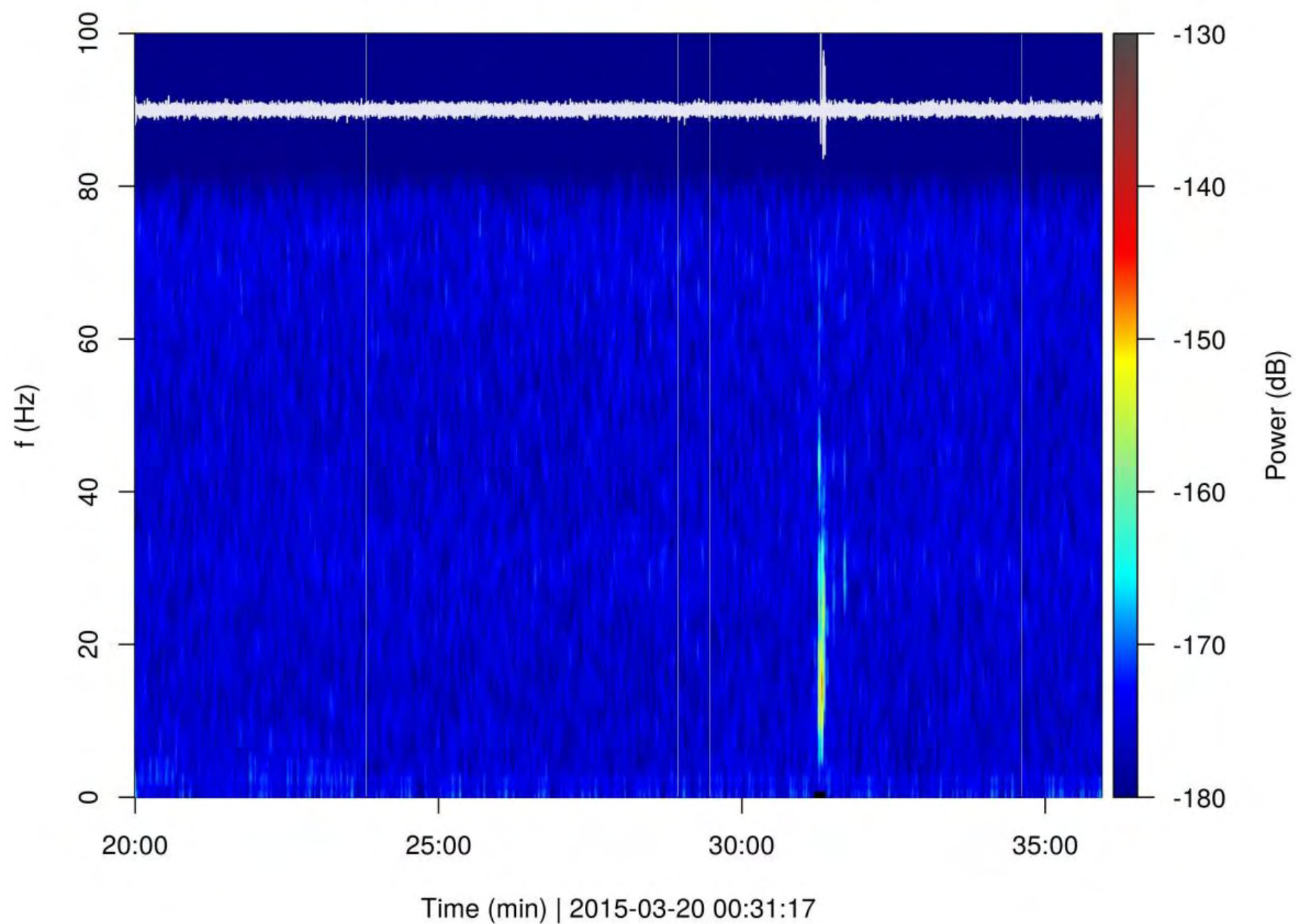
Event 20 @ Funny Rain (1-80 Hz)



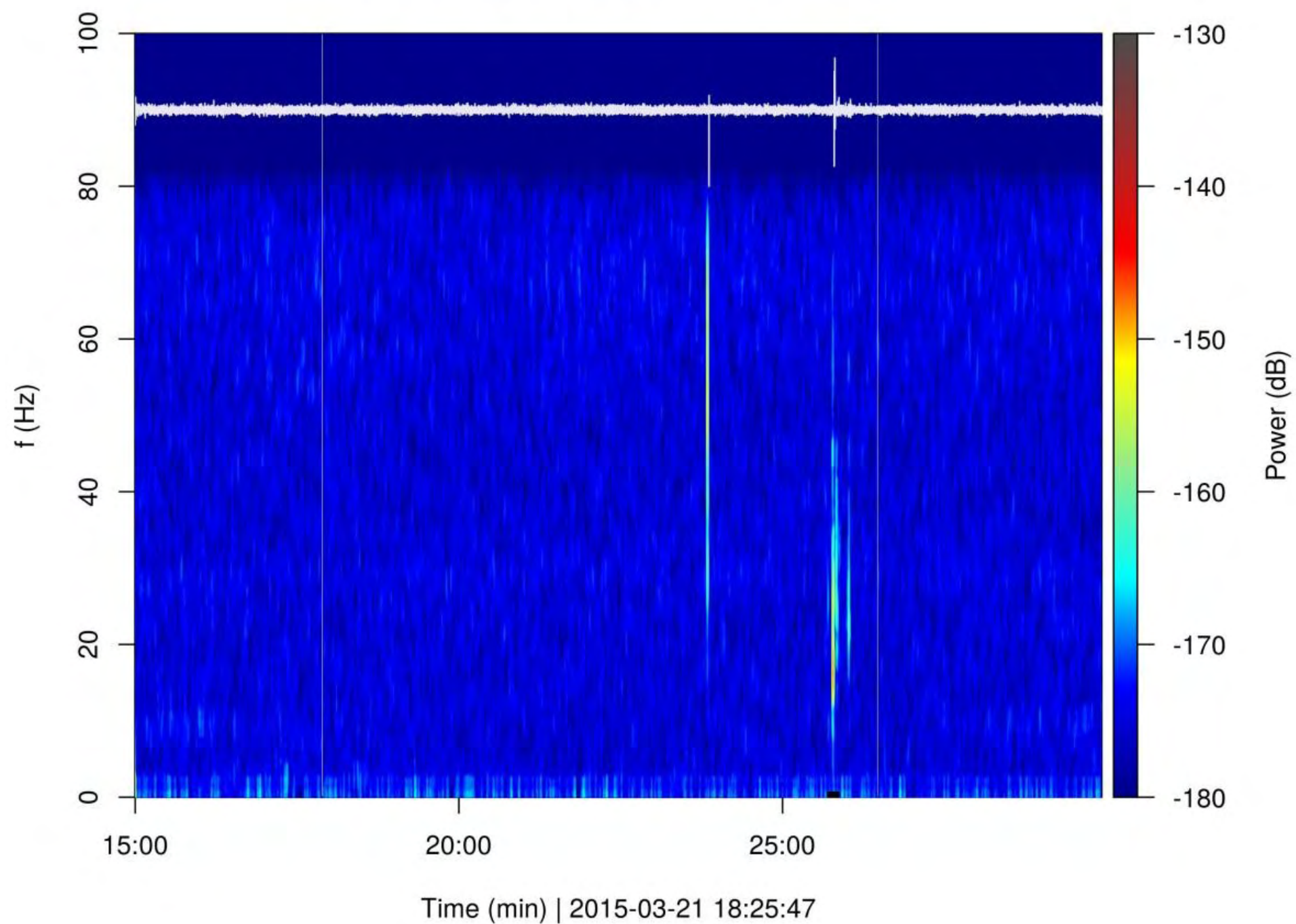
Event 21 @ Gate of China (1-80 Hz)



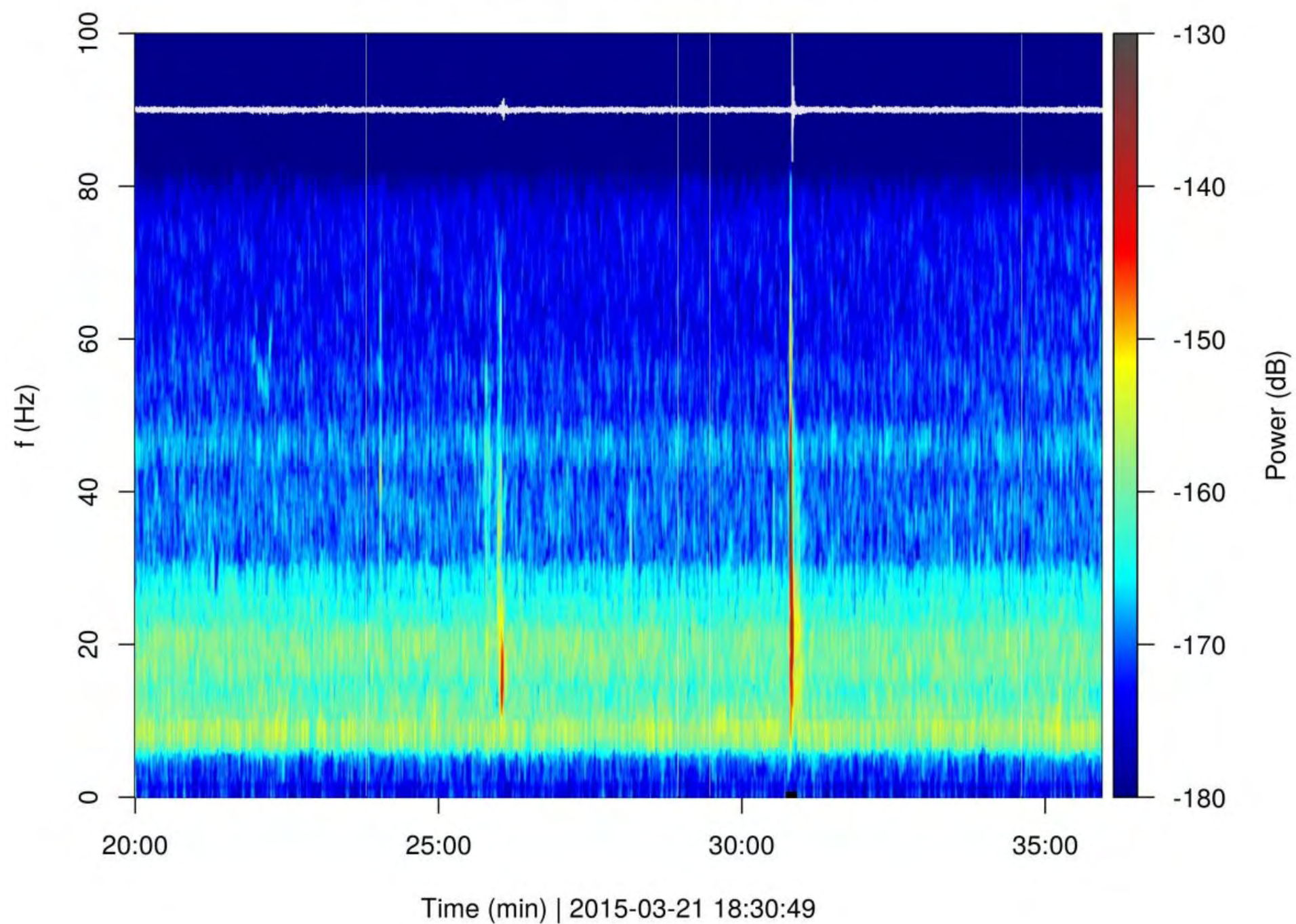
Event 22 @ Gate fo China (1-80 Hz)



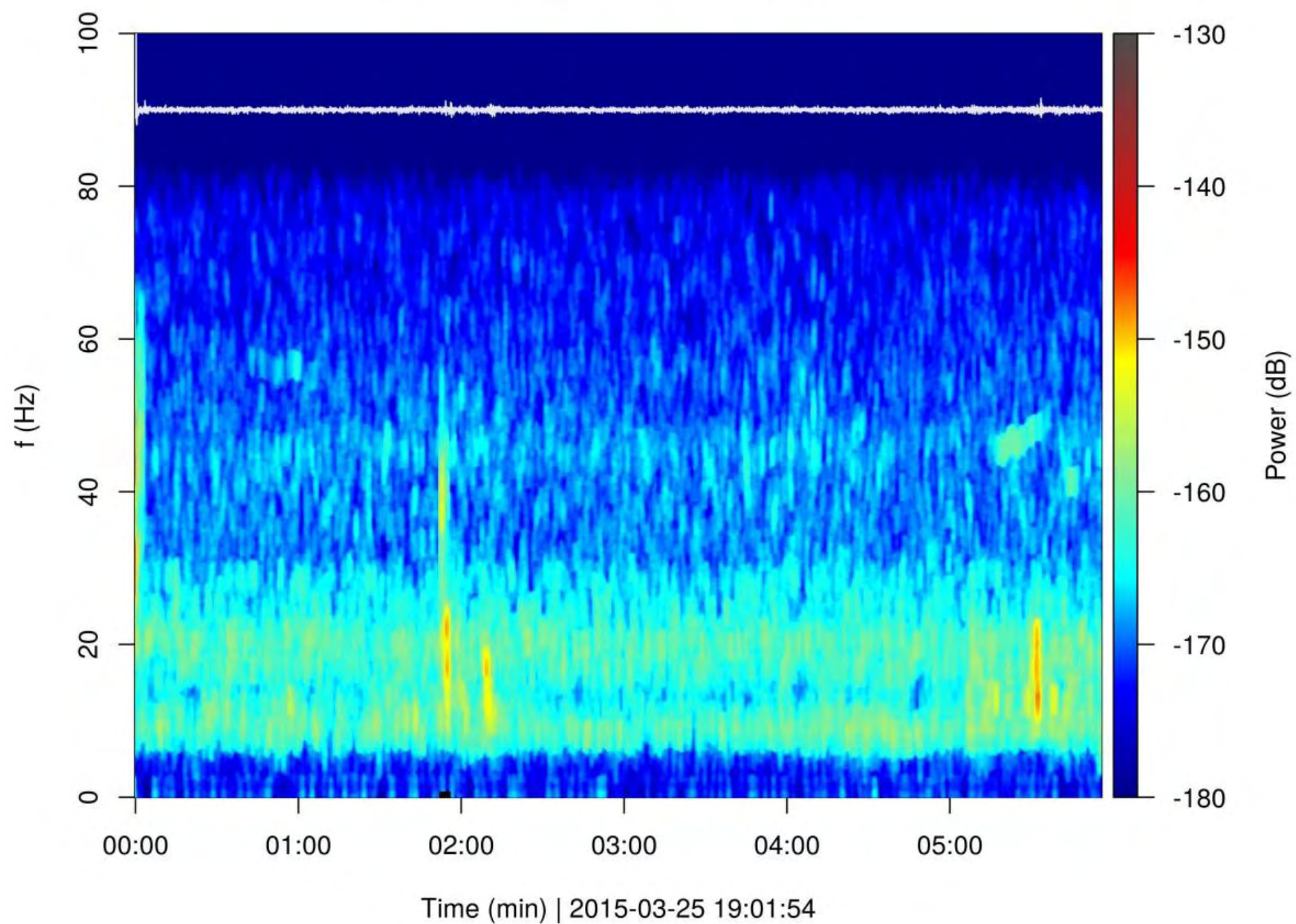
Event 23 @ Gate of China (1-80 Hz)



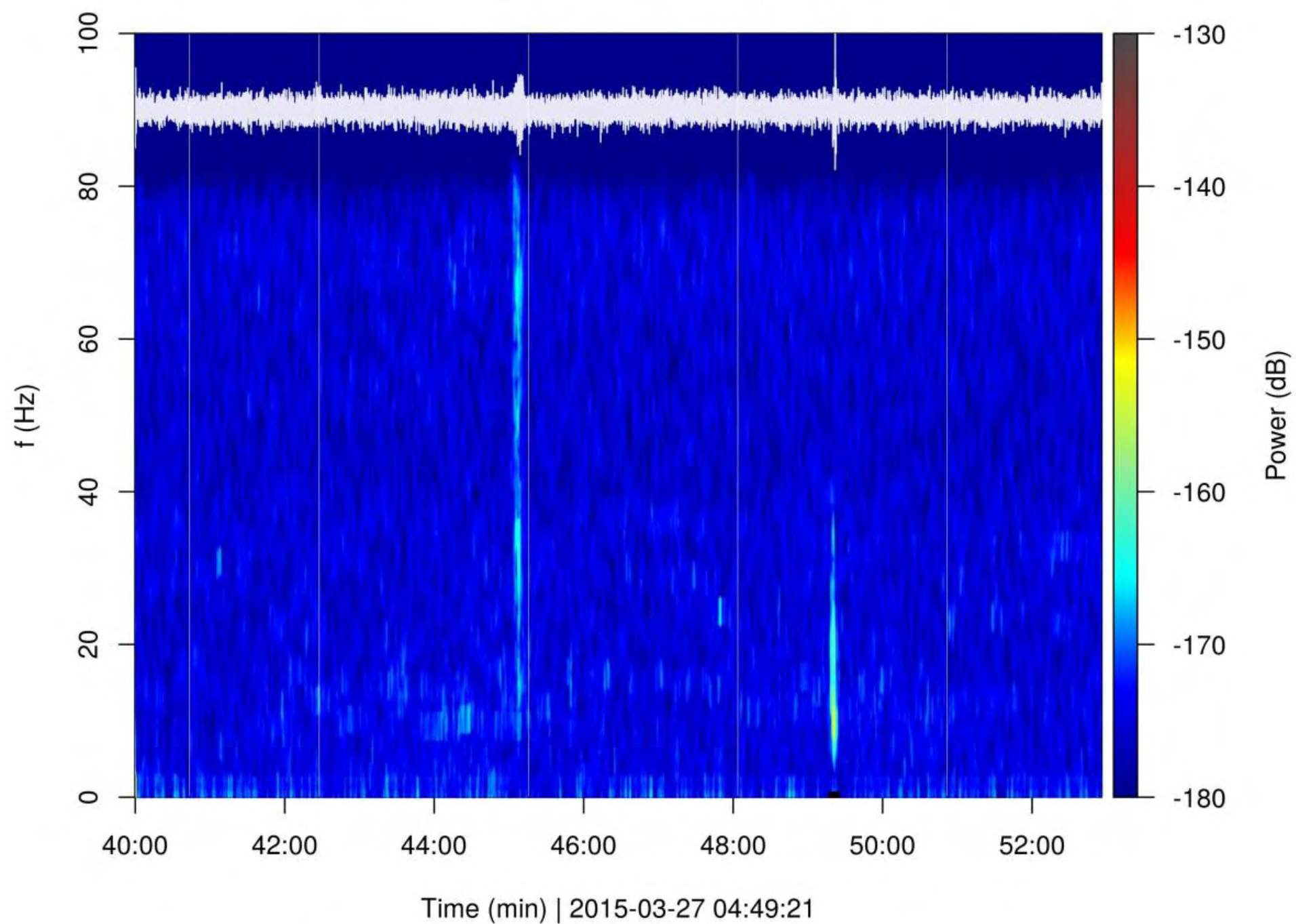
Event 24 @ Funny Rain (1-80 Hz)



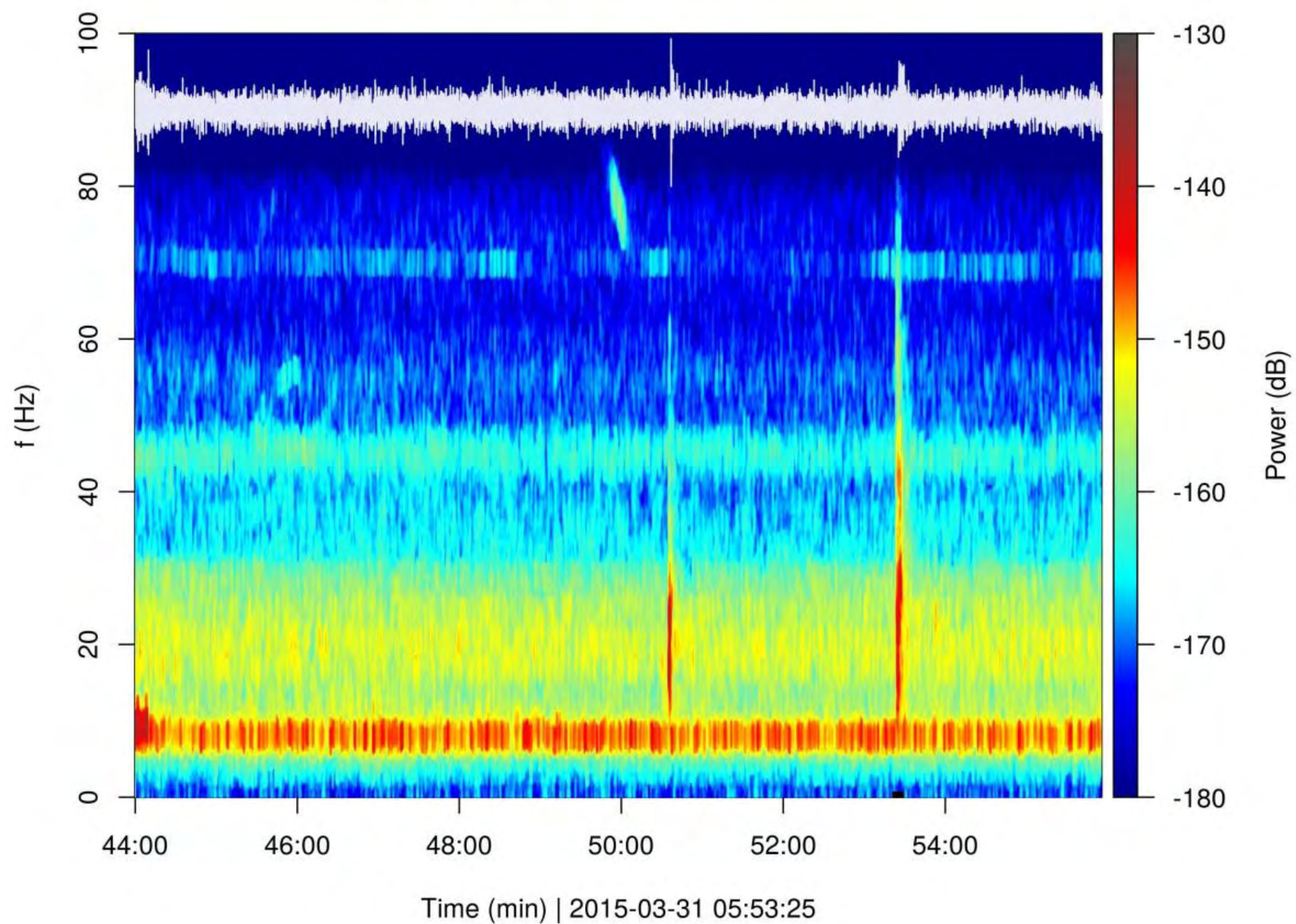
Event 25 @ Funny Rain (1-80 Hz)



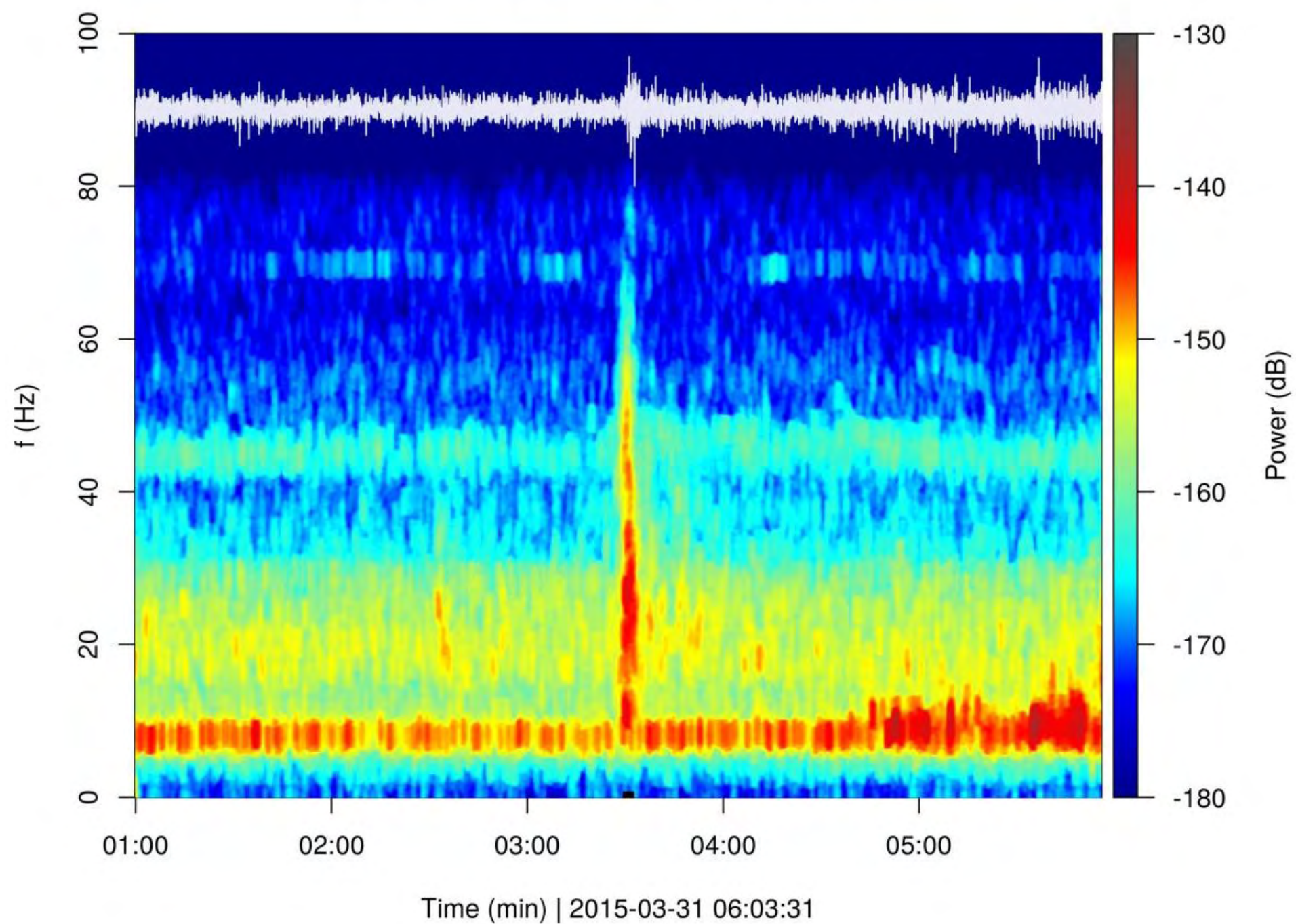
Event 26 @ Gate fo China (1-80 Hz)



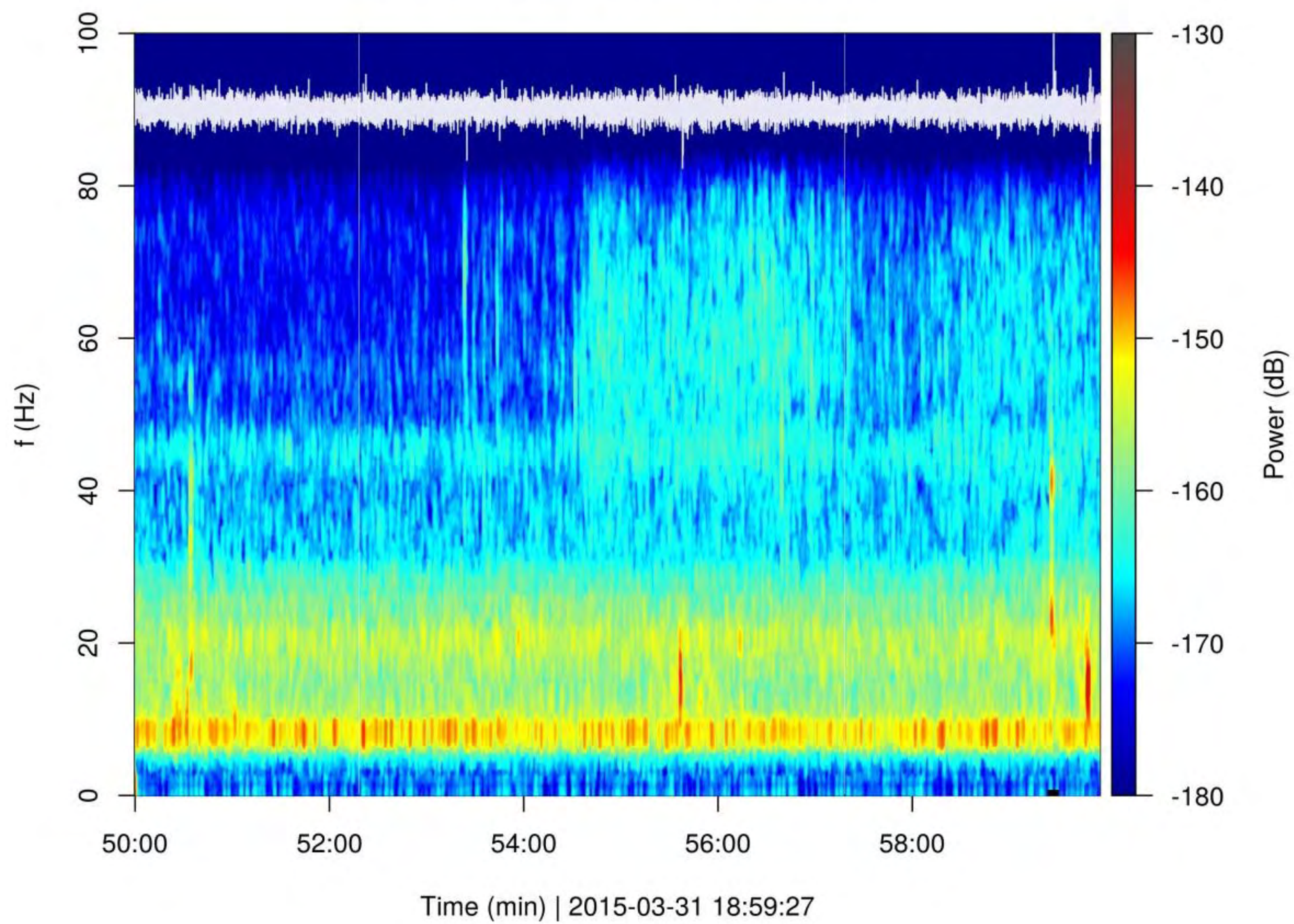
Event 26 @ Funny Rain (1-80 Hz)



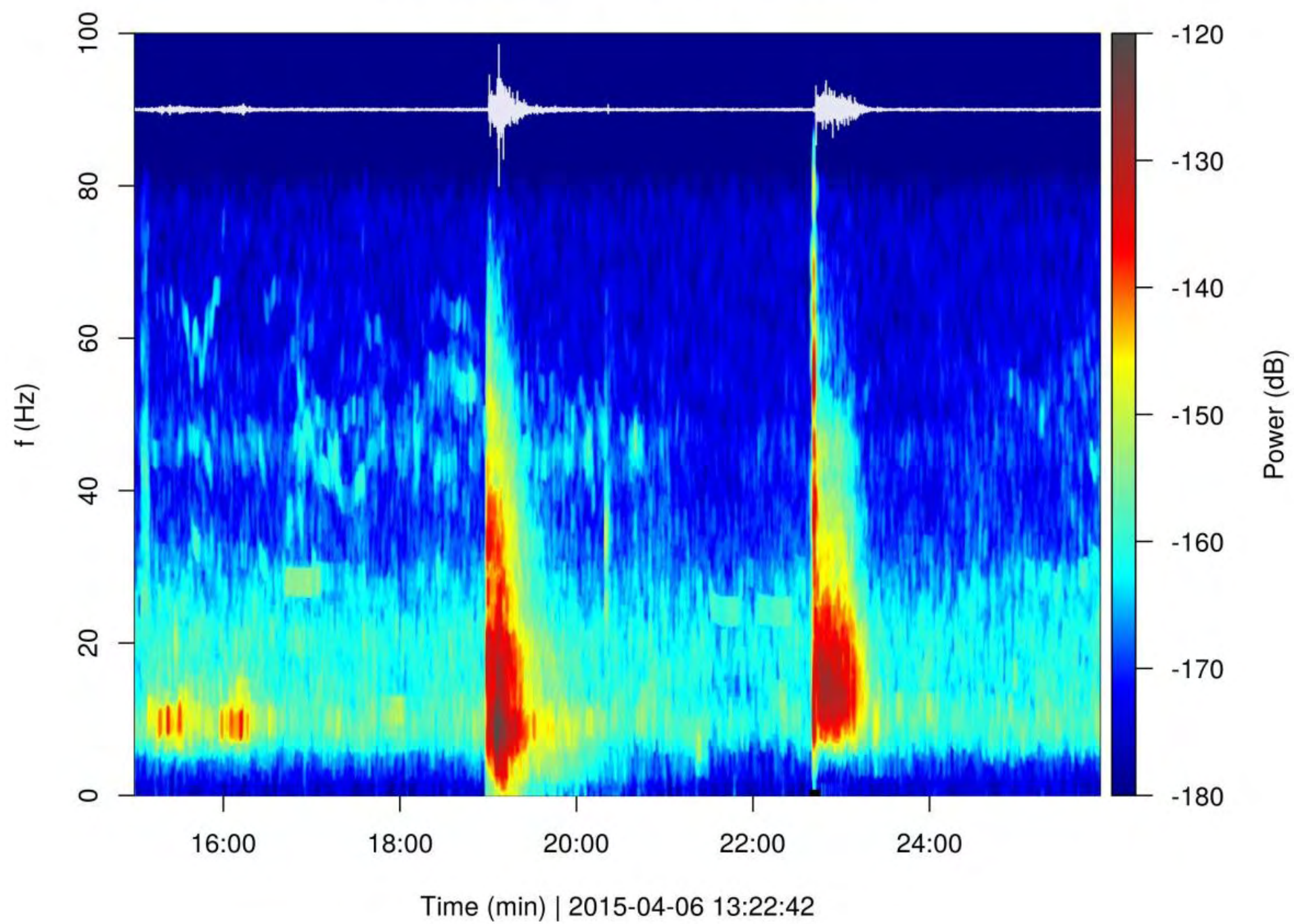
Event 28 @ Funny Rain (1-80 Hz)



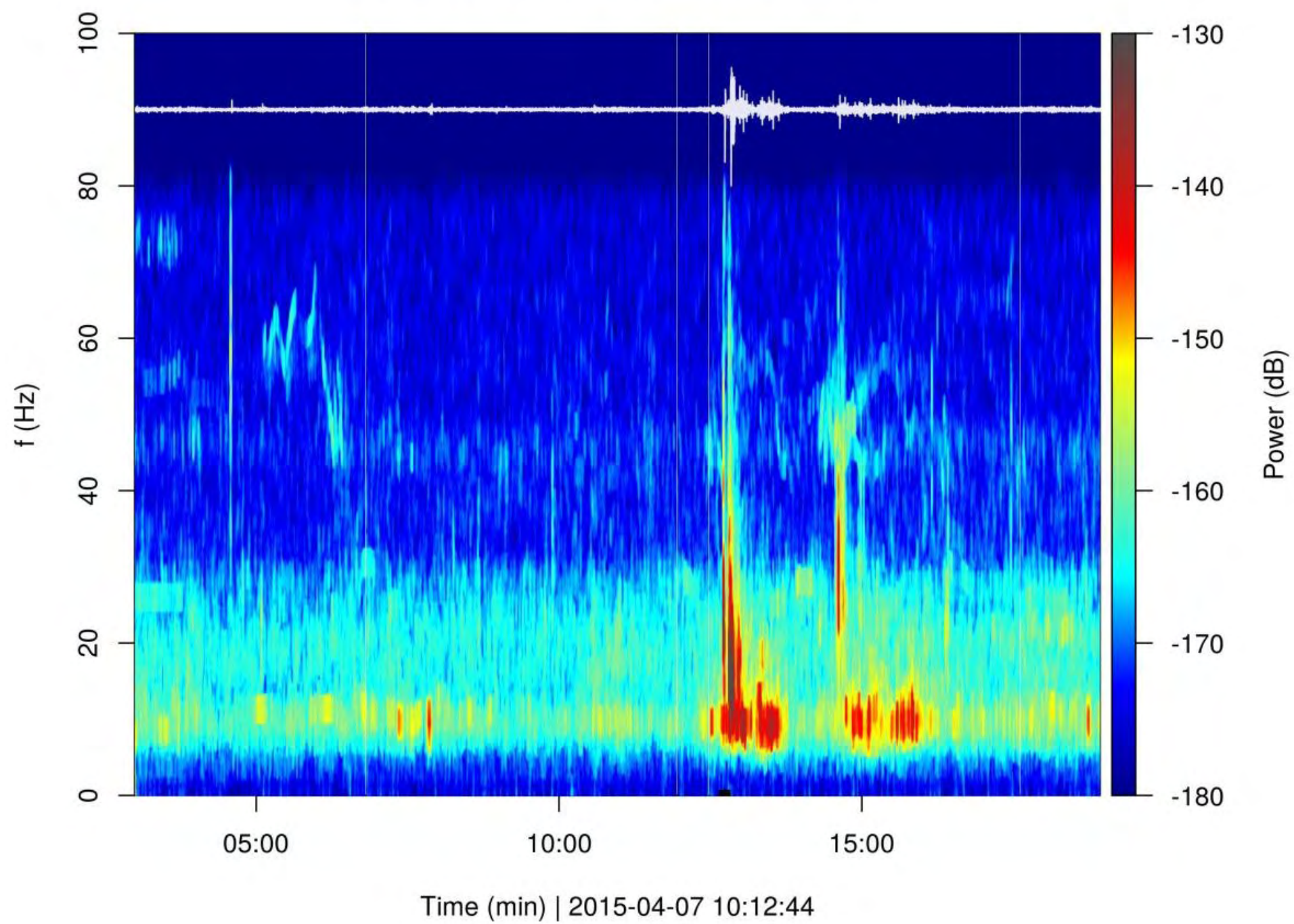
Event 29 @ Funny Rain (1-80 Hz)



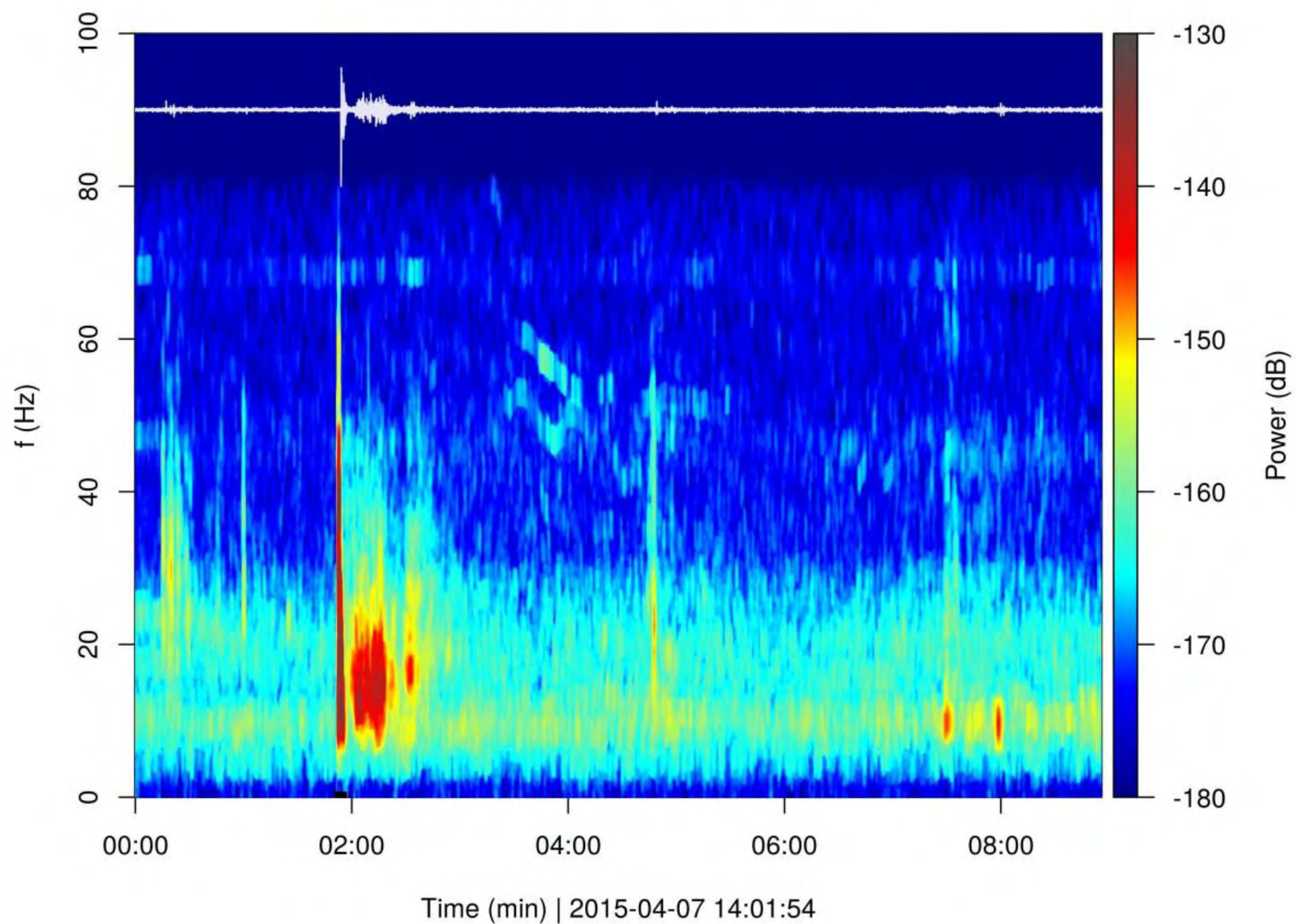
Event 30 @ Funny Rain (1-80 Hz)



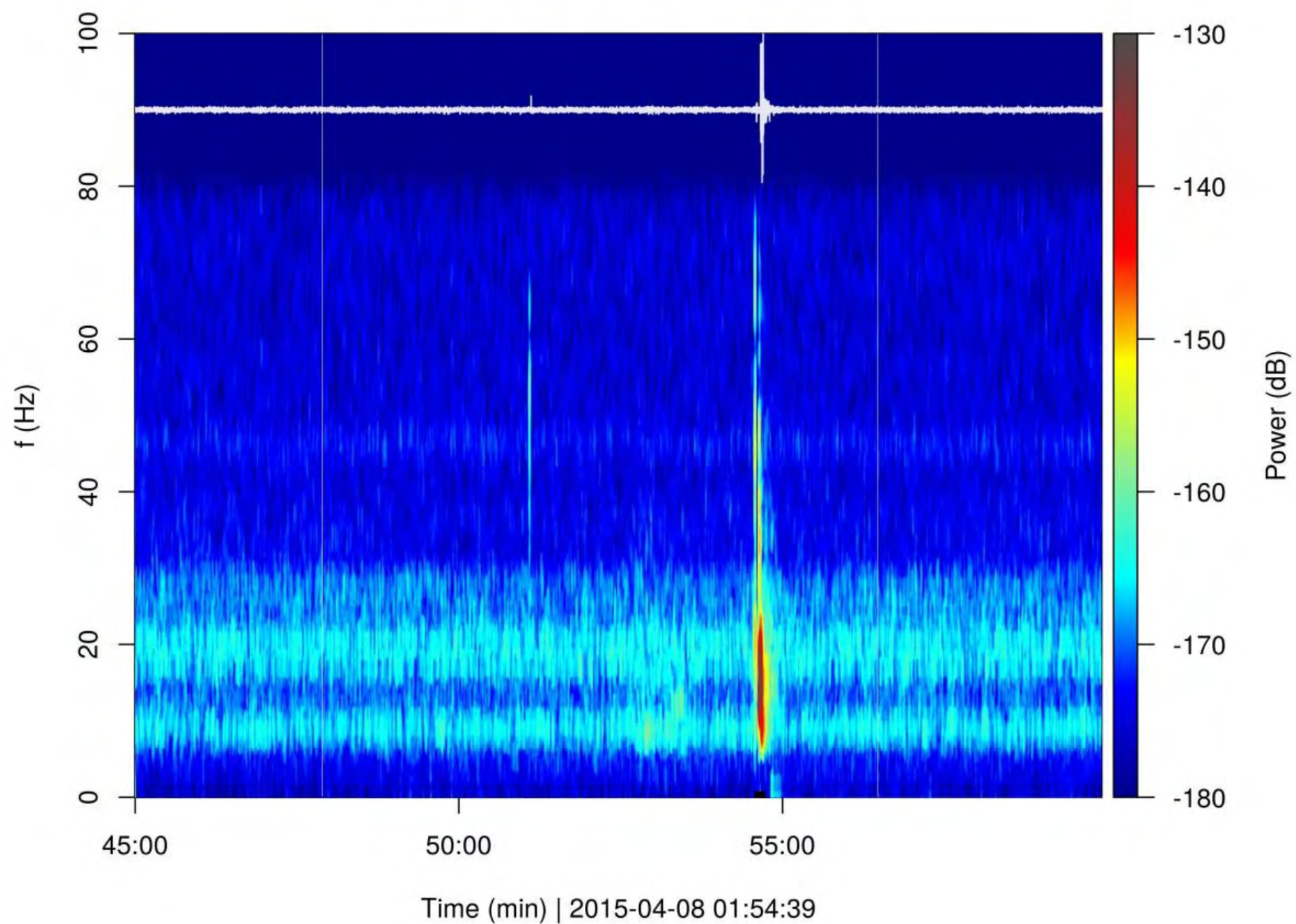
Event 31 @ Funny Rain (1-80 Hz)



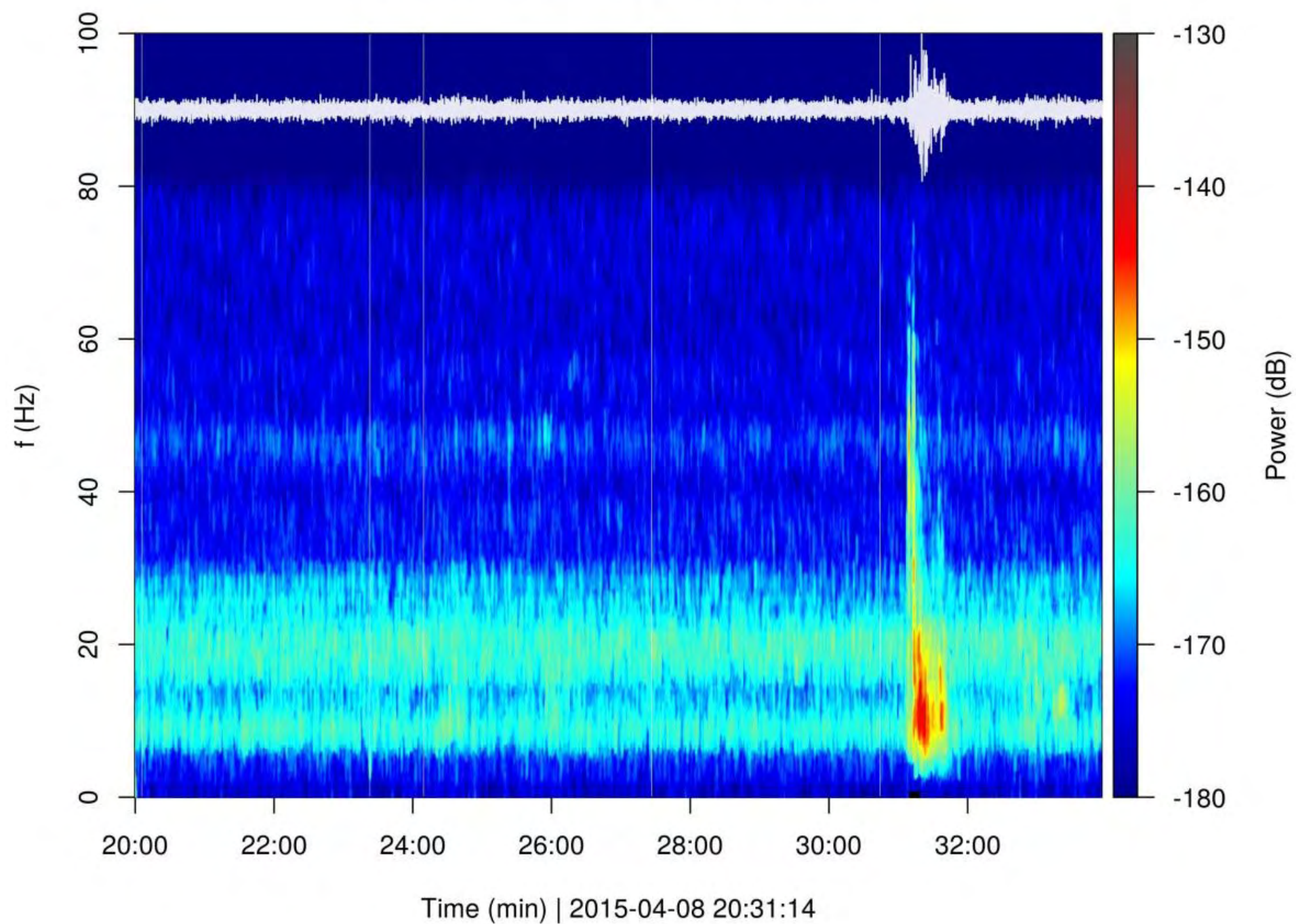
Event 32 @ Funny Rain (1-80 Hz)



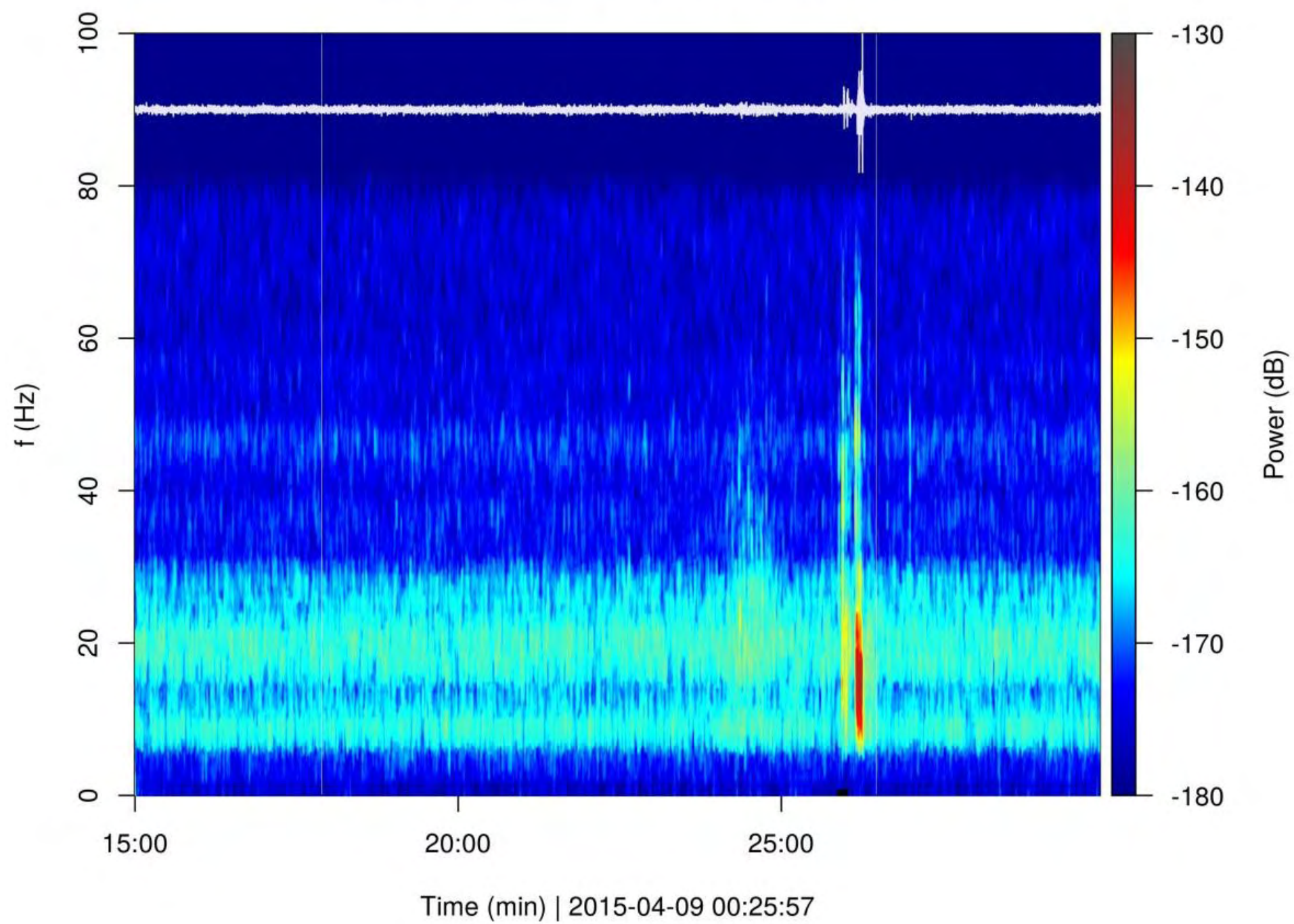
Event 33 @ Funny Rain (1-80 Hz)



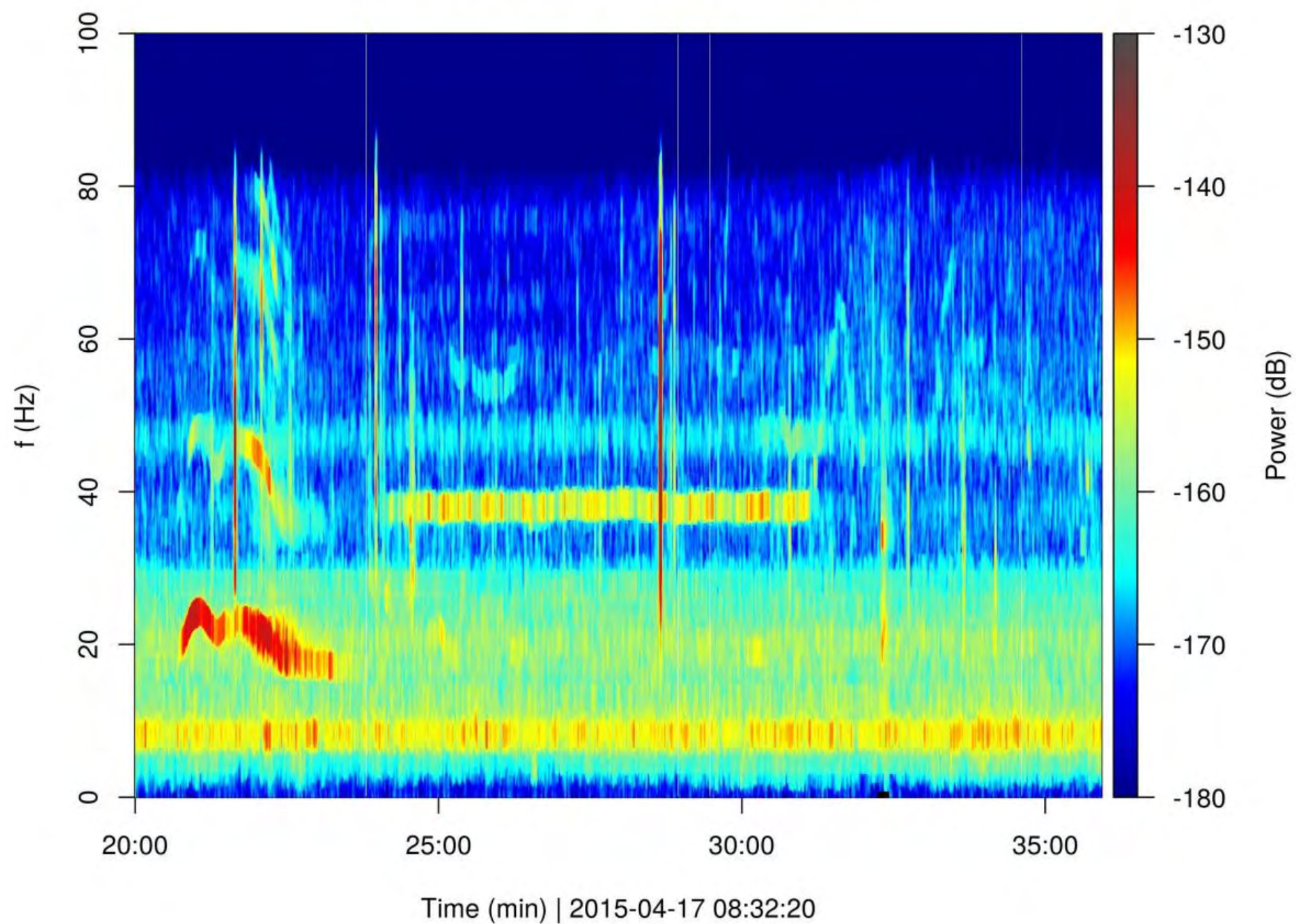
Event 34 @ Funny Rain (1-80 Hz)



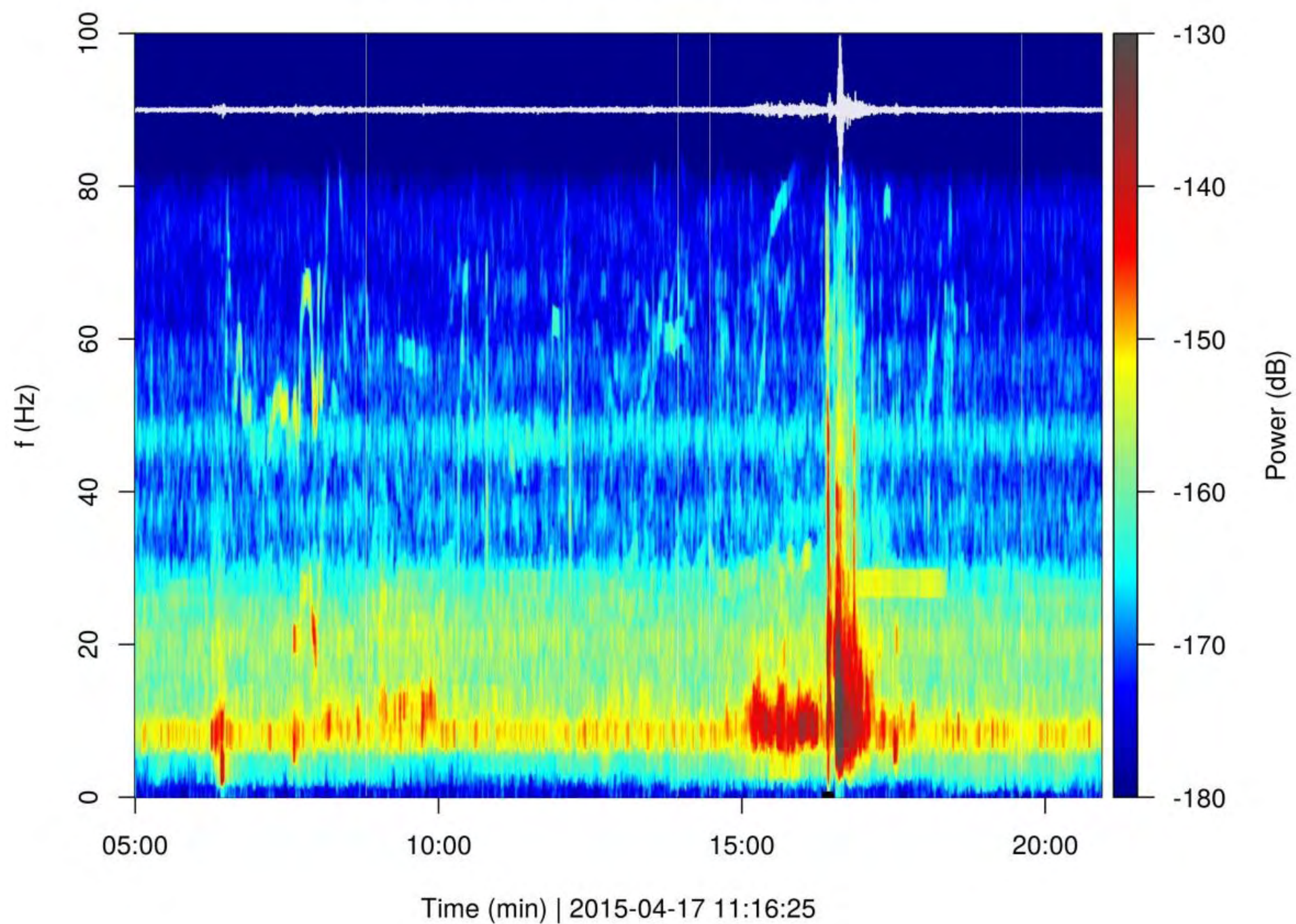
Event 35 @ Funny Rain (1-80 Hz)



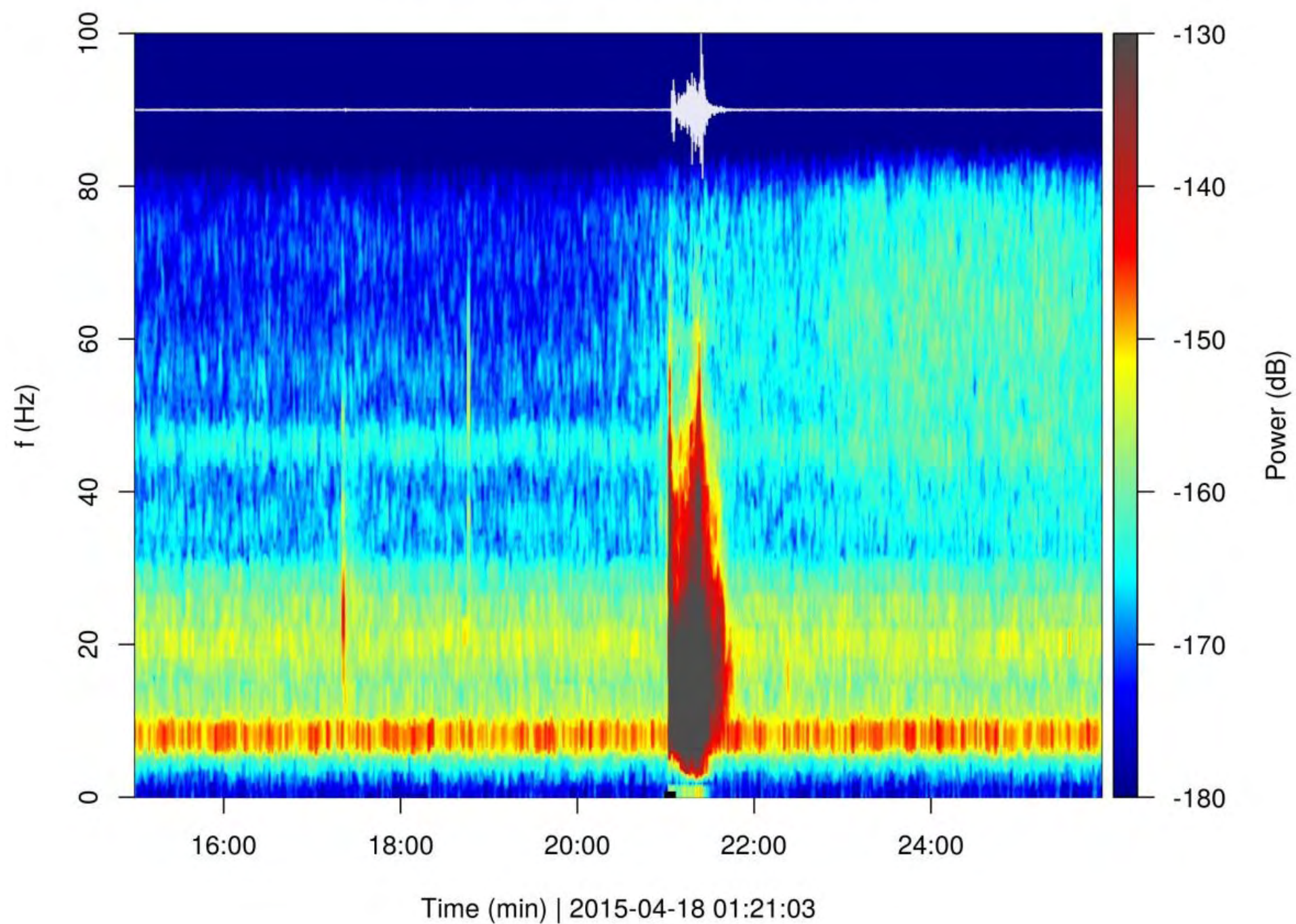
Event 36 @ Funny Rain (1-80 Hz)



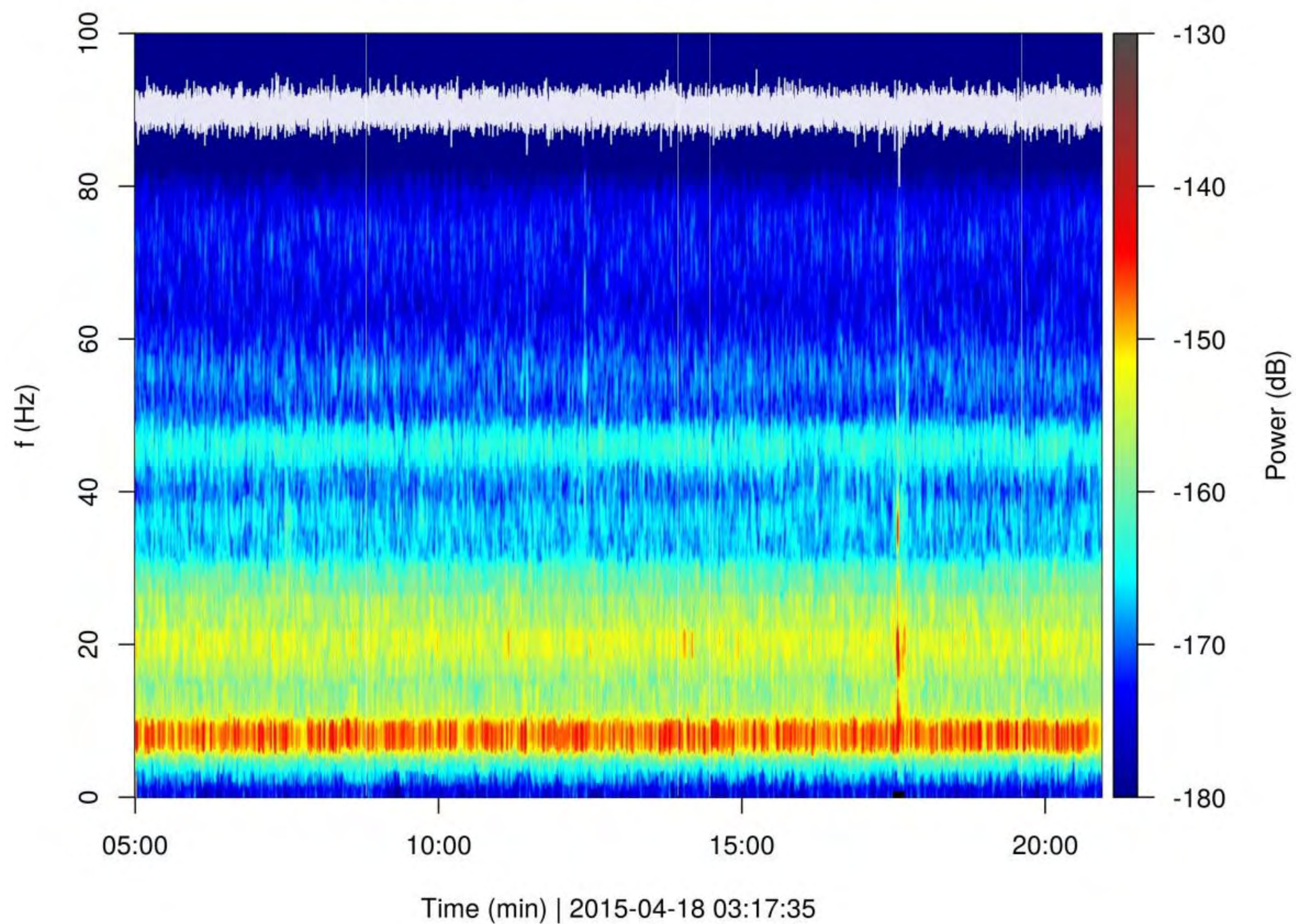
Event 37 @ Funny Rain (1-80 Hz)



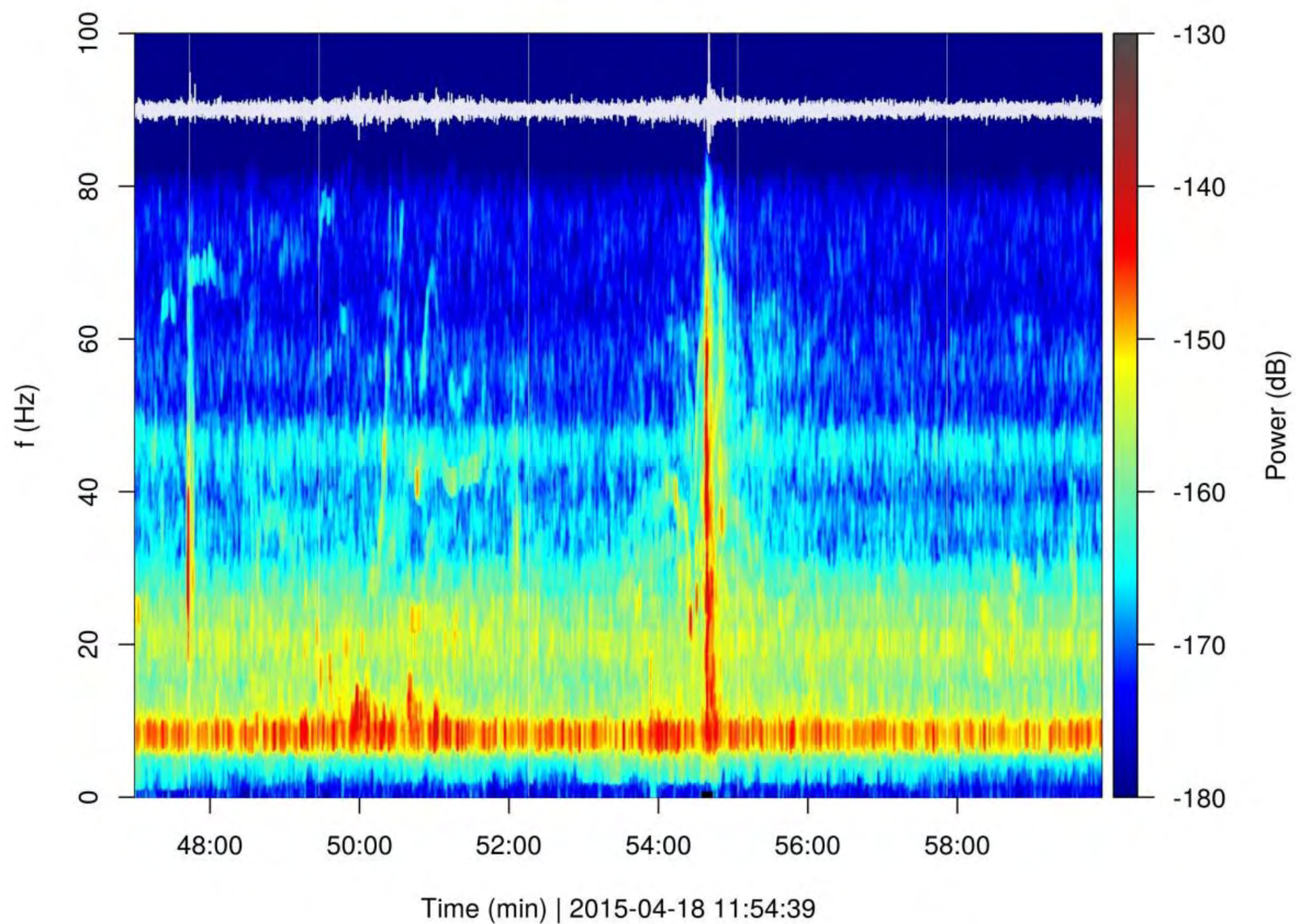
Event 38 @ Funny Rain (1-80 Hz)



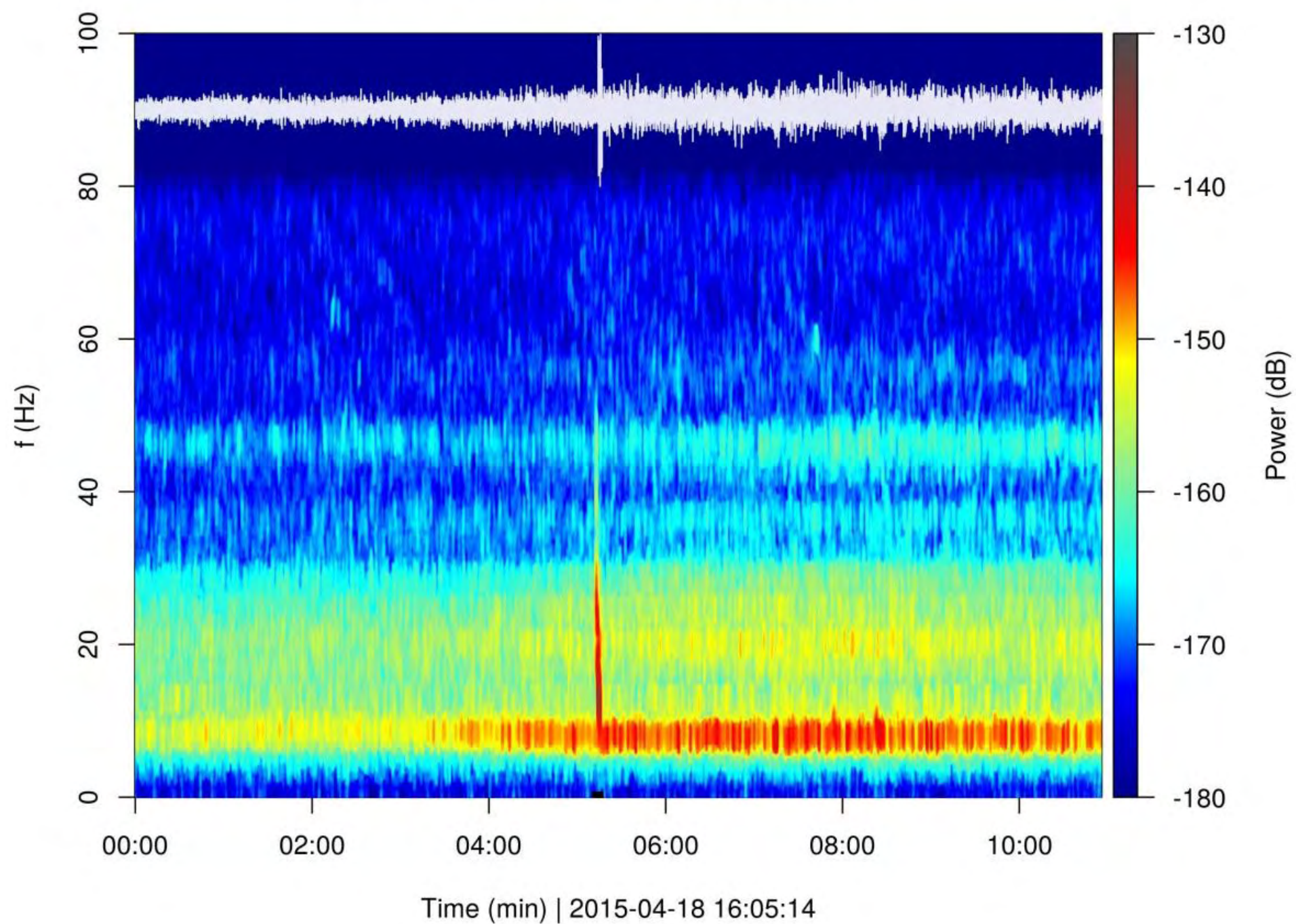
Event 39 @ Funny Rain (1-80 Hz)



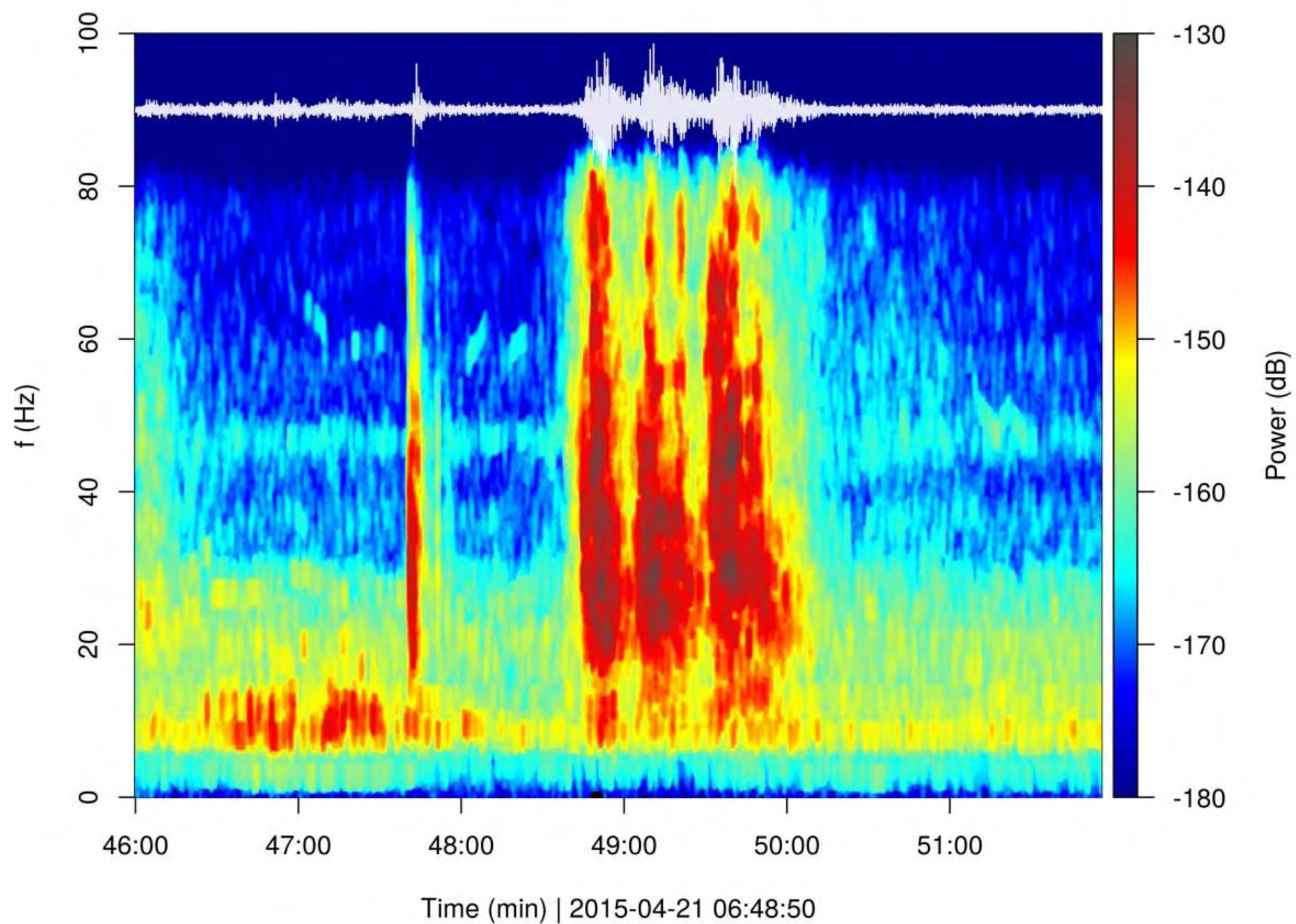
Event 40 @ Funny Rain (1-80 Hz)



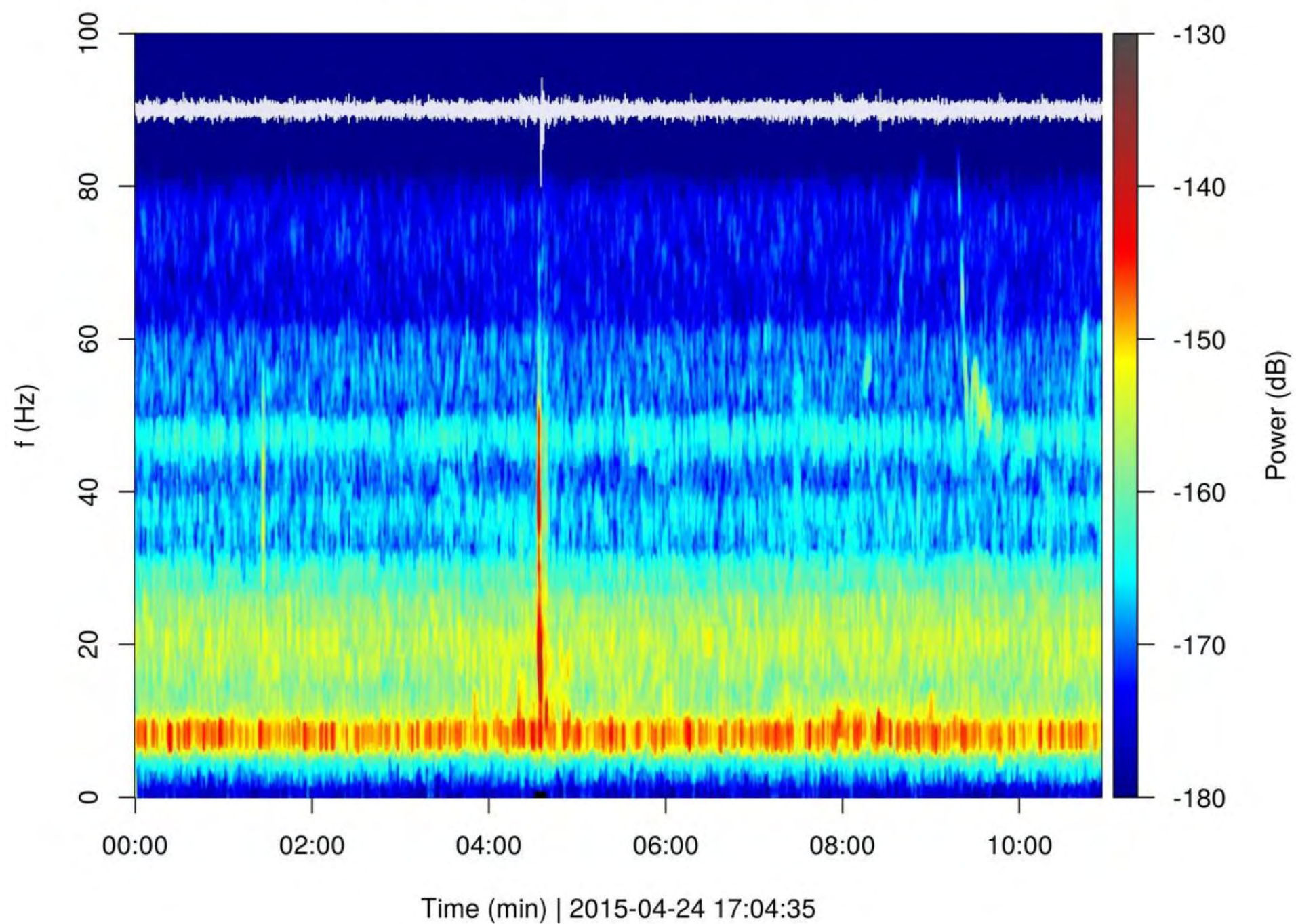
Event 41 @ Funny Rain (1-80 Hz)



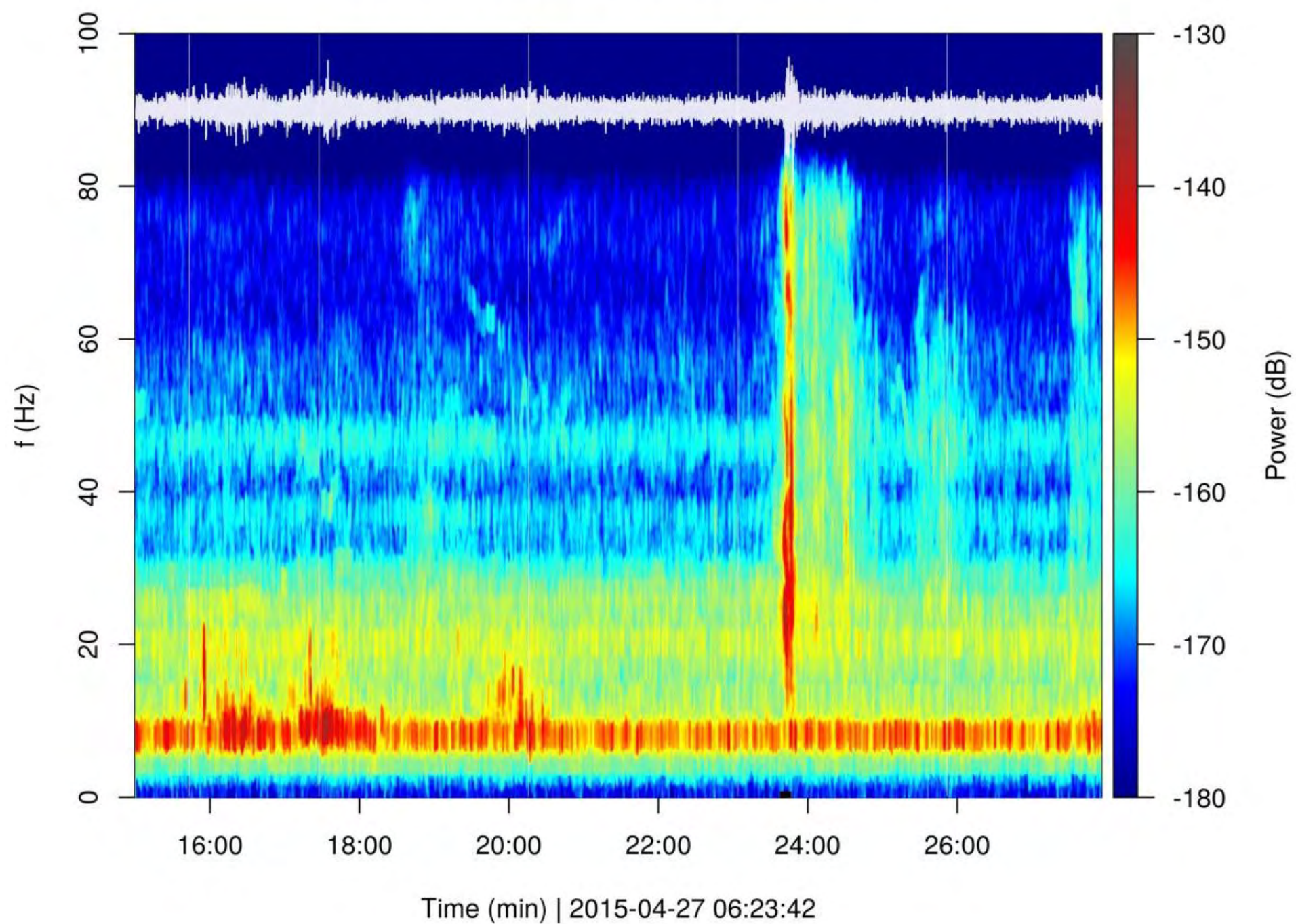
Event 42 @ Funny Rain (1-80 Hz)



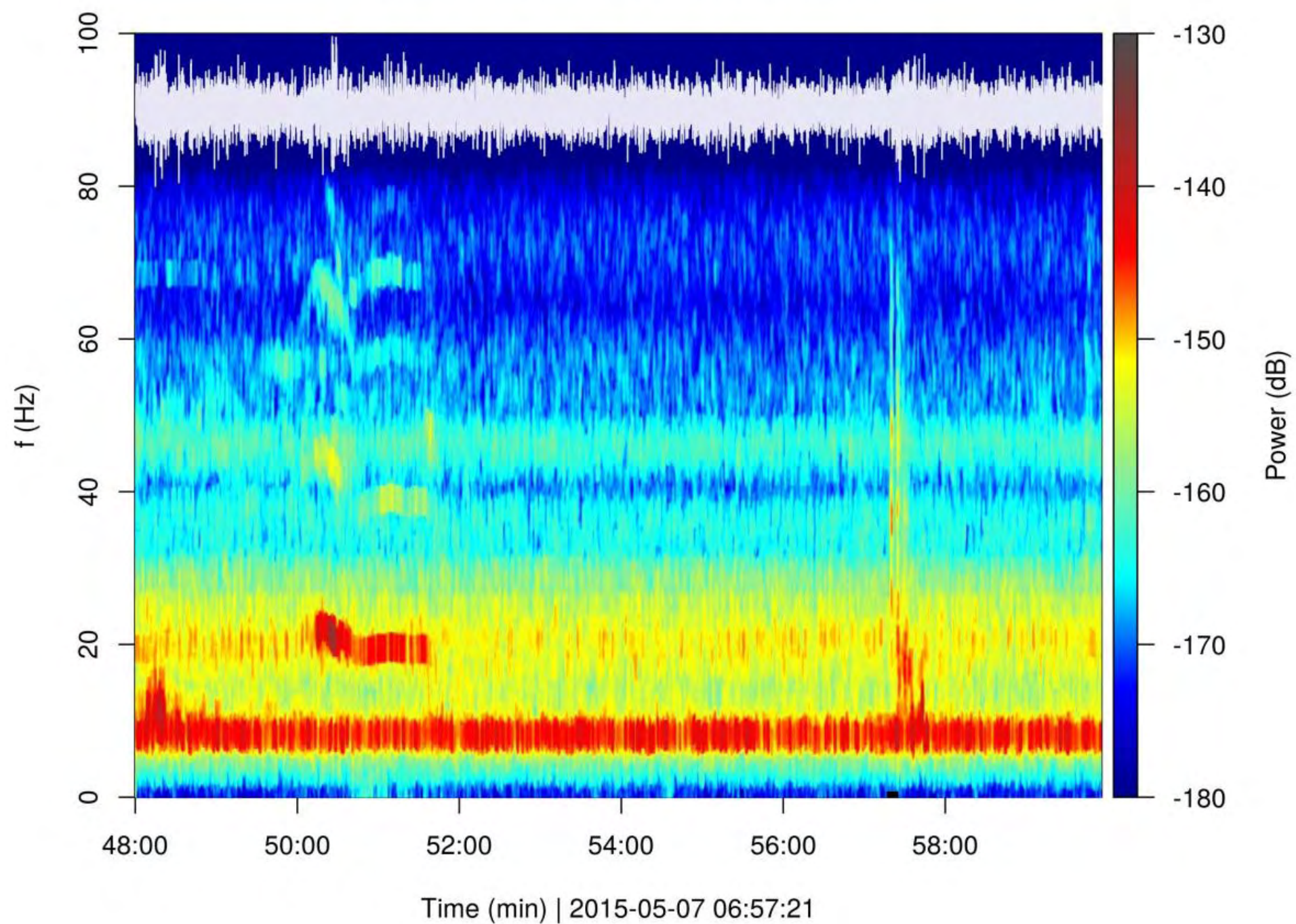
Event 43 @ Funny Rain (1-80 Hz)



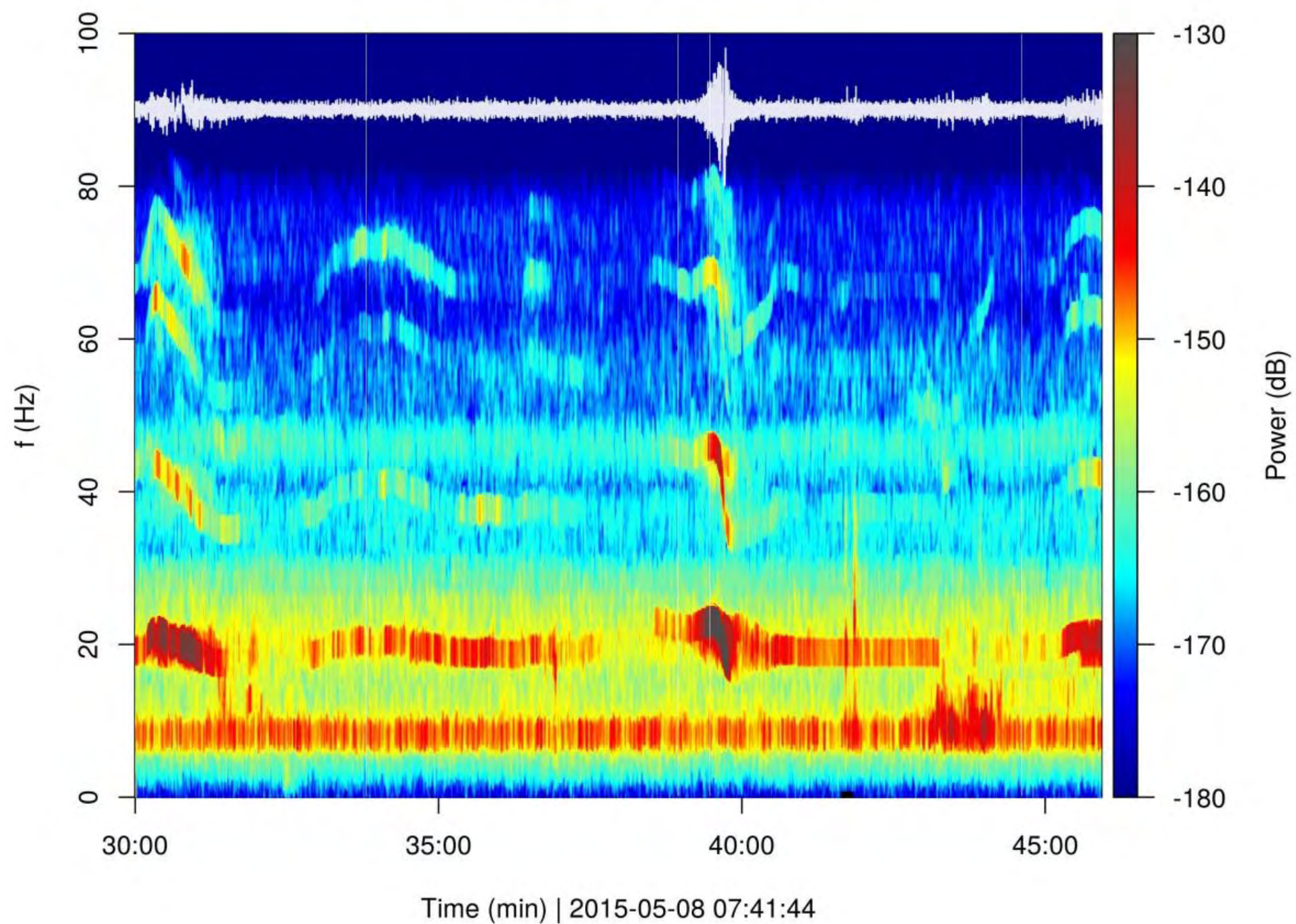
Event 44 @ Funny Rain (1-80 Hz)



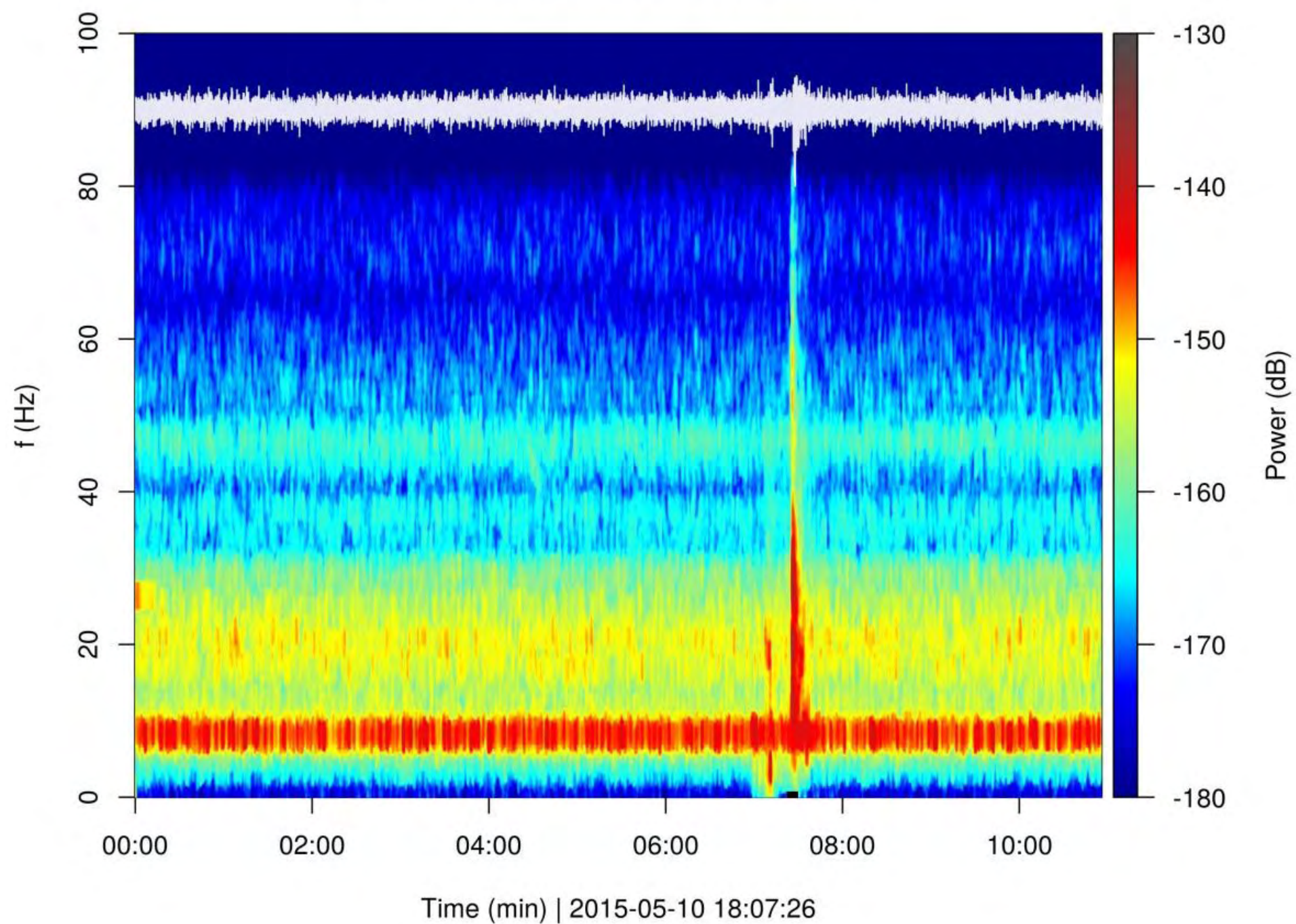
Event 45 @ Funny Rain (1-80 Hz)



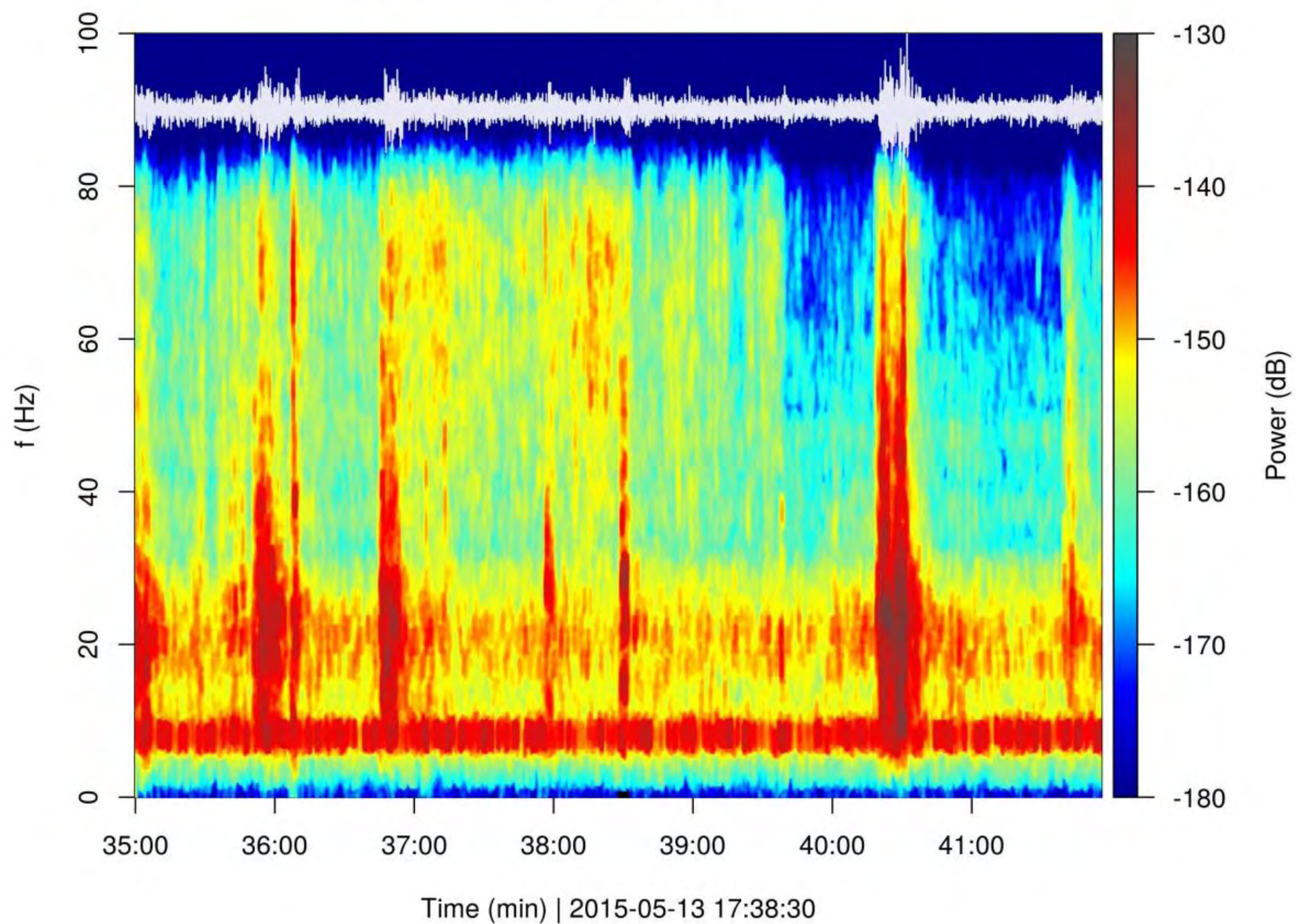
Event 46 @ Funny Rain (1-80 Hz)



Event 47 @ Funny Rain (1-80 Hz)



Event 48 @ Funny Rain (1-80 Hz)



Event 49 @ Funny Rain (1-80 Hz)

