

Spatiotemporal patterns and triggers of seismically detected rockfalls – Supplementary material

Michael Dietze, Jens M. Turowski, Kristen L. Cook, Niels Hovius (GFZ Potsdam, Section 5.1 Geomorphology)

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1 Explanations

This supplementary material contains a documentation of all 49 detected rockfall events from the article Spatiotemporal patterns and triggers of seismically detected rockfalls by Michael Dietze, Kristen L. Cook, Jens M. Turowski and Niels Hovius. 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.

Furthermore, for all events with a preceeding and posterior time window 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 after the 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.

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. SNR_{station} is the signal-to-noise ratio threshold that needed to be passed to allow localisation of an event. SNR₁ to SNR₄ 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)	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. $X_{seismic}$, $Y_{seismic}$ and $Z_{seismic}$ are the cartesian coordinates of the pixel with the highest seismic source location probability density P_{max} . Z_{lidar} (m asl.) is the rockfall detachment height based on the lidar study by Dietze et al. (NHES). Type denotes rockfall evolutionary type (cf. main article). $Event_{pre}$ and $Event_{post}$ indicate the time lag to previous and posterior seismic signals that could be attributed to rockfall activity. Location is a descriptive 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	$X_{seismic}$ (m)	$Y_{seismic}$ (m)	$Z_{seismic}$ (m asl.)	Z_{lidar} (m asl.)	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	A	NA	NA	cliff	6.2	26.9	NA	NA
2	416035	5158531	1085	NA	A	NA	0.9	cliff	6.2	35.6	NA	NA
3	415485	5156861	1240	NA	B	NA	NA	cliff	1.2	34.3	NA	NA
4	415855	5157551	1088	NA	B	NA	1.5	cliff	6	0.6	NA	NA
5	416025	5158561	1064	NA	B	3.7	1.6	cliff	36.2	0.2	NA	NA
6	416015	5158471	1089	NA	A	1.6	1.6	cliff	4	0.3	NA	NA
7	415465	5156501	1119	NA	B	3.9	NA	cliff	8.8	22.7	NA	NA
8	416015	5157781	918	1005	B	NA	10.3	cliff	2.2	6.1	NA	NA
9	416115	5158701	916	984	C	NA	NA	cliff	3.2	19.4	NA	NA
10	415975	5158271	1186	1108	B	NA	NA	cliff	3.2	52.0	NA	NA
11	415485	5156561	1089	1064	A	NA	NA	cliff	1	167.8	NA	NA
12	415505	5156541	1036	1018	A	NA	NA	cliff	0.2	2.0	NA	NA
13	416065	5158811	1127	1218	C	NA	NA	cliff	1.6	7.2	NA	NA
14	415505	5156871	1198	1104	B	NA	NA	cliff	3.4	79.1	NA	NA
15	415515	5156841	1177	954	B	NA	4.3	cliff	3.4	83.2	NA	NA
16	415635	5156991	1016	955	A	NA	NA	cliff	4.2	0.8	12.8	NA
17	416015	5157891	919	994	B	NA	1.8	cliff	4	25.1	68.1	NA
18	415885	5158261	1442	NA	A	3.4	4.7	cliff	0.2	335.6	89.6	NA
19	415795	5157441	1293	NA	A	1.4	NA	cliff	0.2	340.3	94.3	2.6
20	416045	5158751	1252	NA	A	5.4	NA	cliff	0.2	342.4	96.4	4.7
21	415605	5157571	1533	NA	A	NA	NA	top	0.2	349.0	103.0	11.3
22	416015	5158481	1112	NA	B	NA	2.5	cliff	0.2	358.5	112.5	0.5
23	415935	5158181	1328	NA	B	NA	1.2	cliff	3	0.4	2.4	12.3
24	415835	5157511	1300	NA	A	NA	NA	cliff	3	0.5	2.5	12.4
25	415955	5157971	1240	NA	B	NA	2.1	cliff	1.8	0.0	1.0	5.3
26	416065	5158871	1300	NA	B	NA	1.8	cliff	4	0.8	34.8	1.9
27	415485	5157301	1635	NA	C	NA	NA	top	22.2	1.9	70.9	0.4
28	415865	5157641	1148	NA	C	NA	NA	cliff	22.2	2.1	71.1	0.6
29	415955	5158231	1219	NA	B	0.5	NA	cliff	0.6	1.0	84.0	0.5
30	415795	5157451	1318	NA	A	1.5	1.2	cliff	0.2	24.4	52.4	0.1
31	415985	5158061	1169	NA	A	NA	5.4	cliff	0.2	45.2	73.2	9.1
32	415805	5157451	1293	NA	A	NA	8.4	cliff	0.2	49.0	3.0	12.9
33	415965	5158271	1208	NA	A	3.6	NA	cliff	0.2	60.9	9.9	24.8
34	415485	5156431	986	NA	B	NA	21	base	0.2	79.5	14.5	4.6
35	415935	5158201	1354	NA	B	3.1	12.4	cliff	0.2	83.4	18.4	8.5
36	416015	5158591	1237	NA	C	NA	NA	cliff	0.2	283.5	218.5	3.7
37	416015	5158541	1266	NA	B	1.2	8.4	cliff	1	2.3	221.3	0.8
38	416055	5157991	866	NA	C	NA	NA	base	5.6	0.4	235.4	3.5
39	416015	5158641	1218	NA	A	NA	NA	cliff	8.2	0.3	237.3	0.0
40	416005	5158021	1094	NA	C	NA	NA	cliff	0.2	6.9	245.9	2.1
41	415645	5157451	1453	NA	A	NA	0.1	top	0.2	3.1	250.1	2.4
42	416135	5159011	1229	NA	C	NA	NA	cliff	0.2	65.8	50.8	0.3
43	415555	5157161	1553	NA	A	NA	3.4	top	0.2	148.1	133.1	1.5
44	415935	5158191	1332	NA	C	NA	NA	cliff	0.4	30.4	194.4	0.2
45	415615	5156941	1006	NA	B	0.8	3.2	base	6.4	23.0	193.0	0.3
46	416205	5159341	879	NA	B	NA	NA	base	6.4	47.7	217.7	1.8
47	415965	5157731	970	NA	C	NA	NA	base	0.4	25.1	276.1	1.0
48	416005	5158021	1094	NA	C	NA	NA	cliff	0.4	96.6	347.6	0.8
49	415945	5157941	1221	NA	A	NA	NA	cliff	2	60.1	179.1	35.4

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



Figure 1: Images from selected seasons of sections of the east facing rock wall of the Lauterbrunnen Vally from internet rechereche. Blue lines indicate identified water outlets that are not linked to waterfall spray or input from hanging valleys. Images without reference were taken from the authors personally.

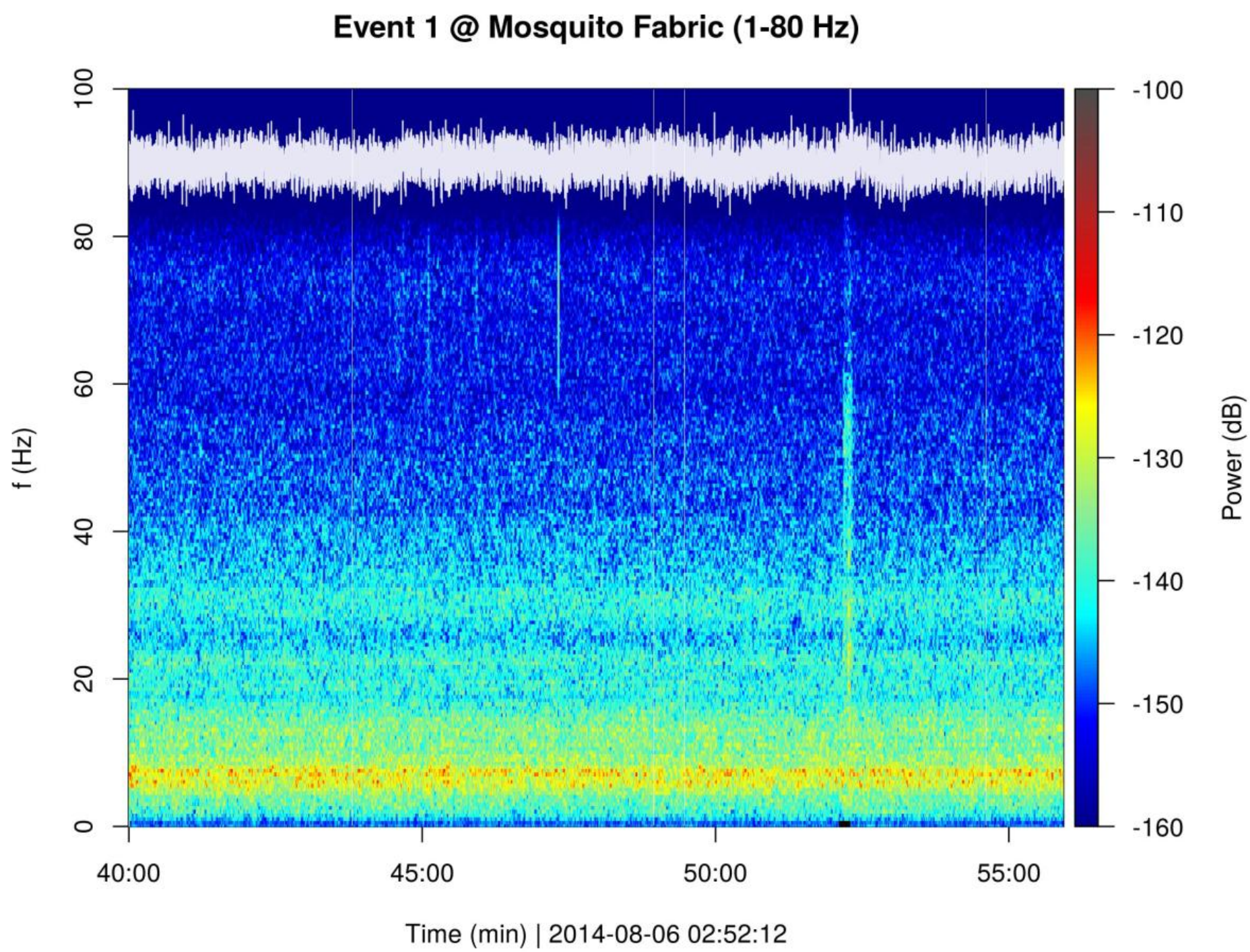


Figure 2:

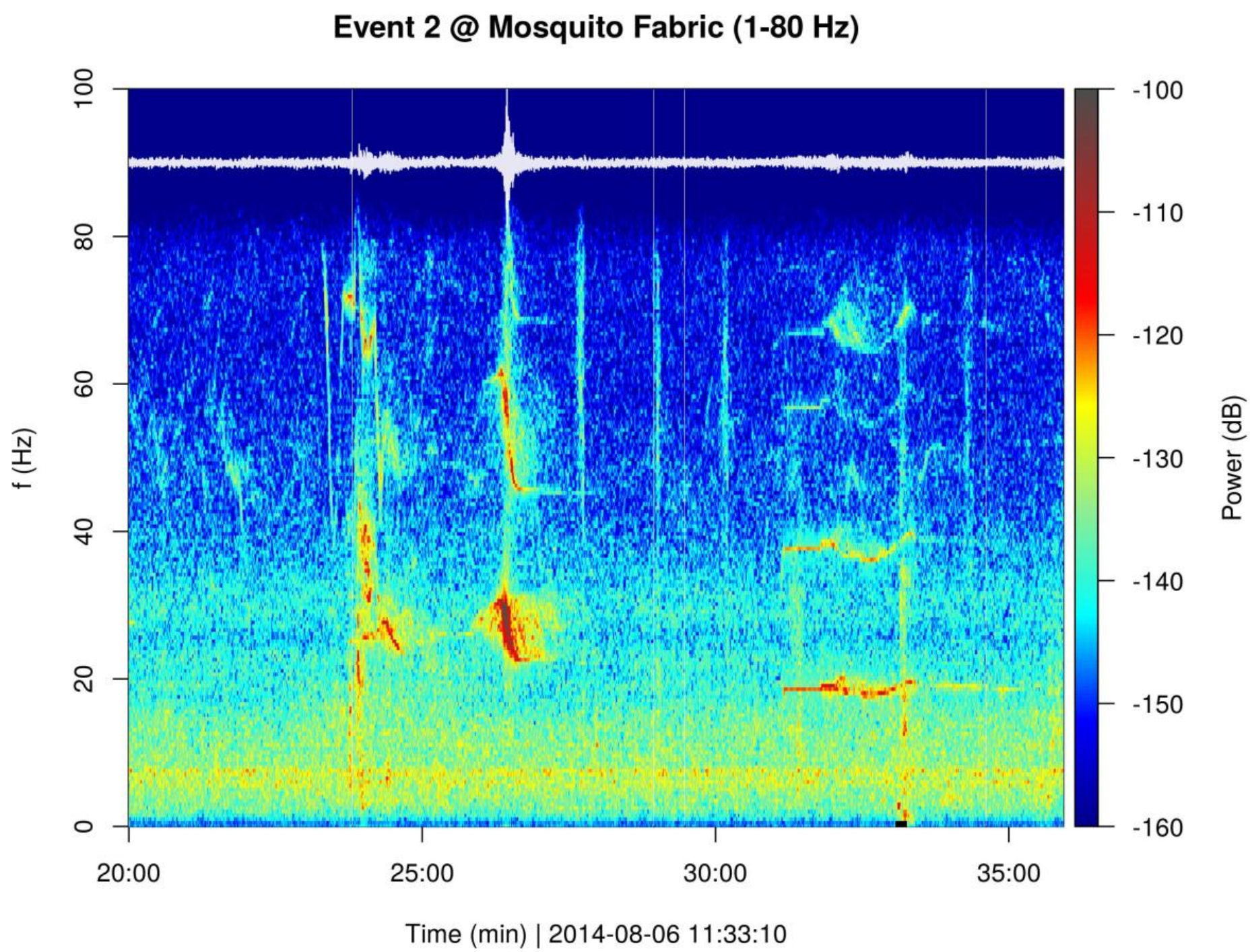


Figure 3:

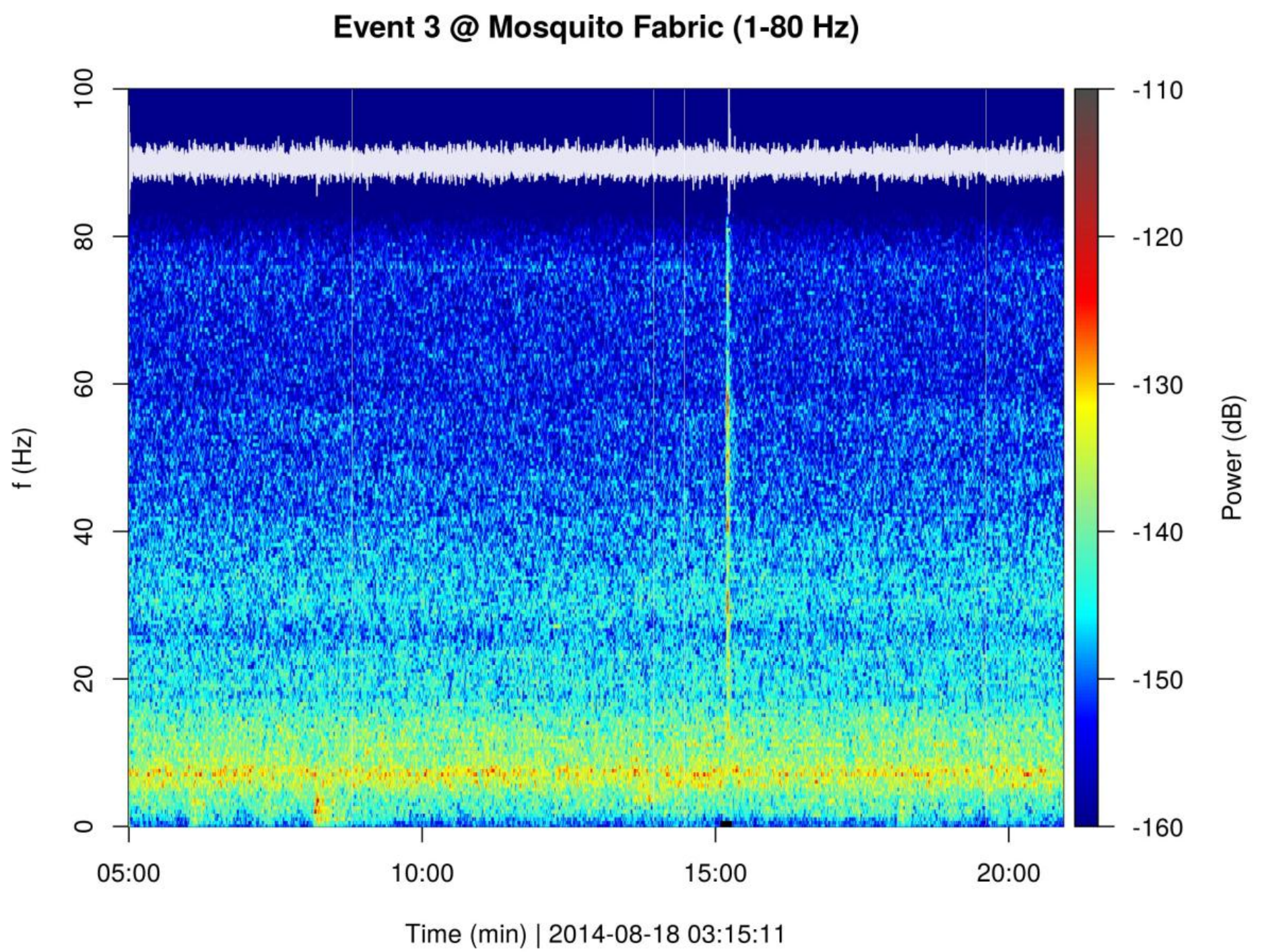


Figure 4:

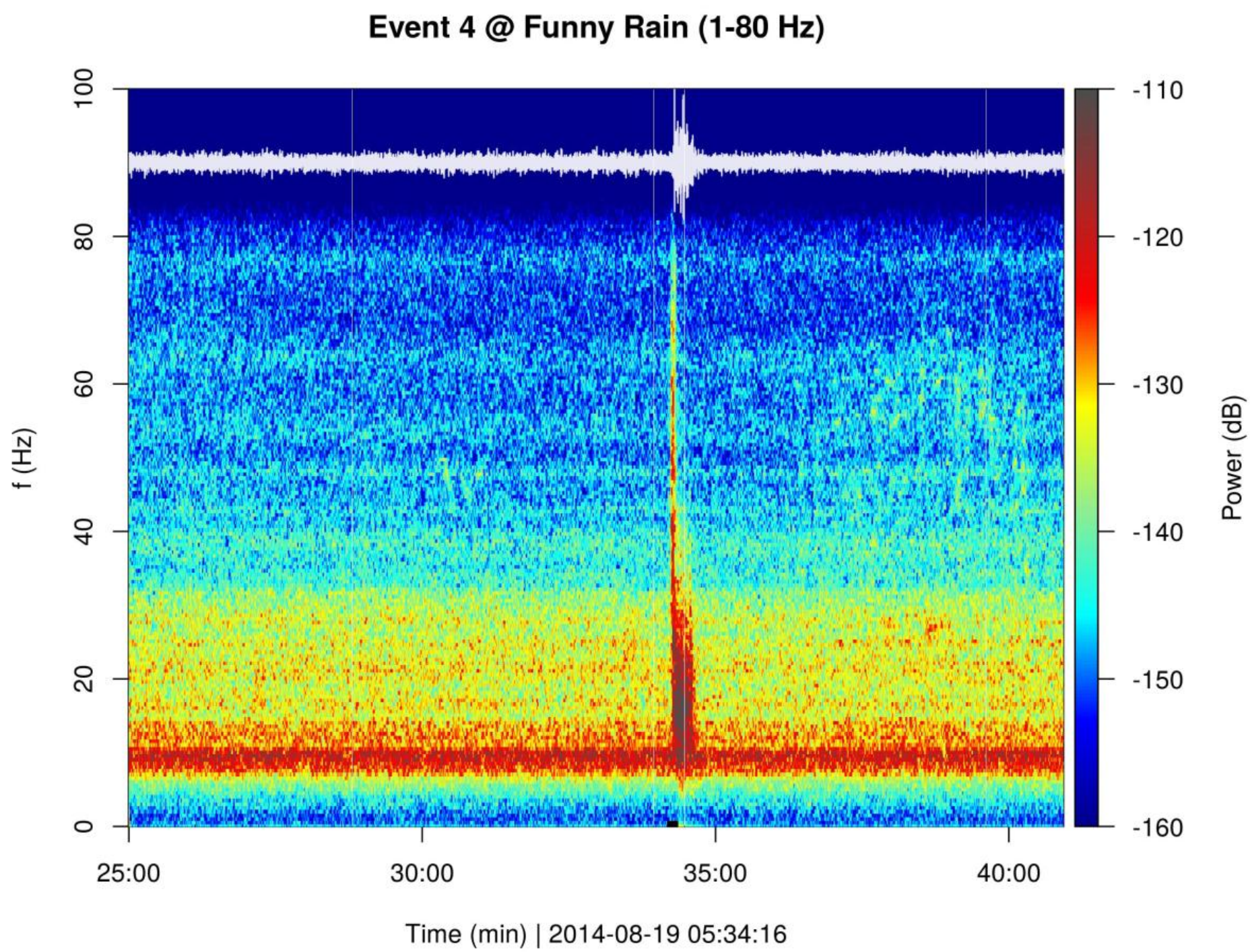


Figure 5:

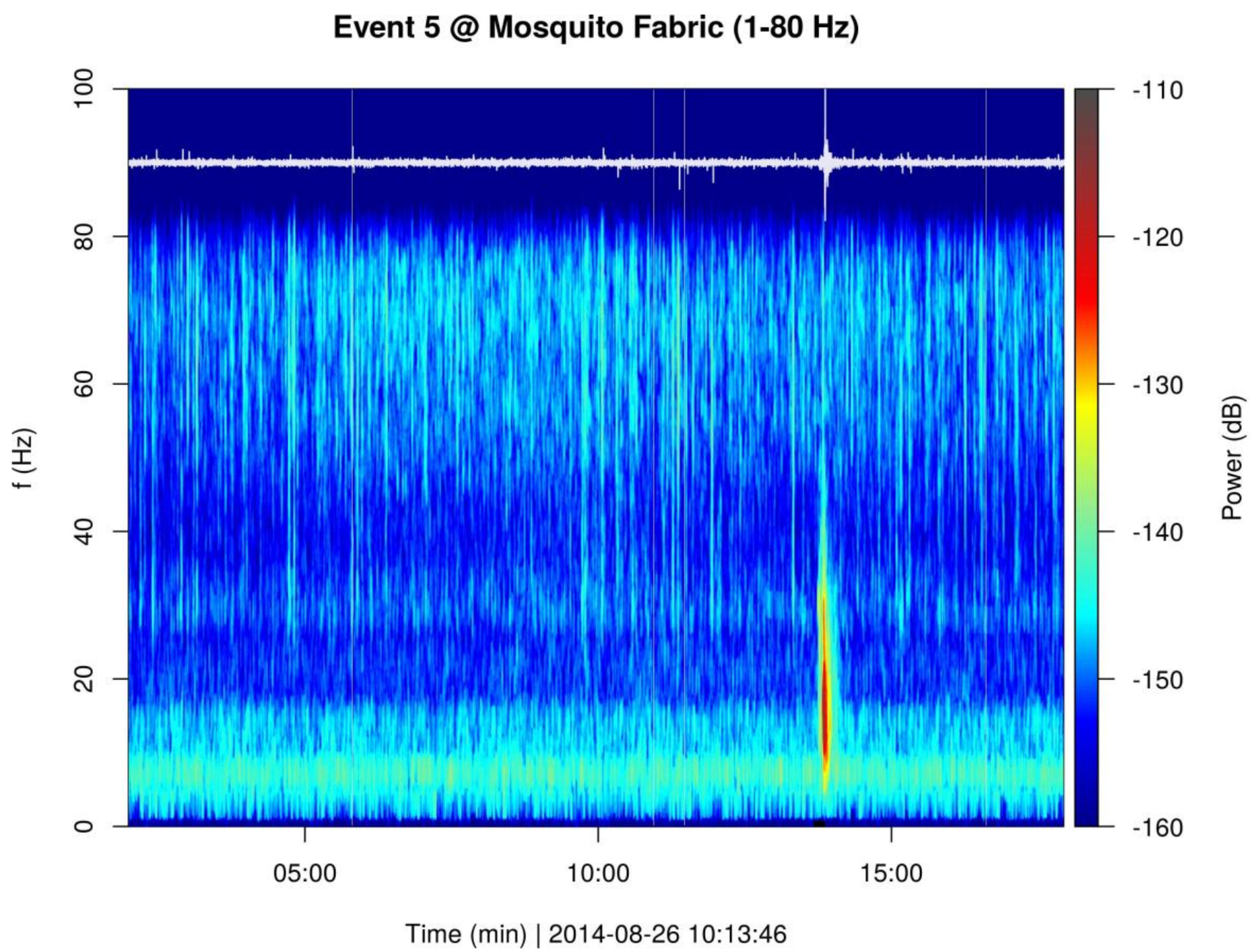


Figure 6:

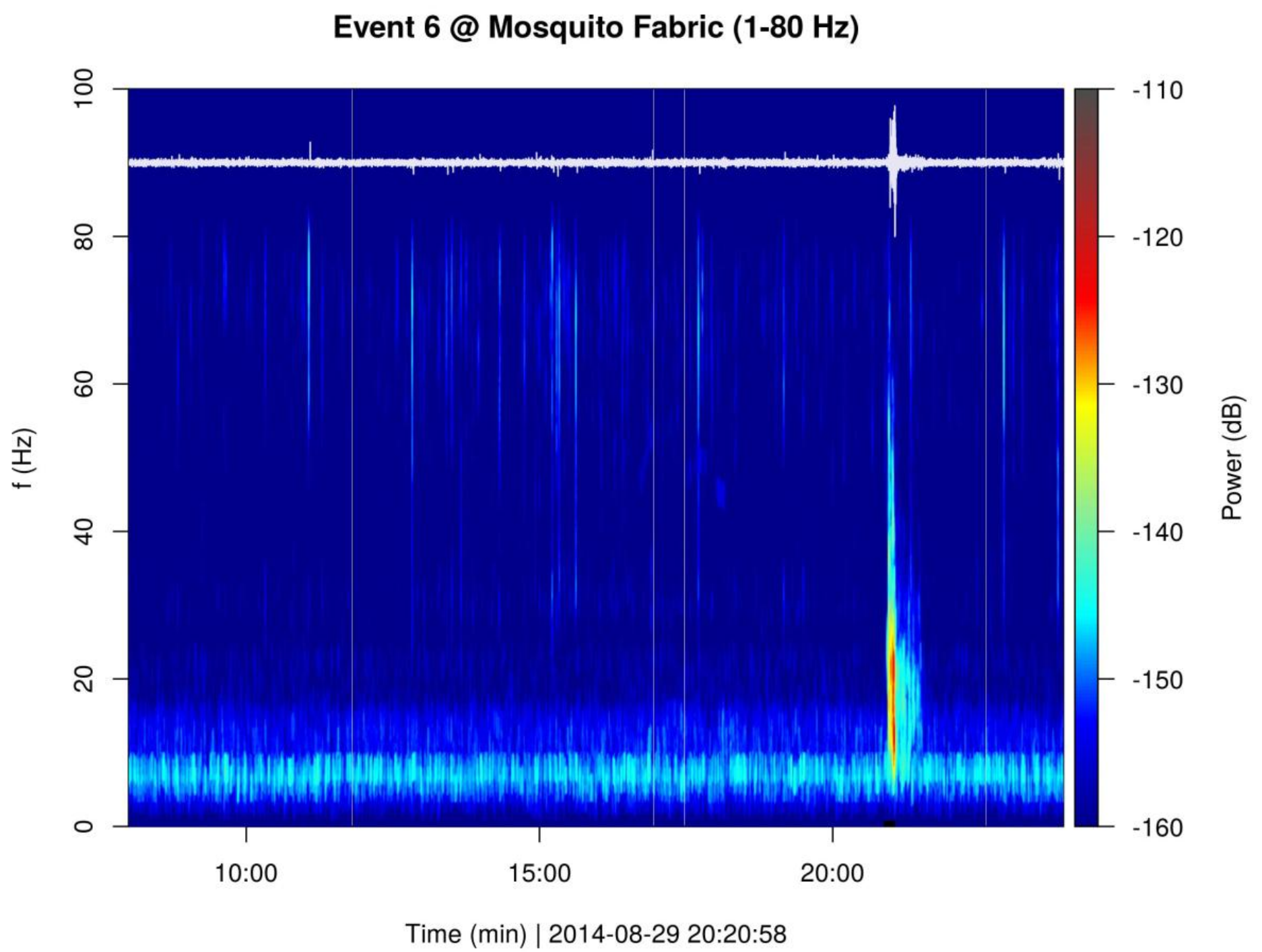


Figure 7:

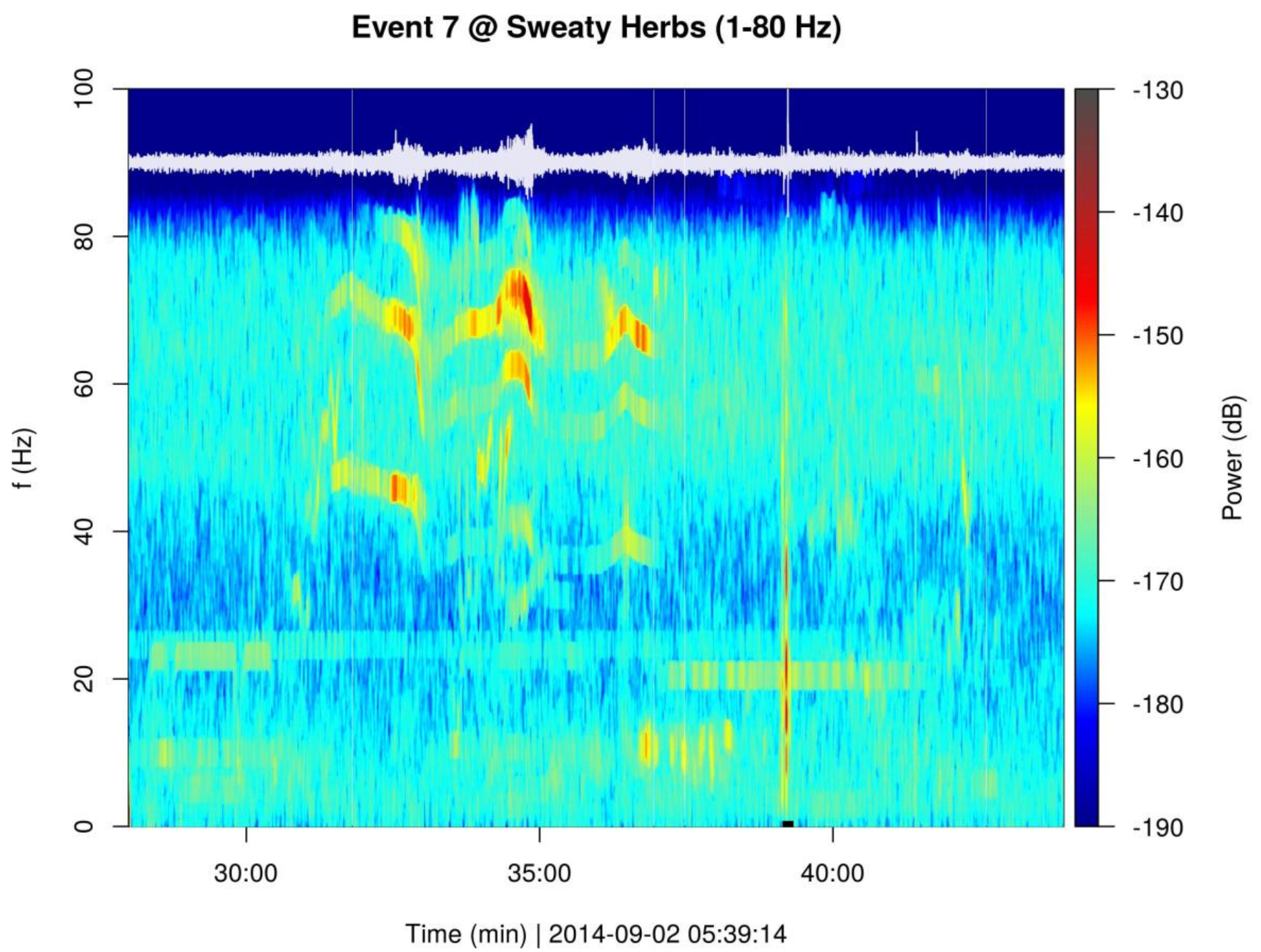


Figure 8:

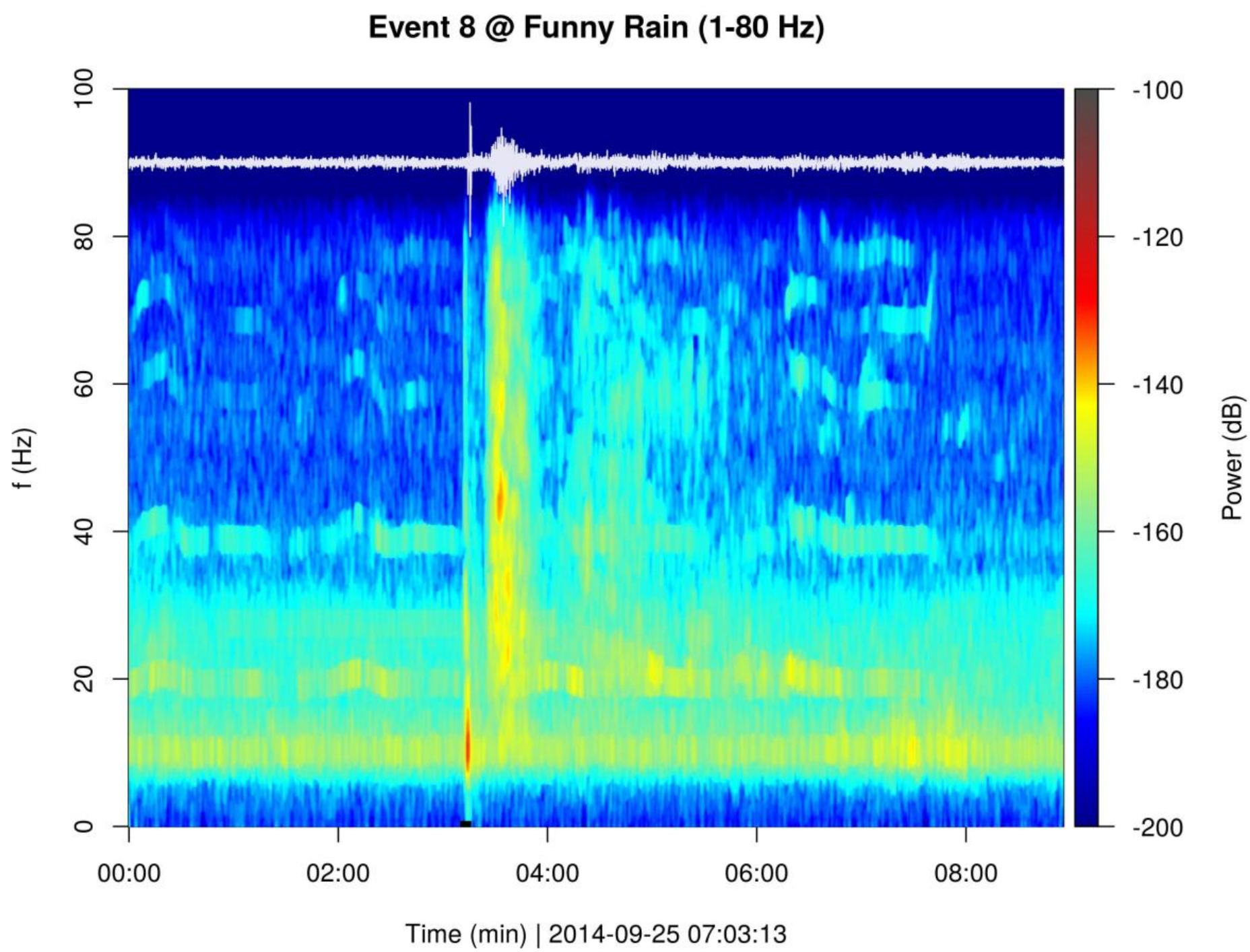


Figure 9:

Event 9 @ Mosque Fabric (1-80 Hz)

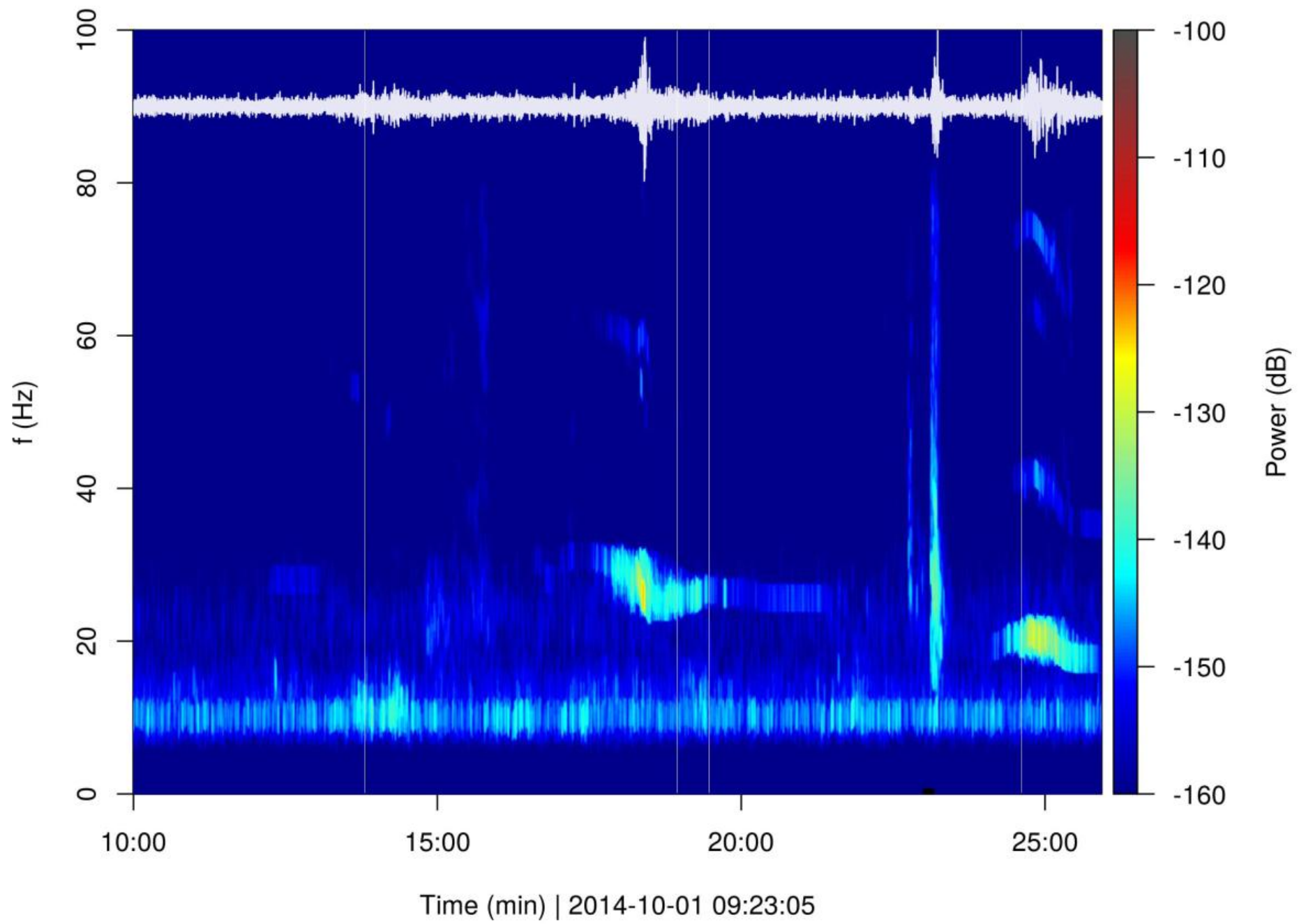


Figure 10:

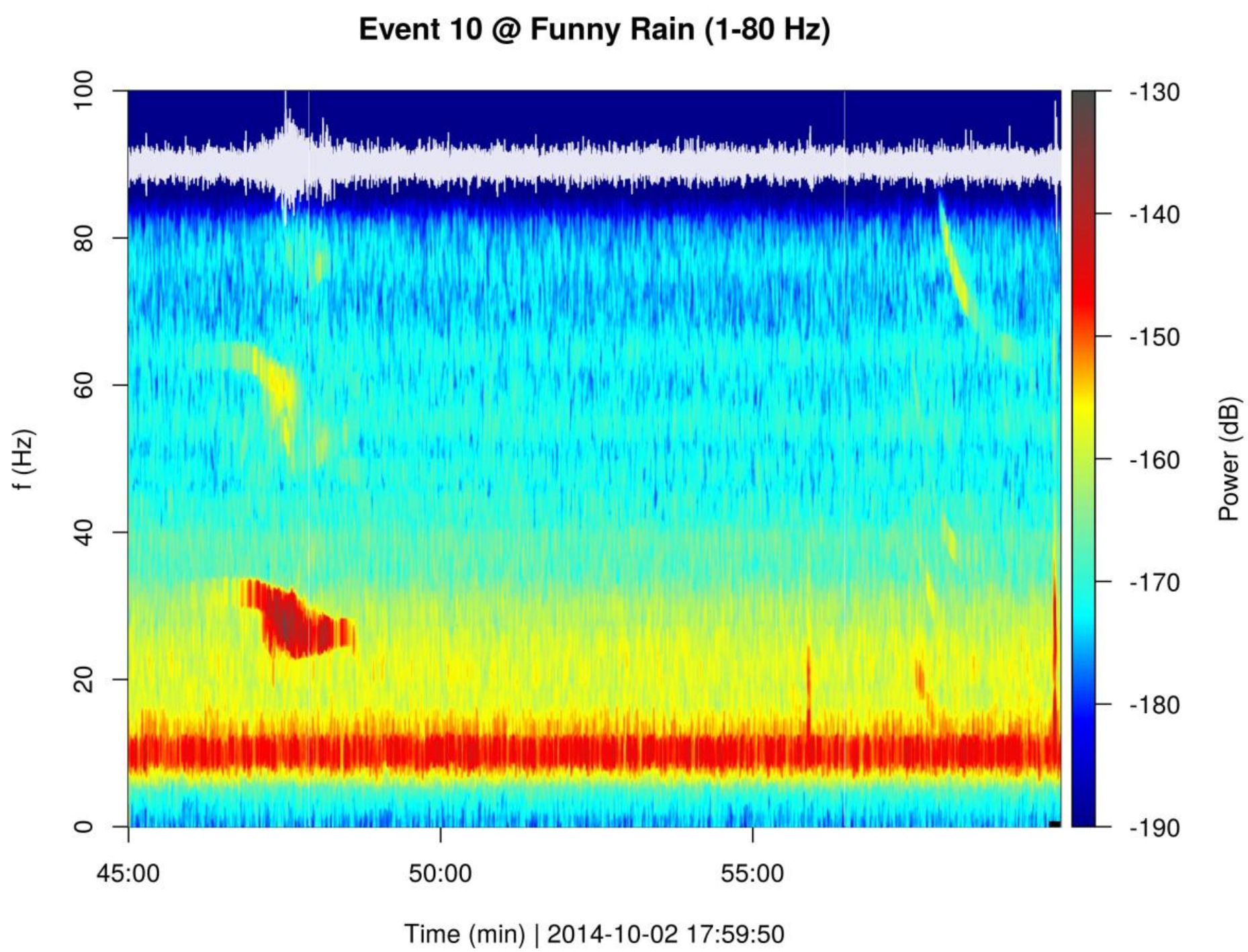


Figure 11:

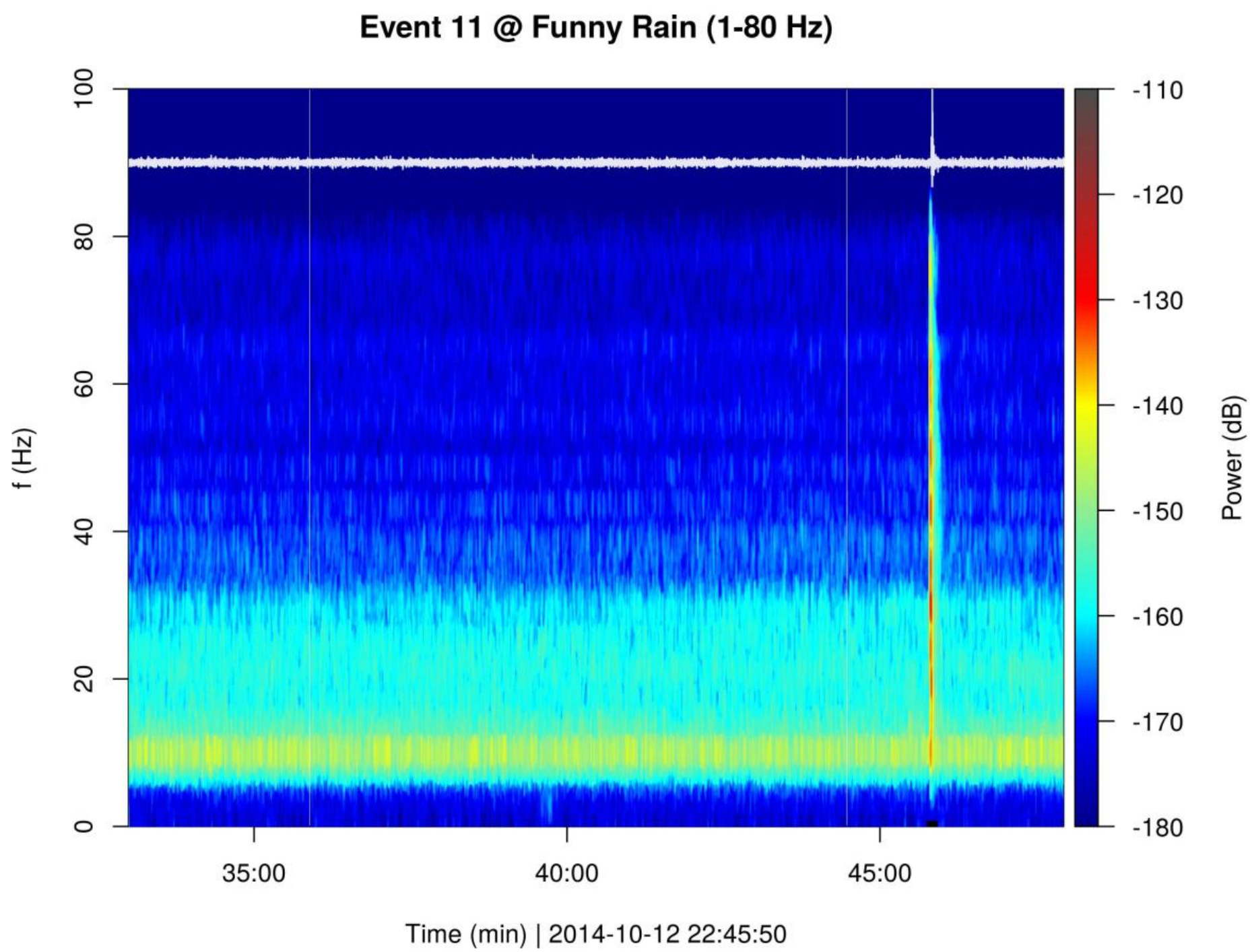


Figure 12:

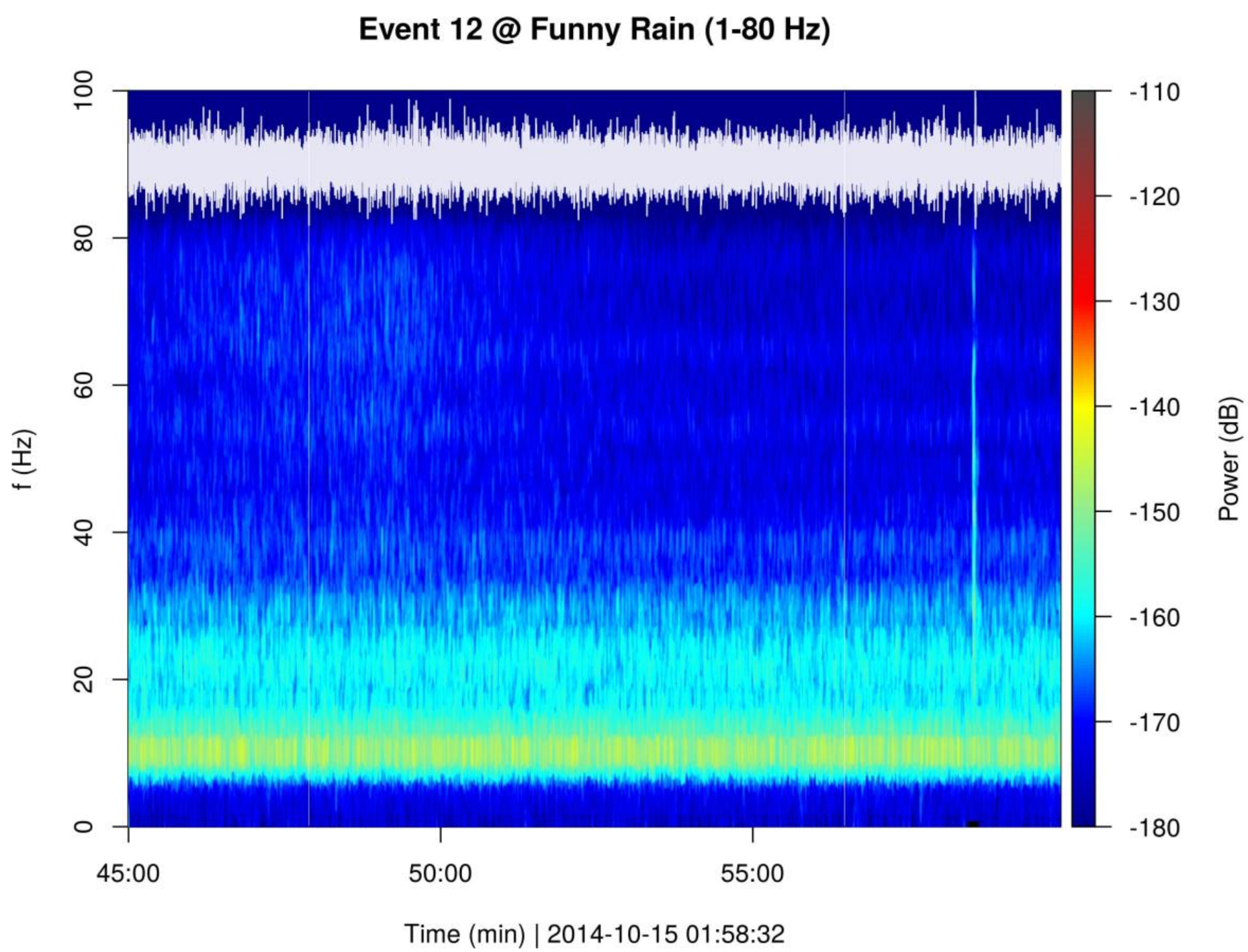


Figure 13:

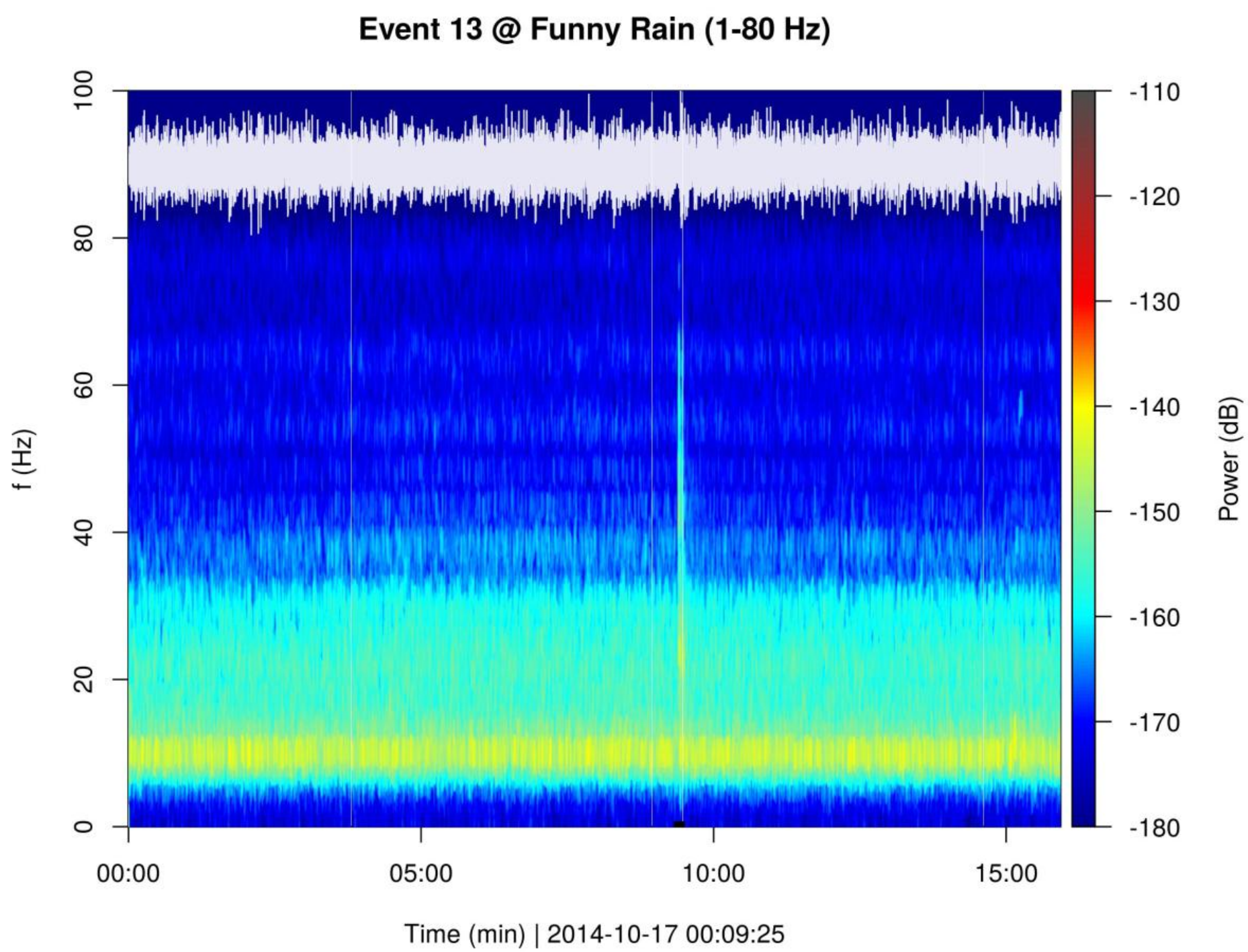


Figure 14:

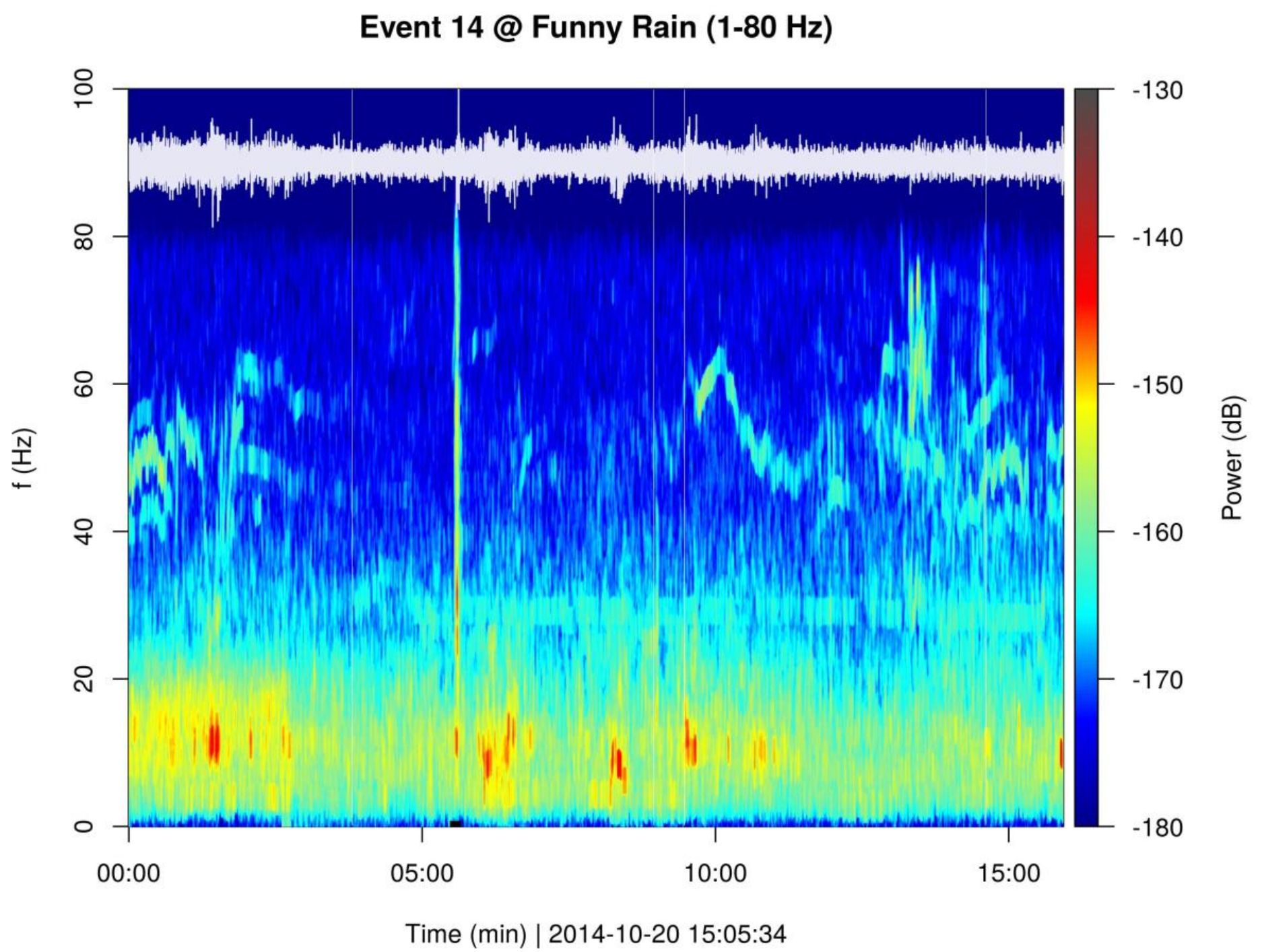


Figure 15:

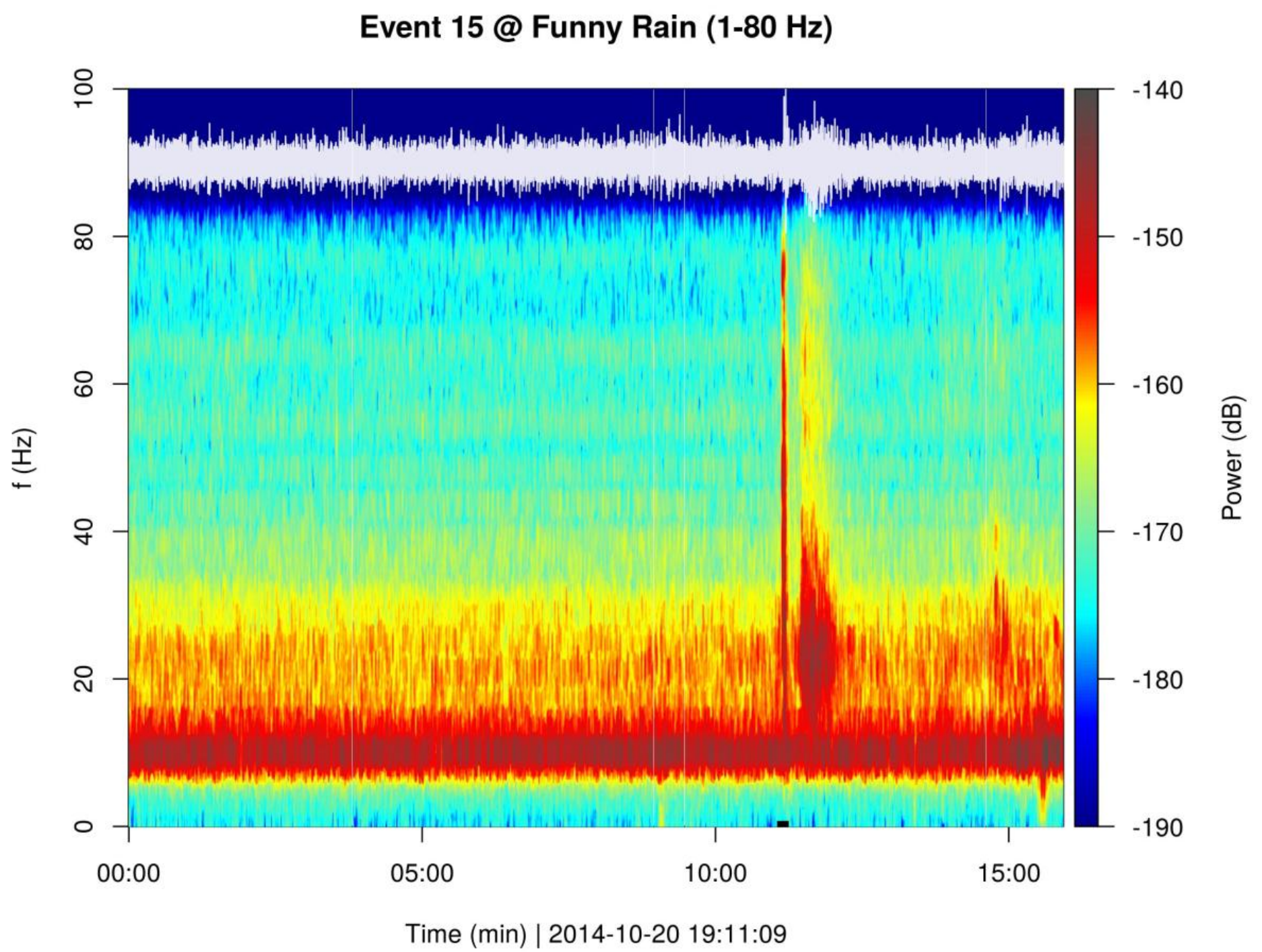


Figure 16:

Event 16 @ Funny Rain (1-80 Hz)

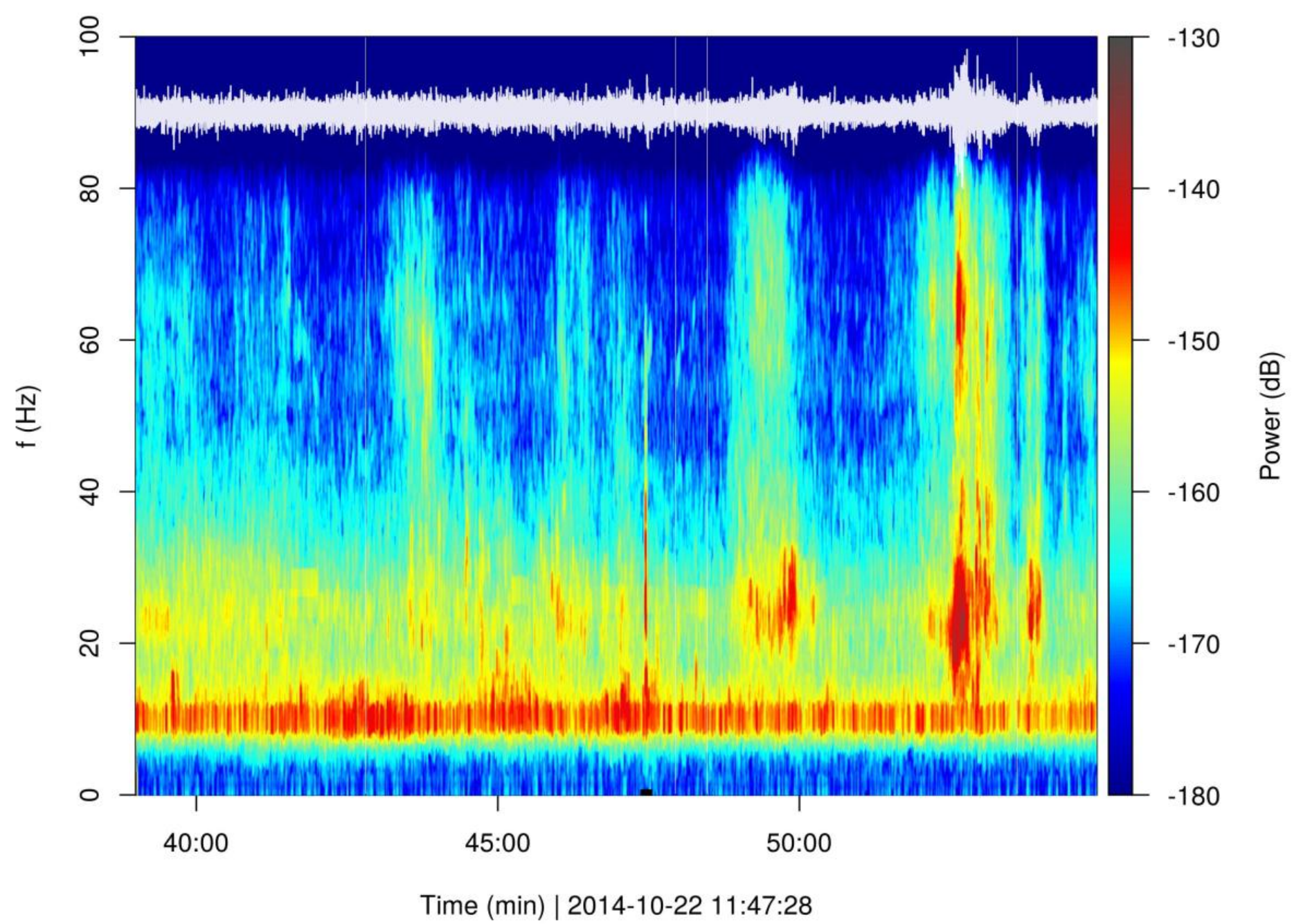


Figure 17:

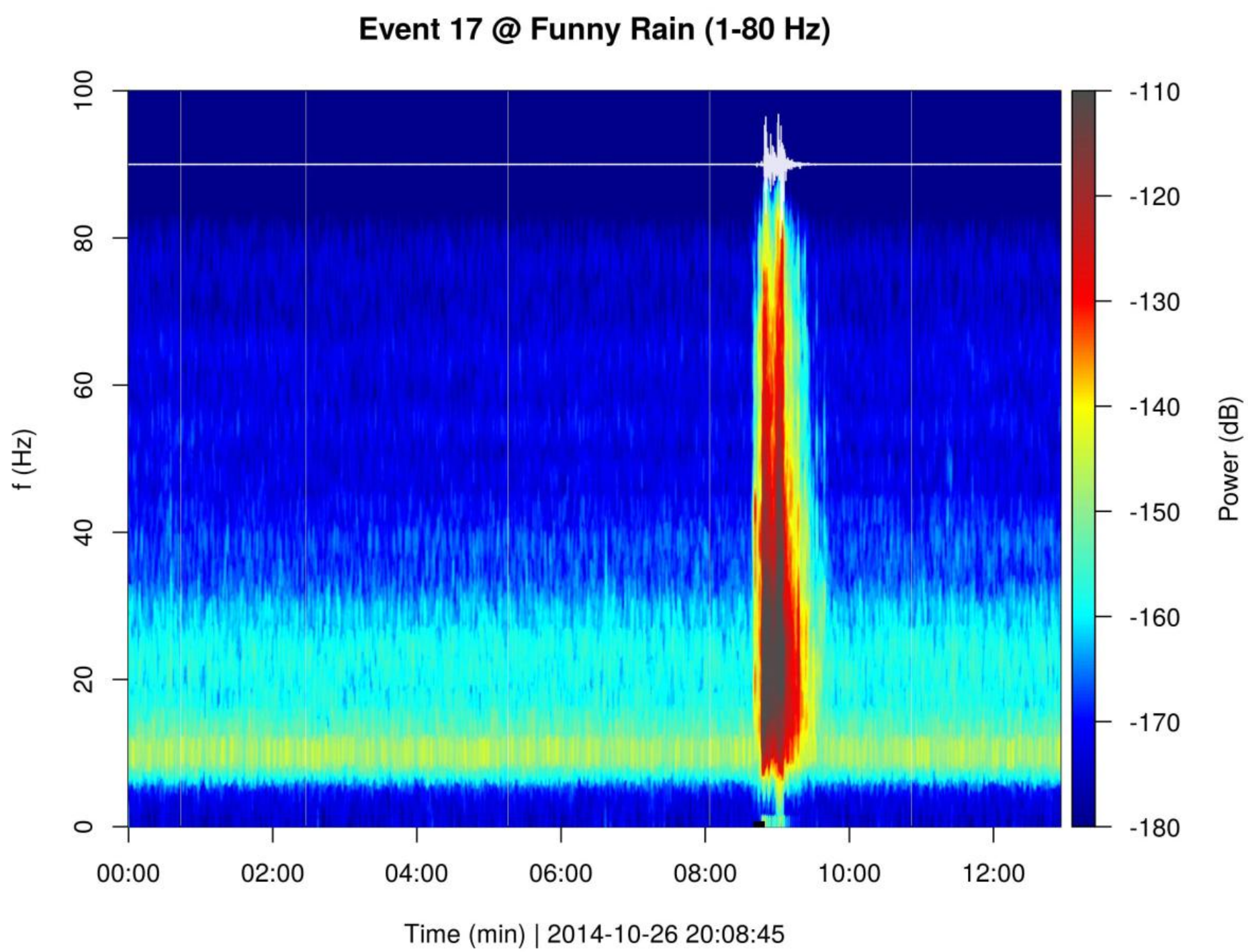


Figure 18:

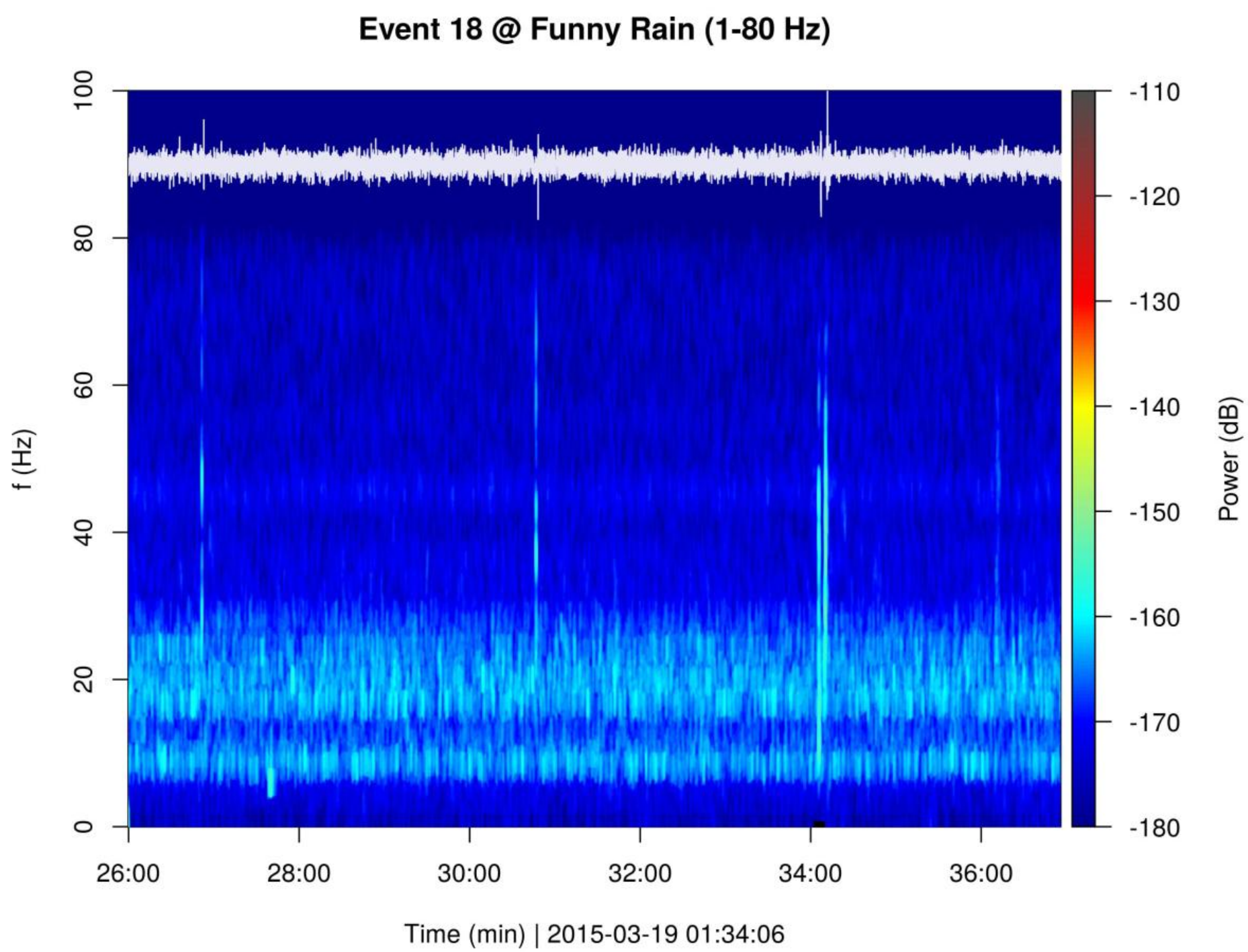


Figure 19:

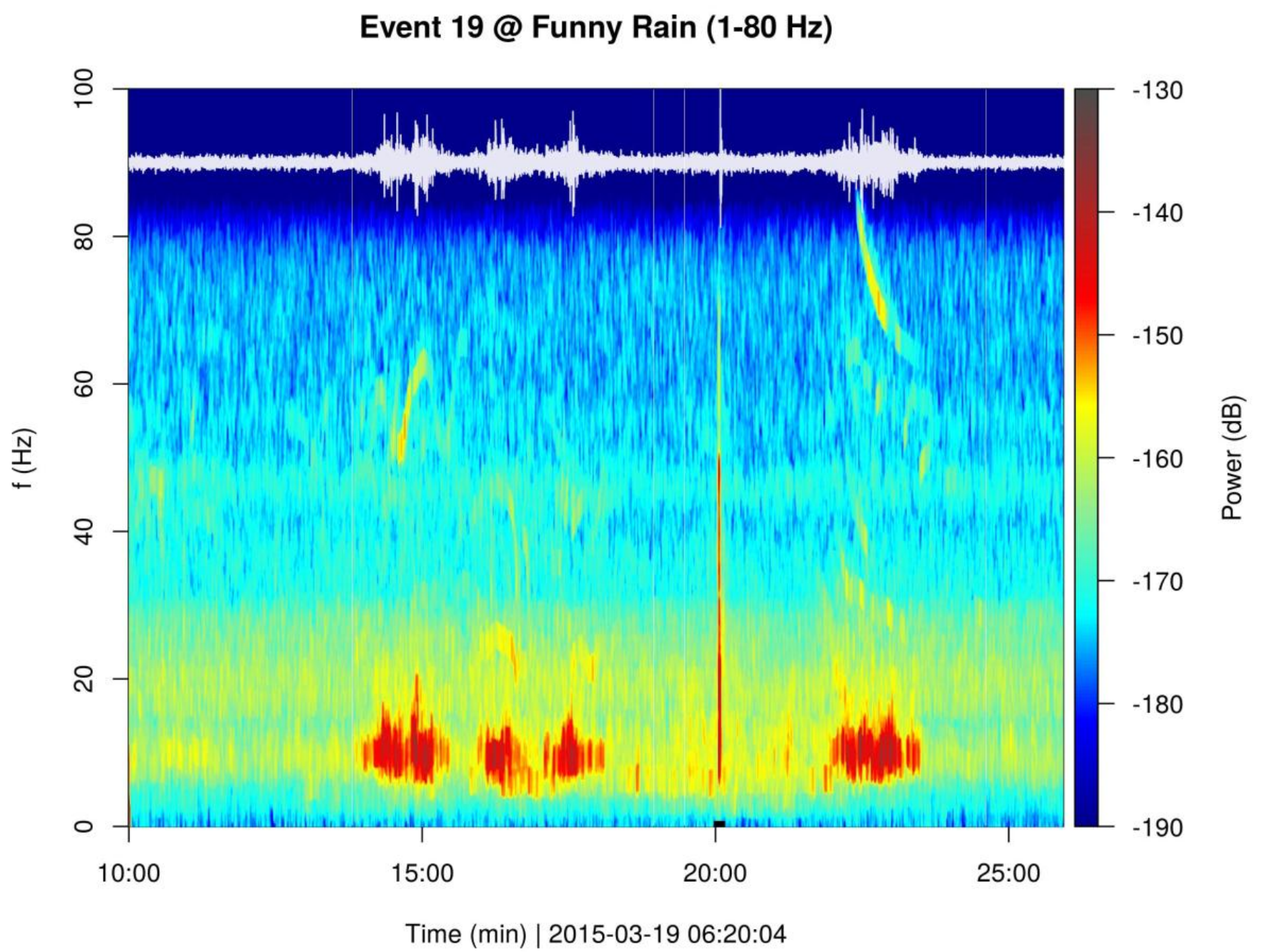


Figure 20:

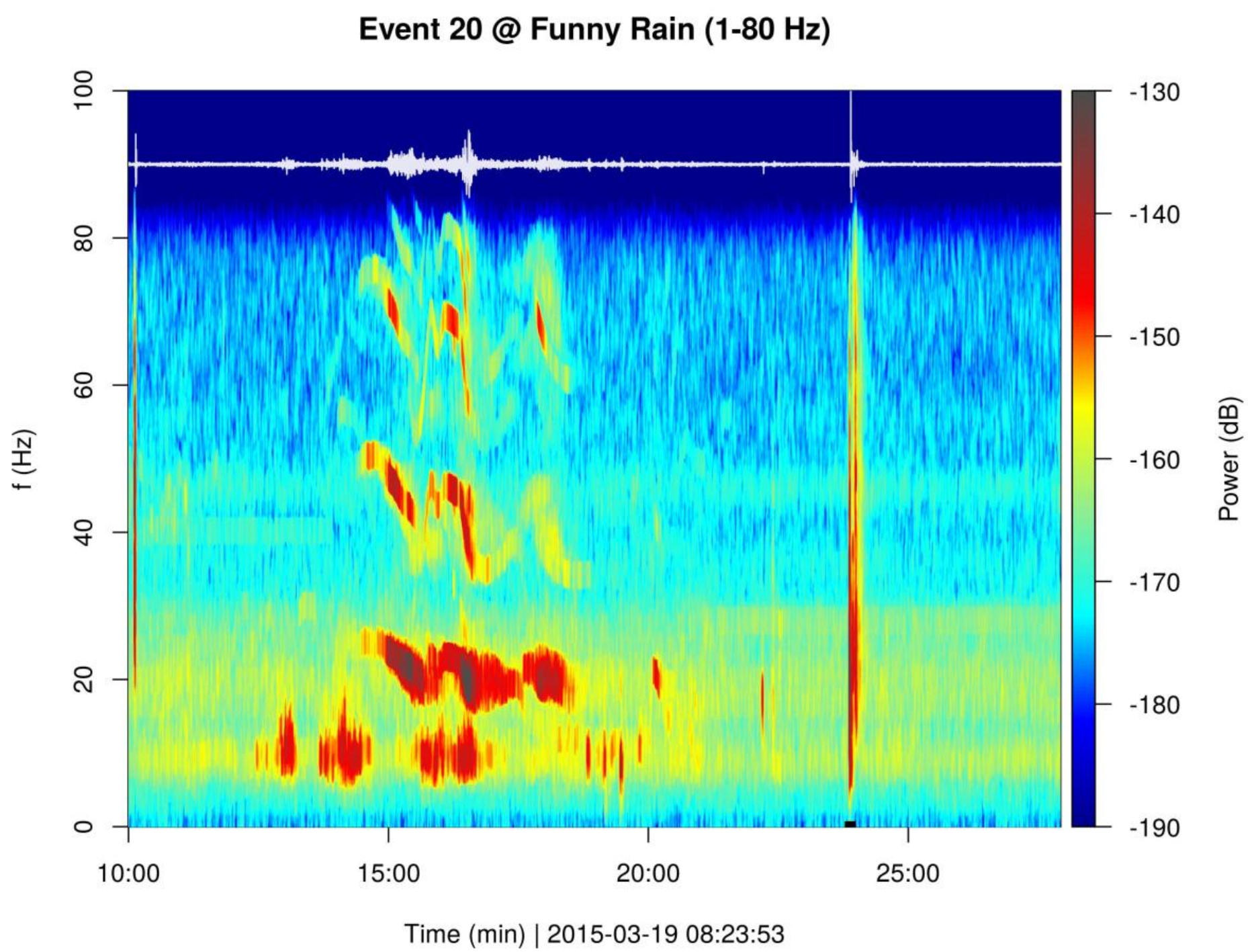


Figure 21:

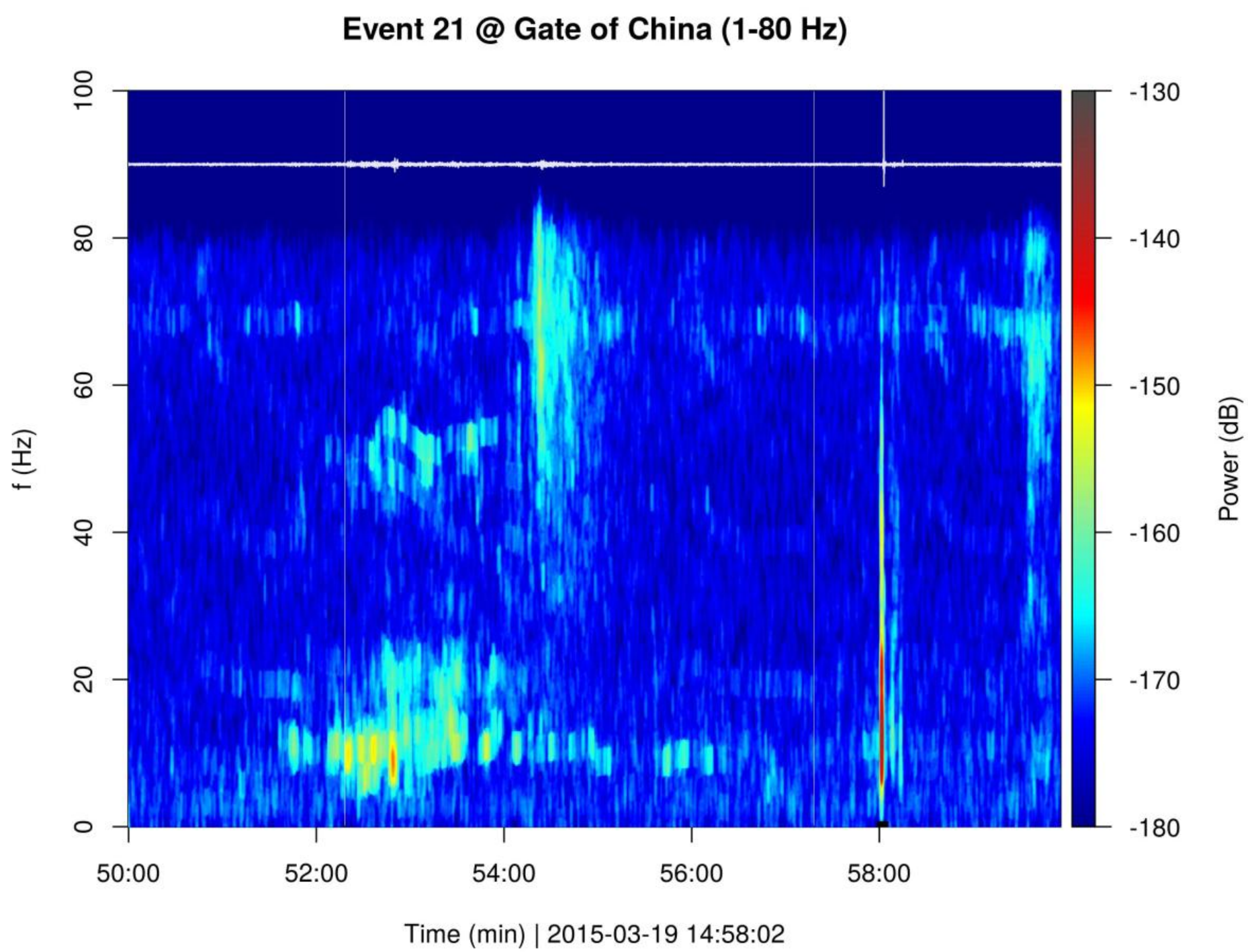


Figure 22:

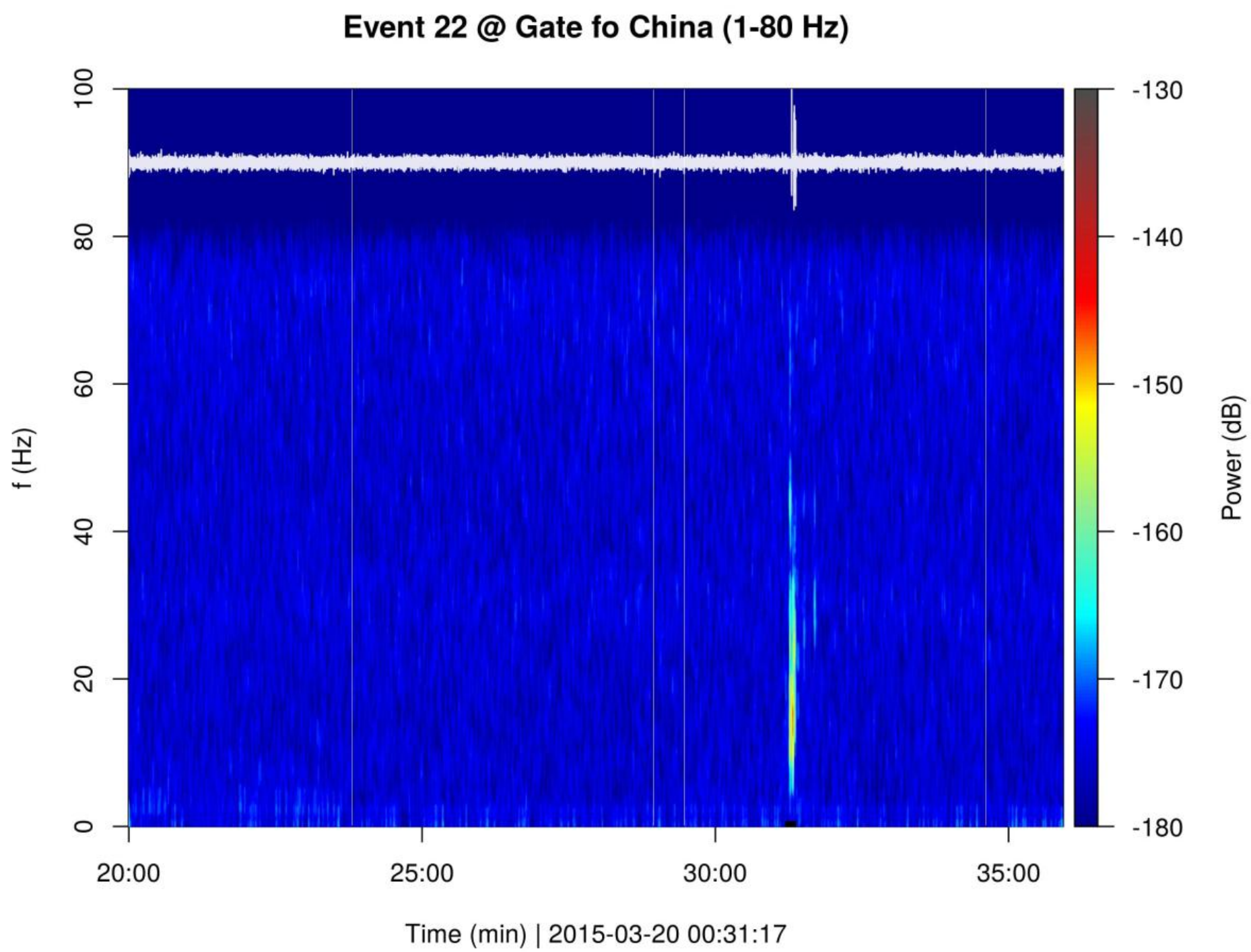


Figure 23:

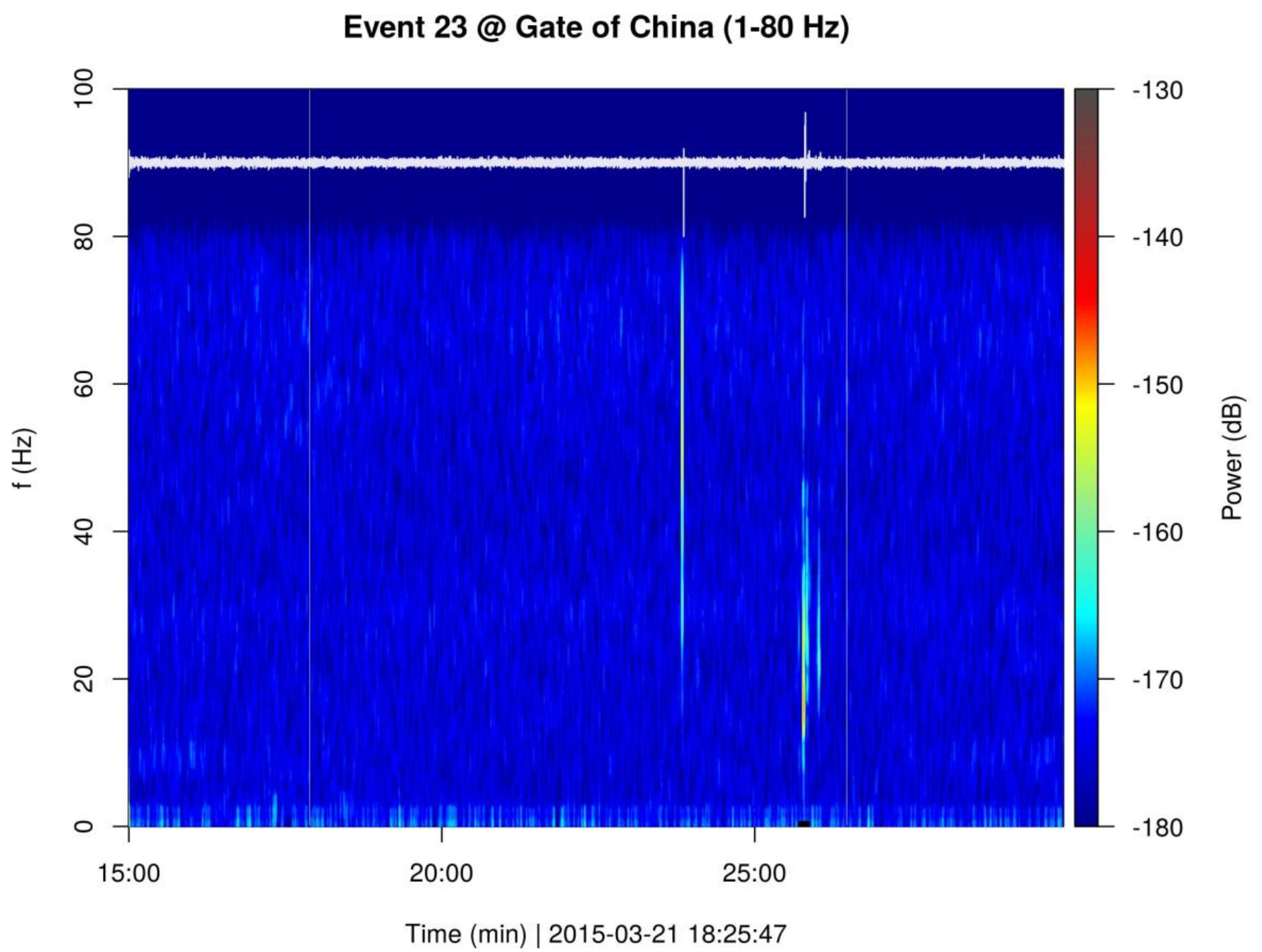


Figure 24:

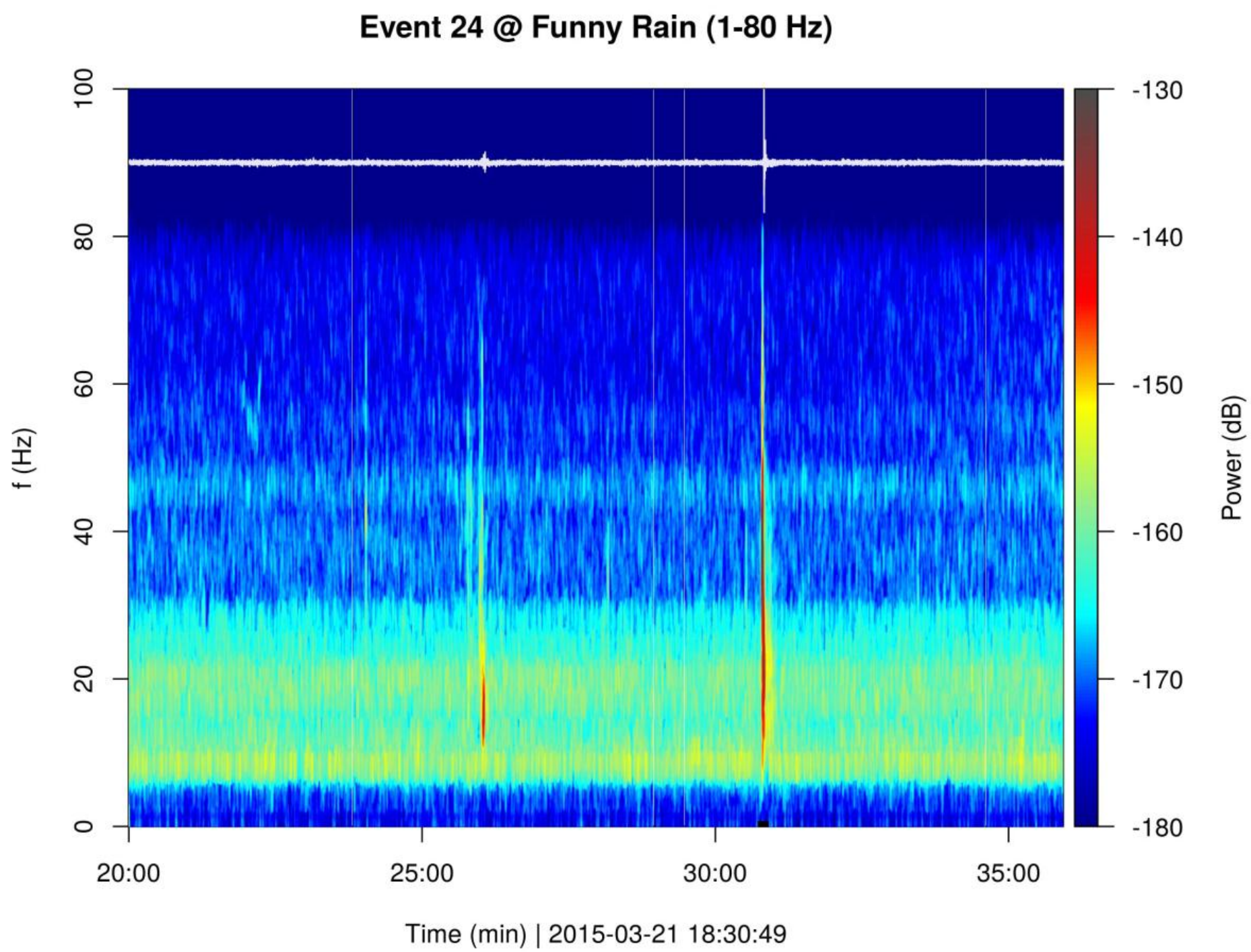


Figure 25:

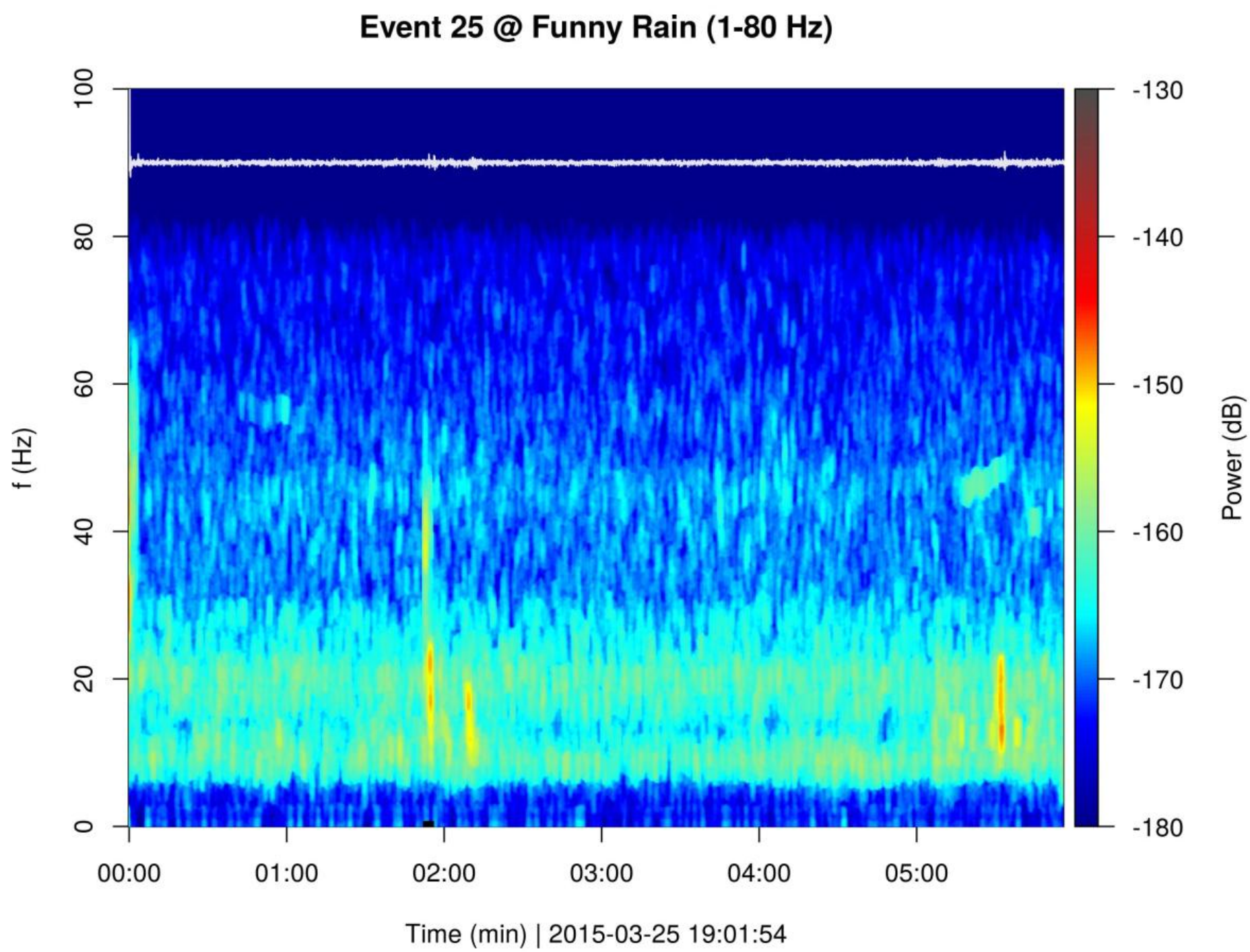


Figure 26:

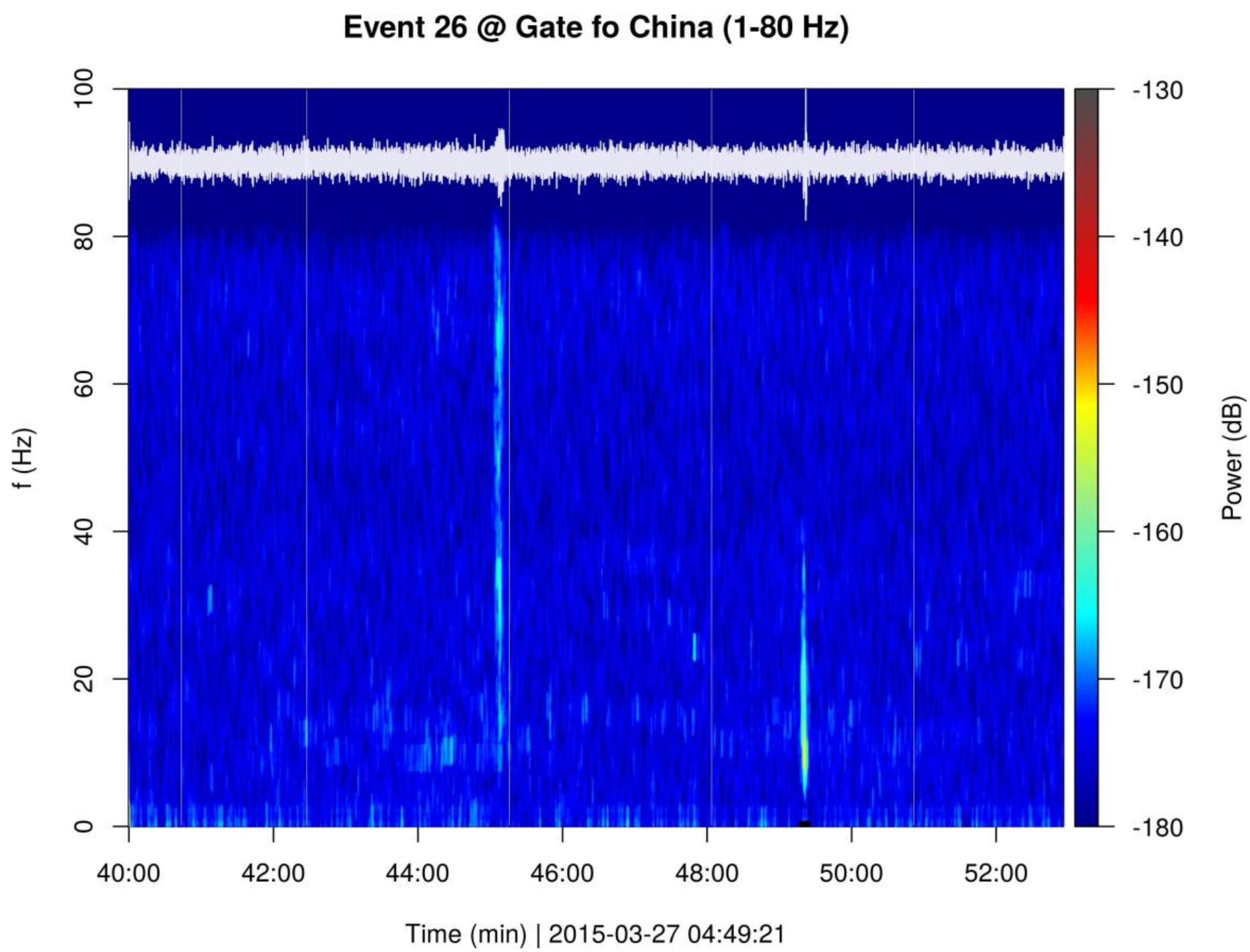


Figure 27:

Event 26 @ Funny Rain (1-80 Hz)

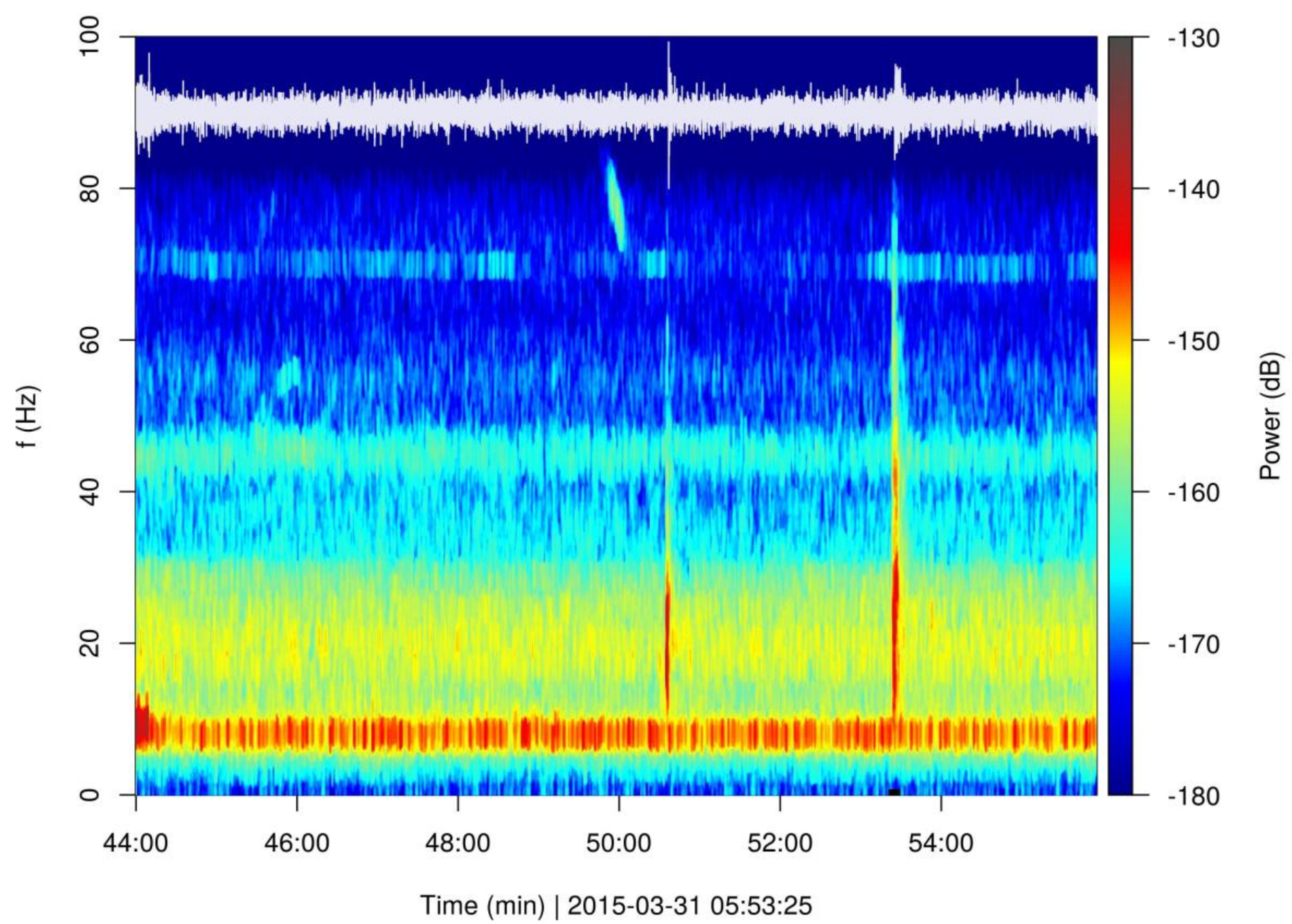


Figure 28:

Event 28 @ Funny Rain (1-80 Hz)

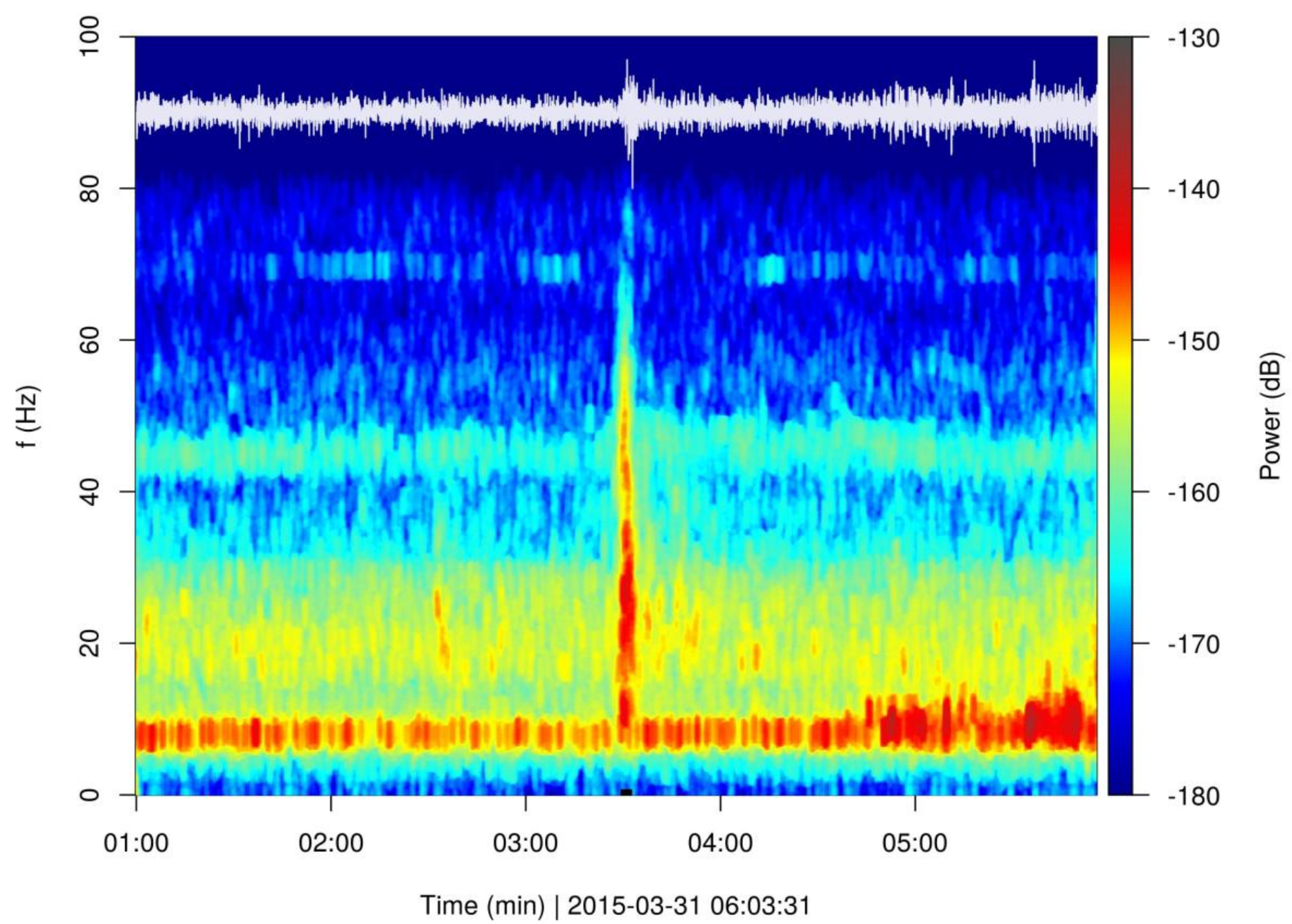


Figure 29:

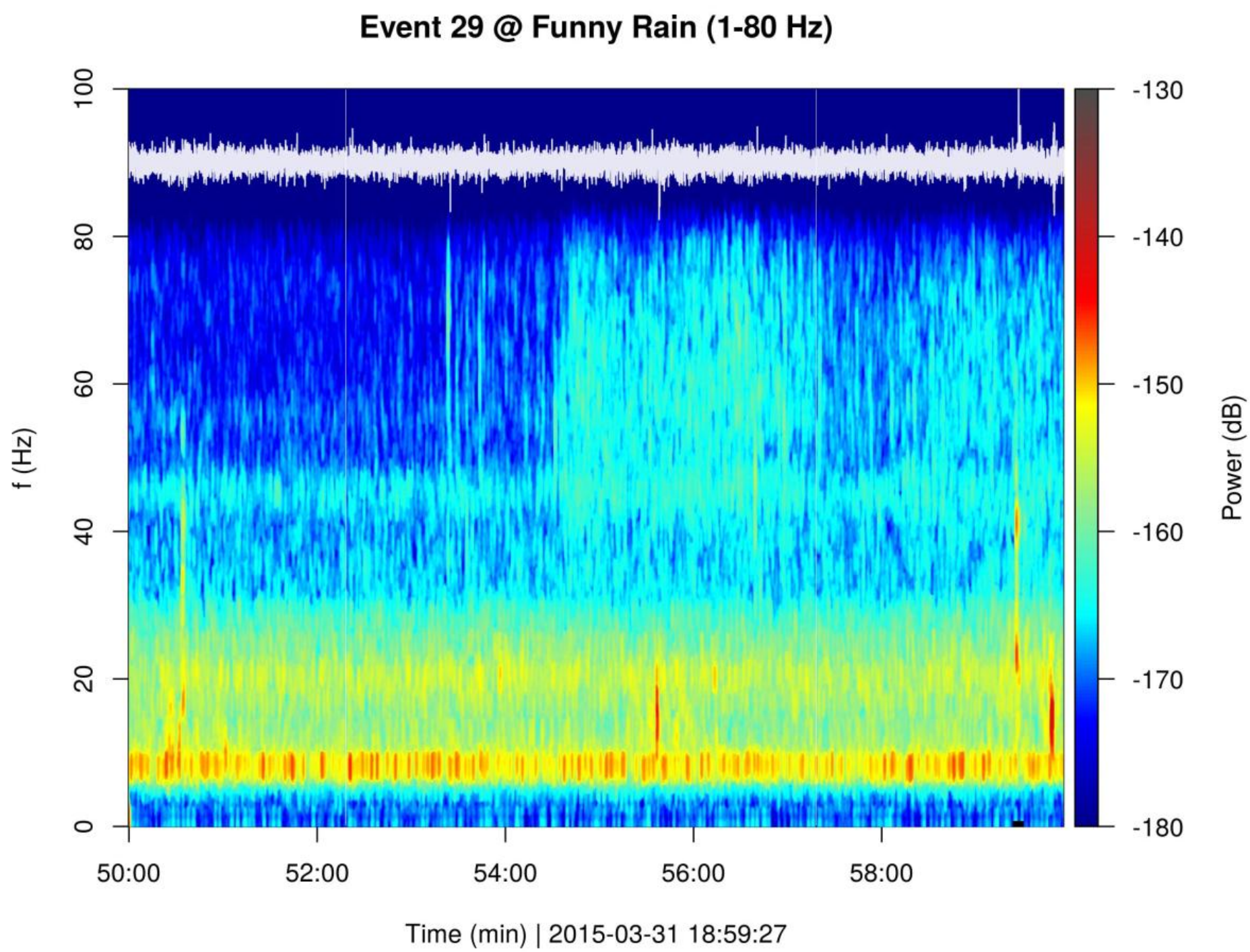


Figure 30:

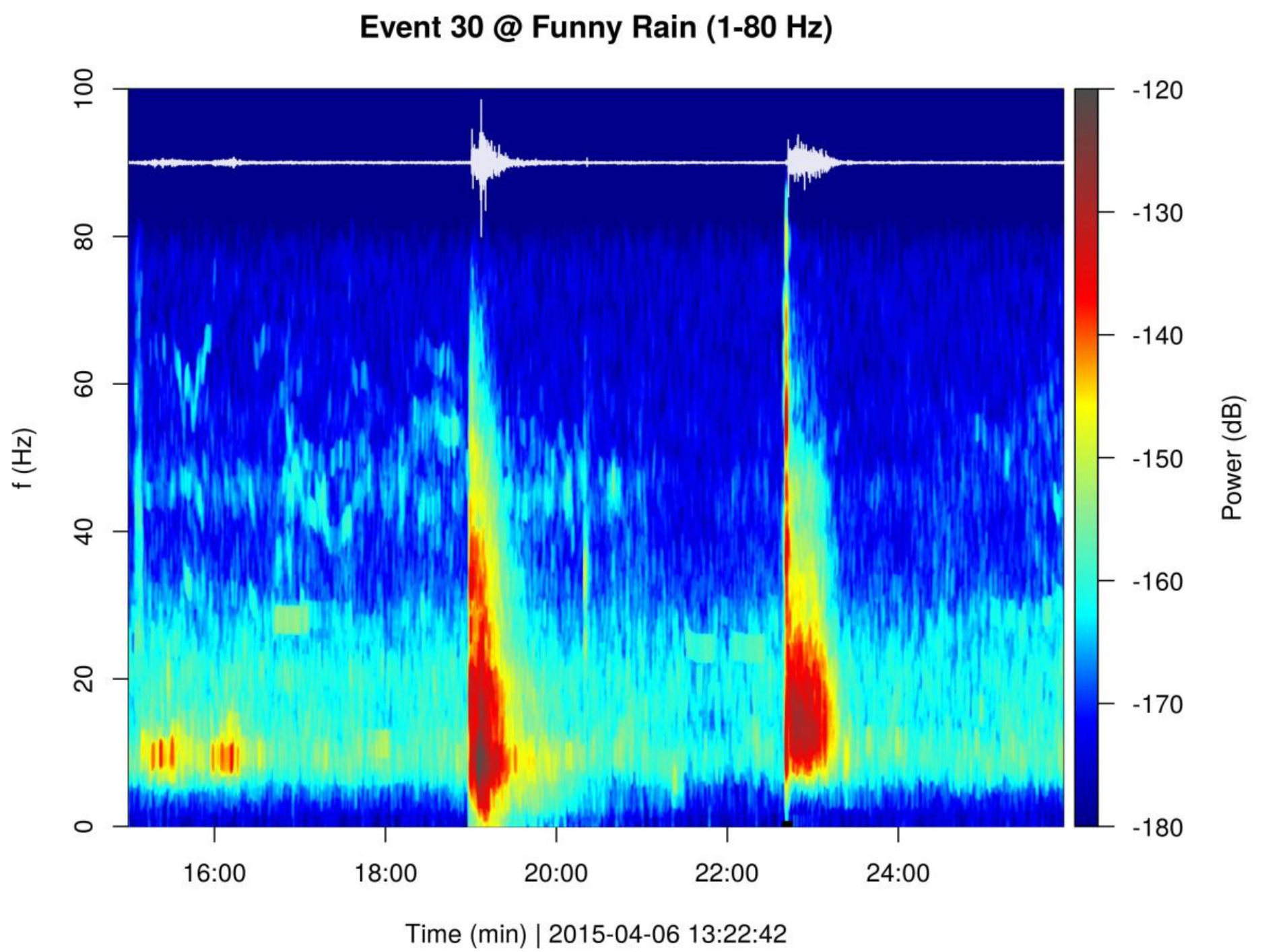


Figure 31:

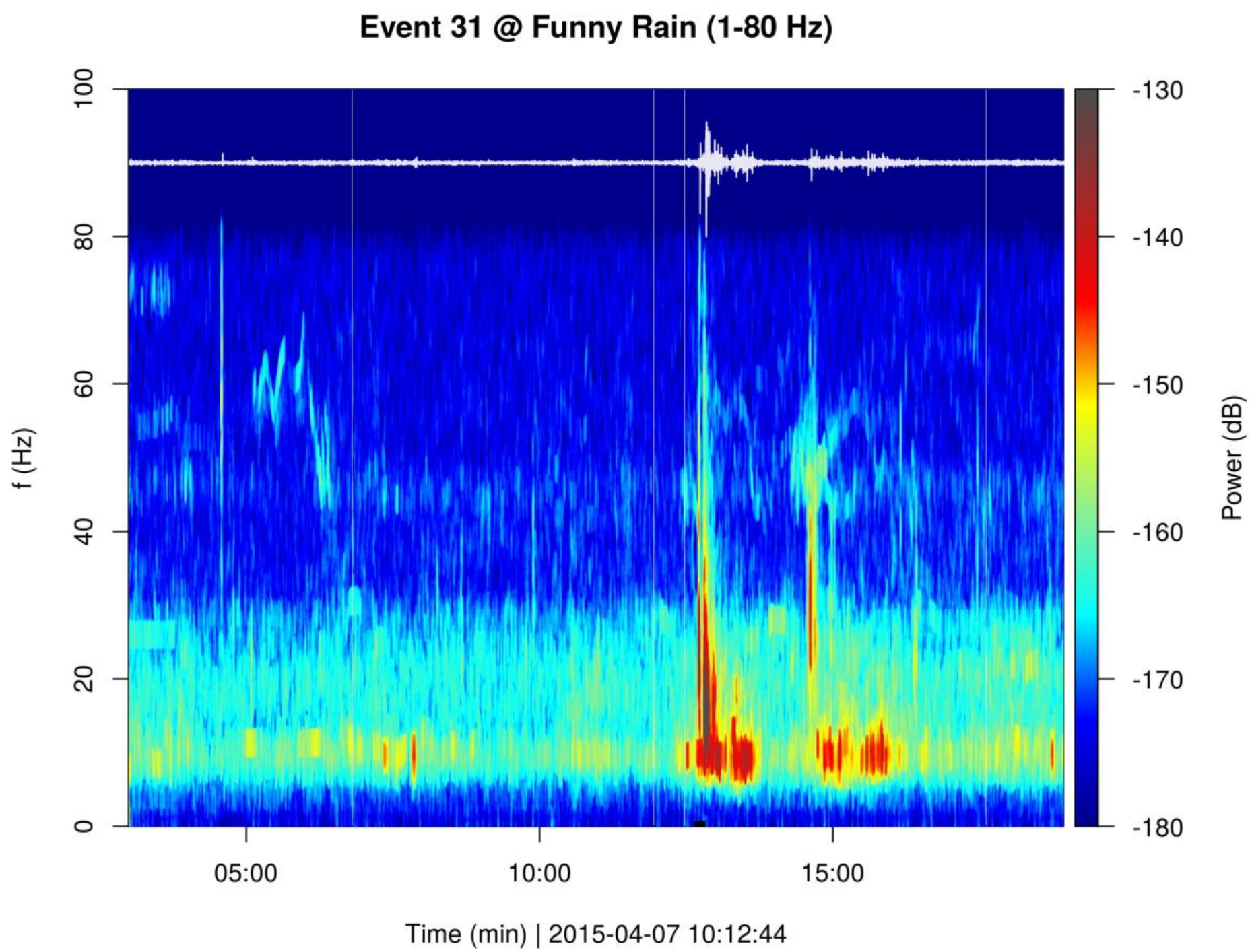


Figure 32:

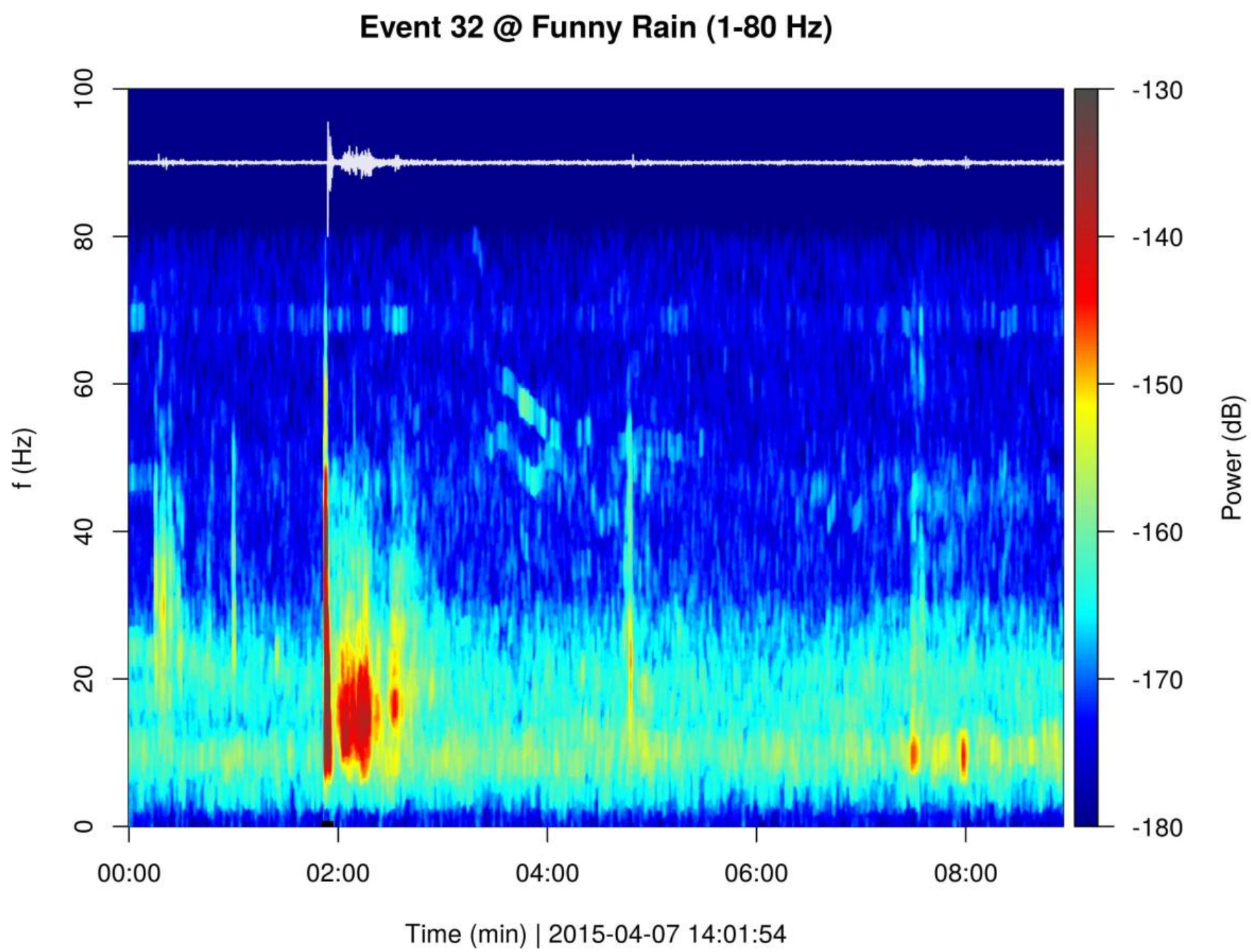


Figure 33:

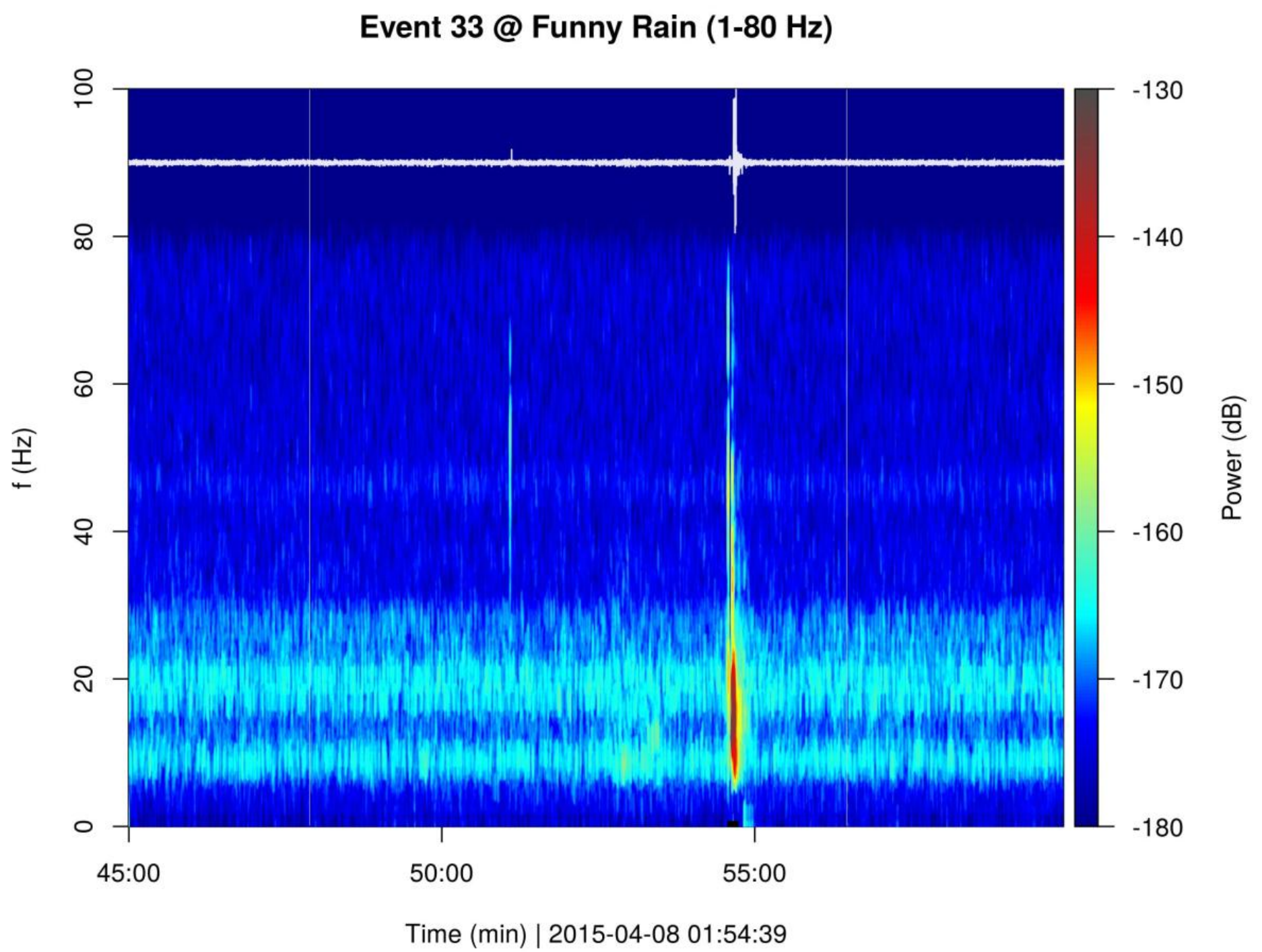


Figure 34:

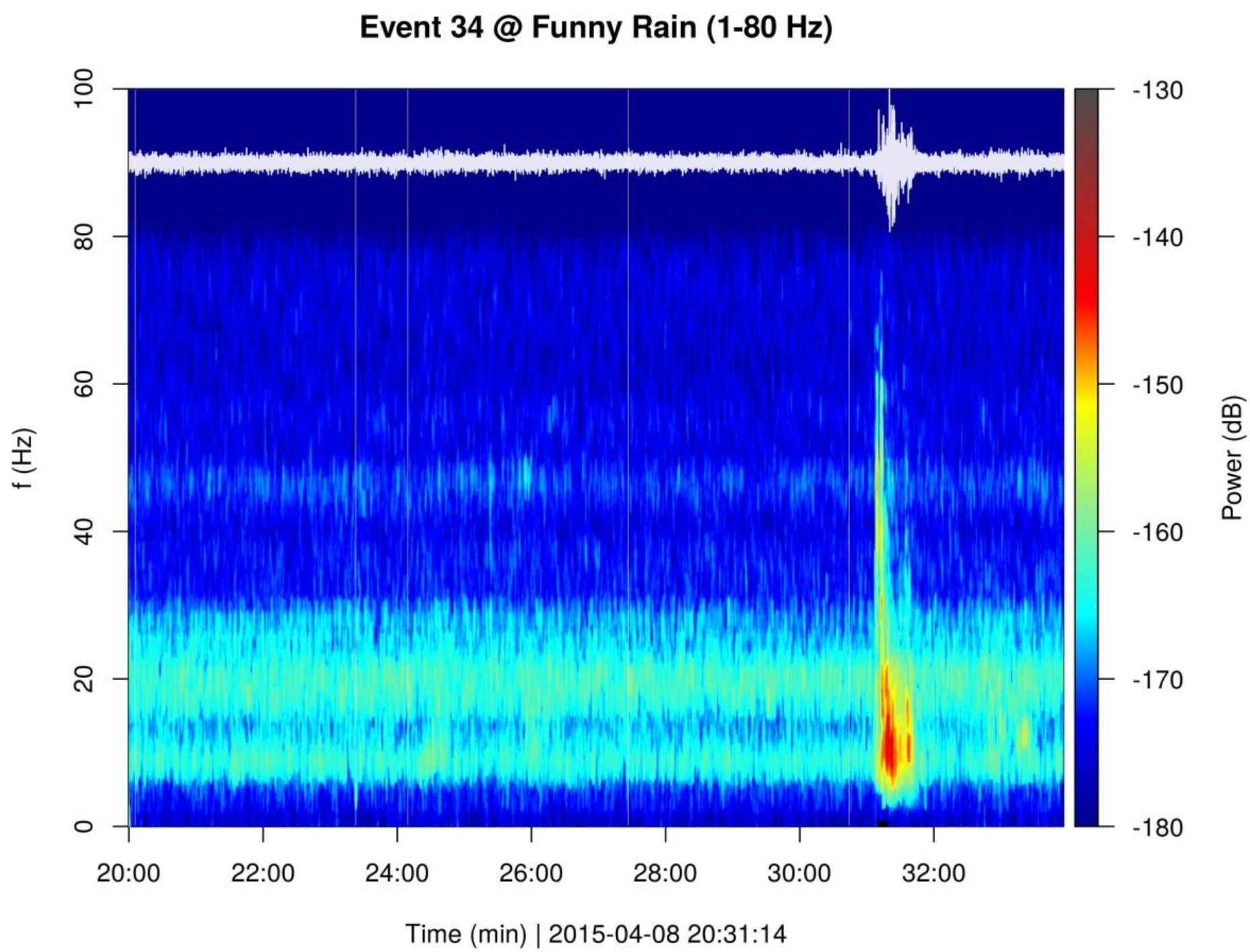


Figure 35:

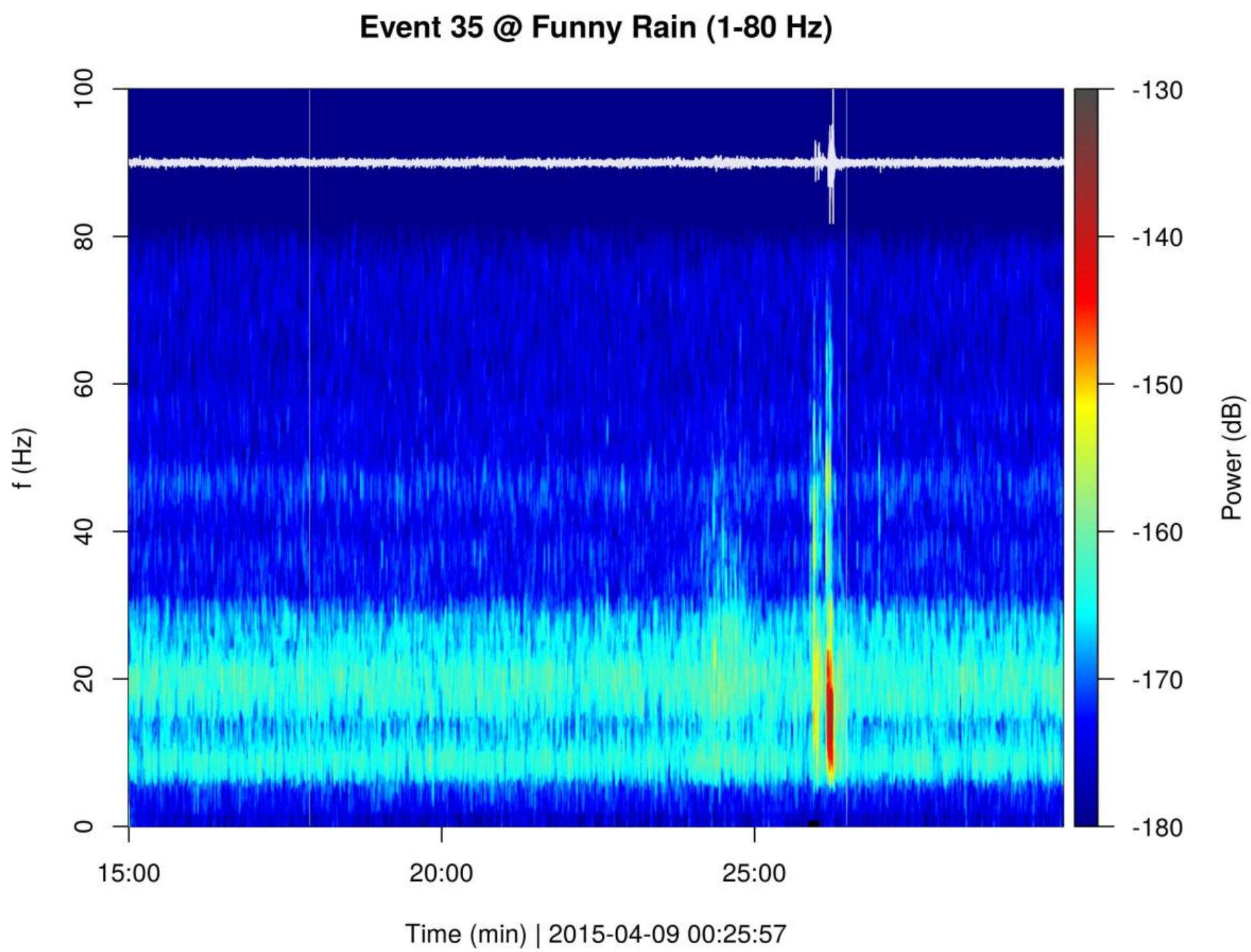


Figure 36:

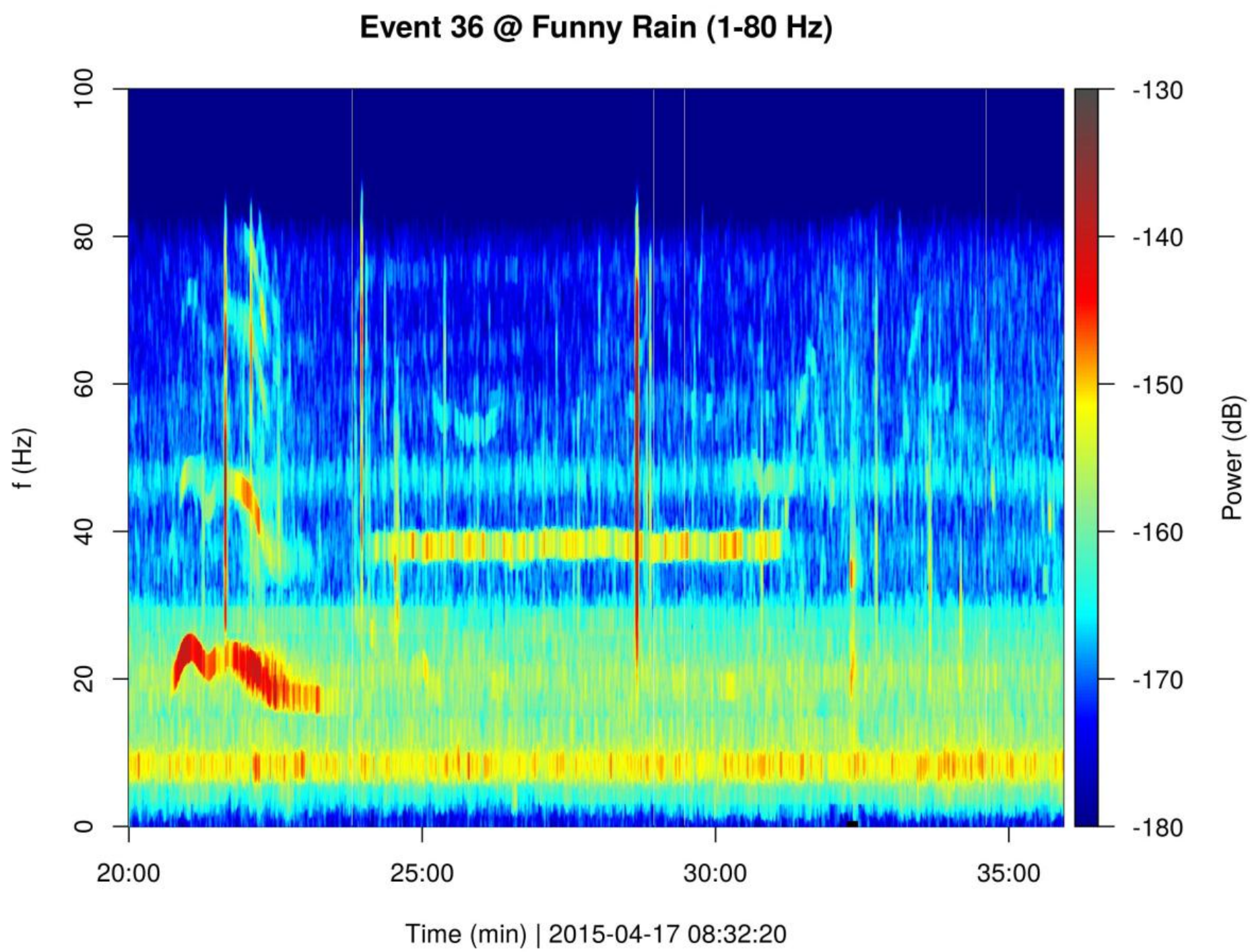


Figure 37:

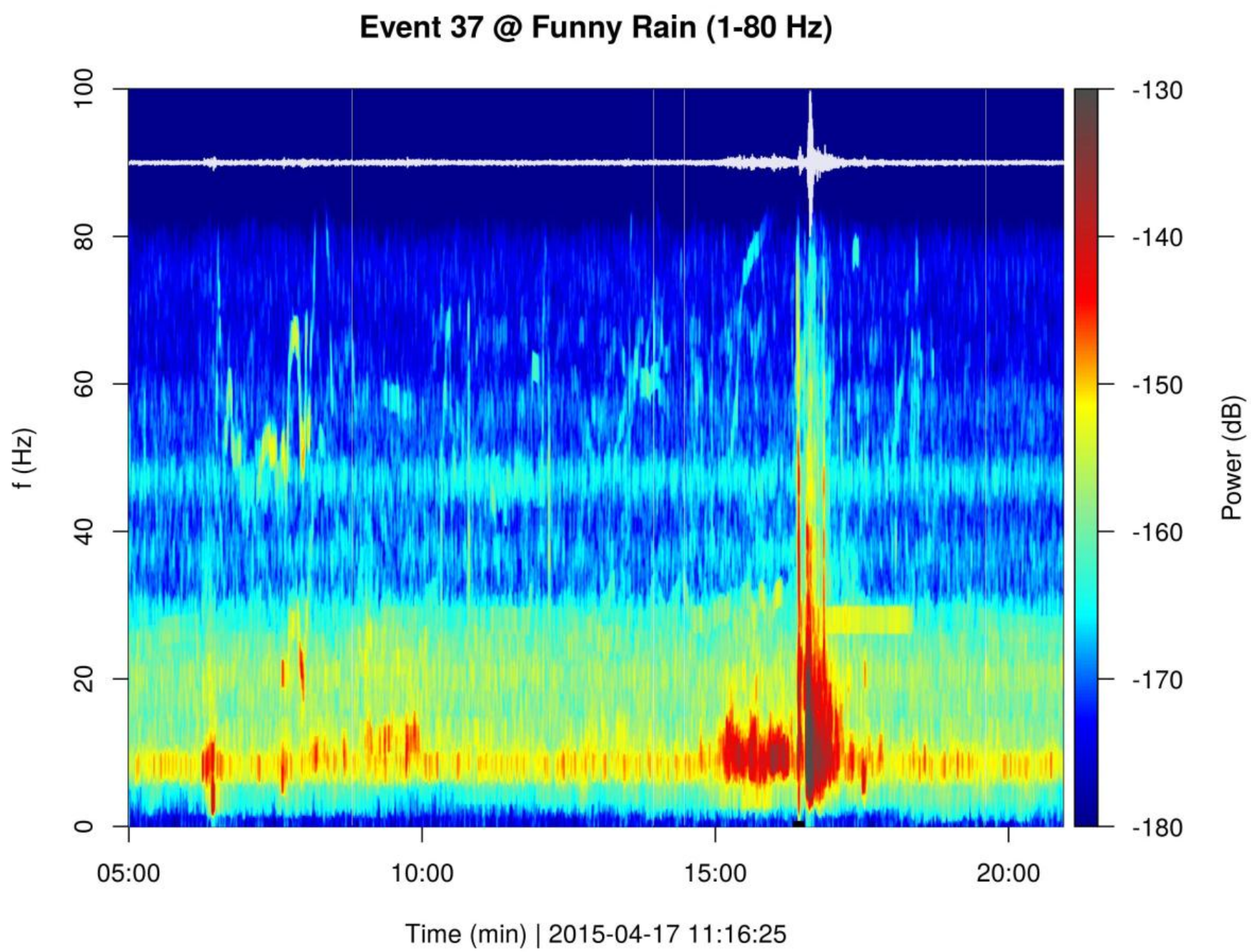


Figure 38:

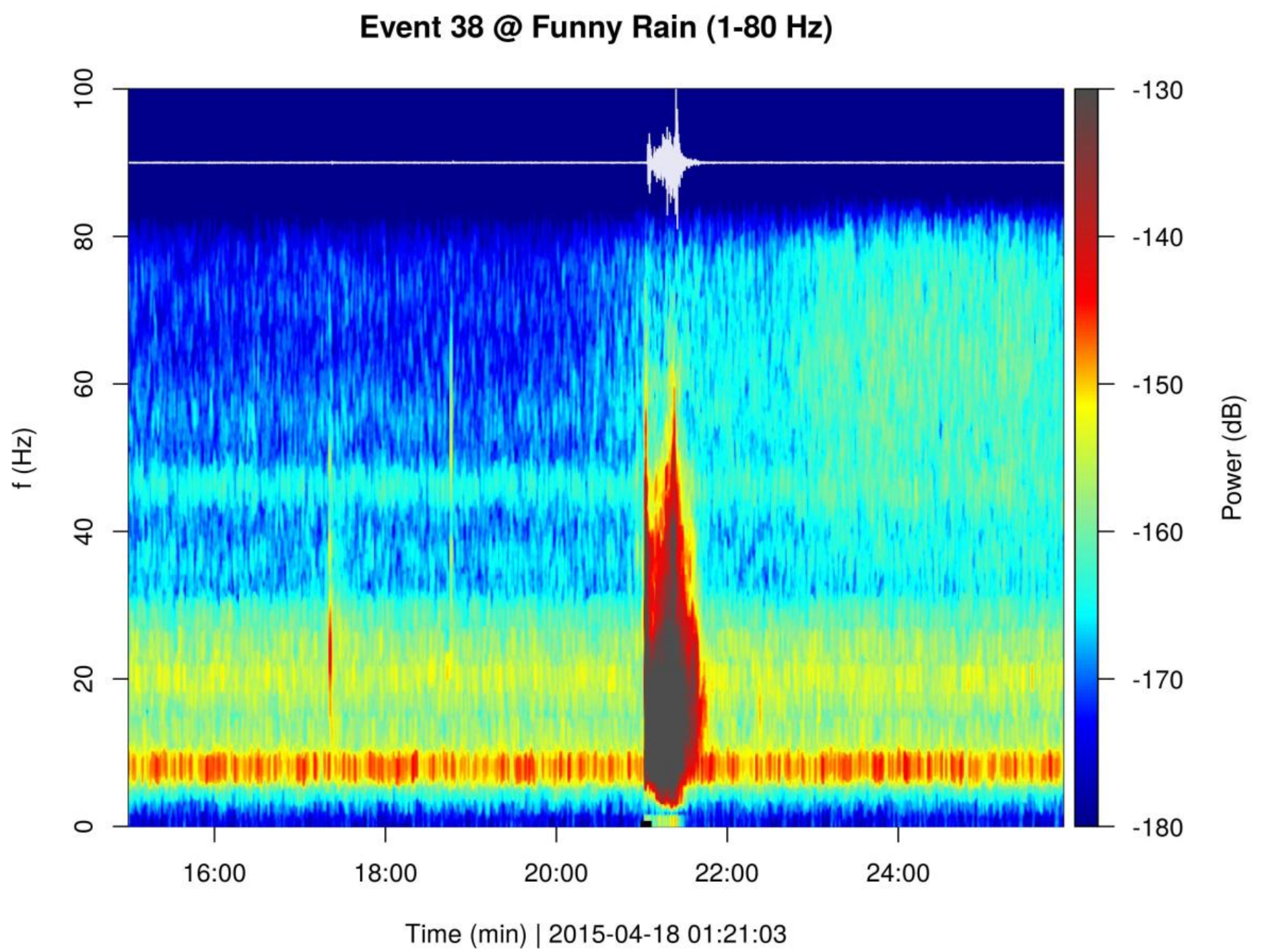


Figure 39:

Event 39 @ Funny Rain (1-80 Hz)

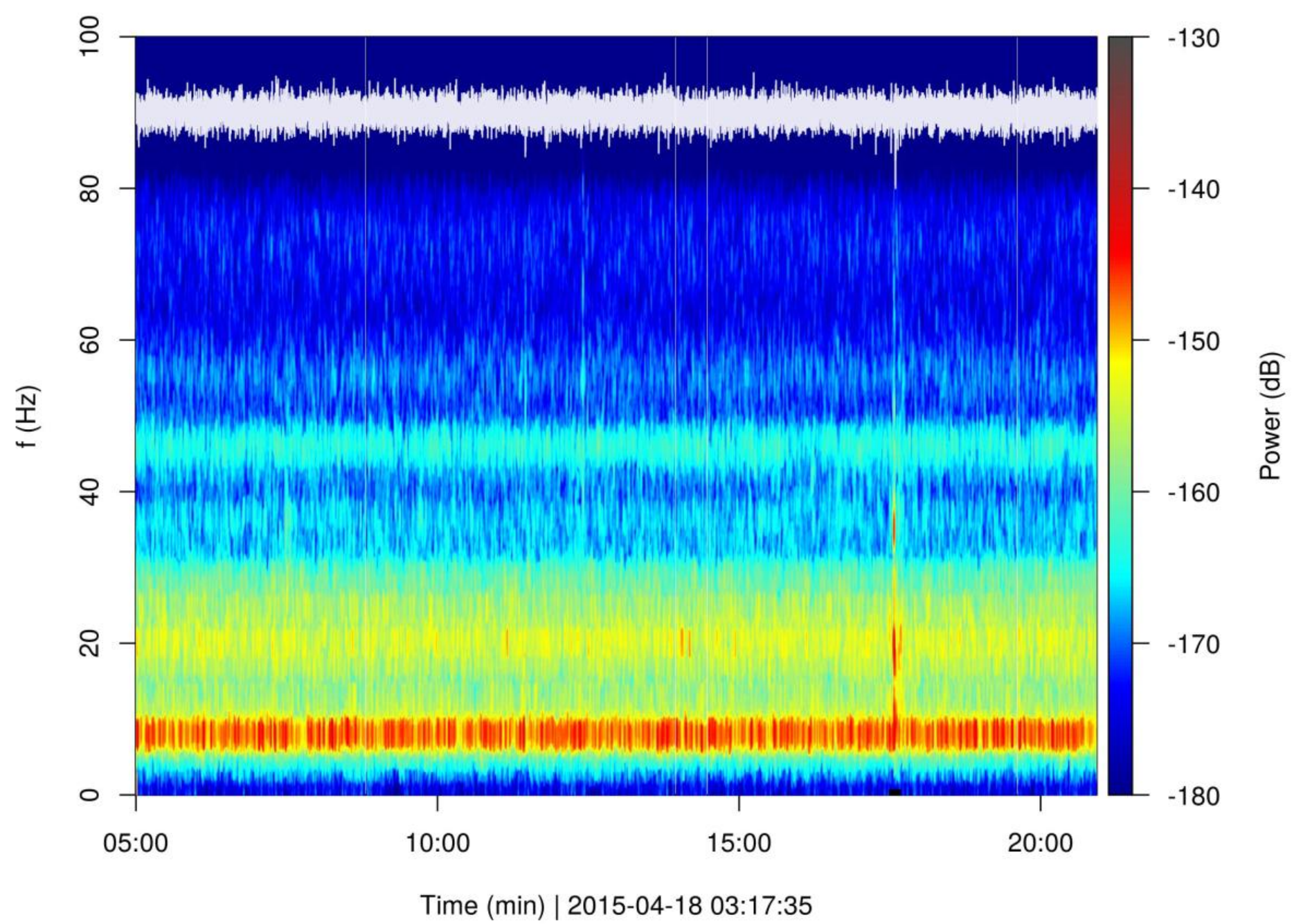


Figure 40:

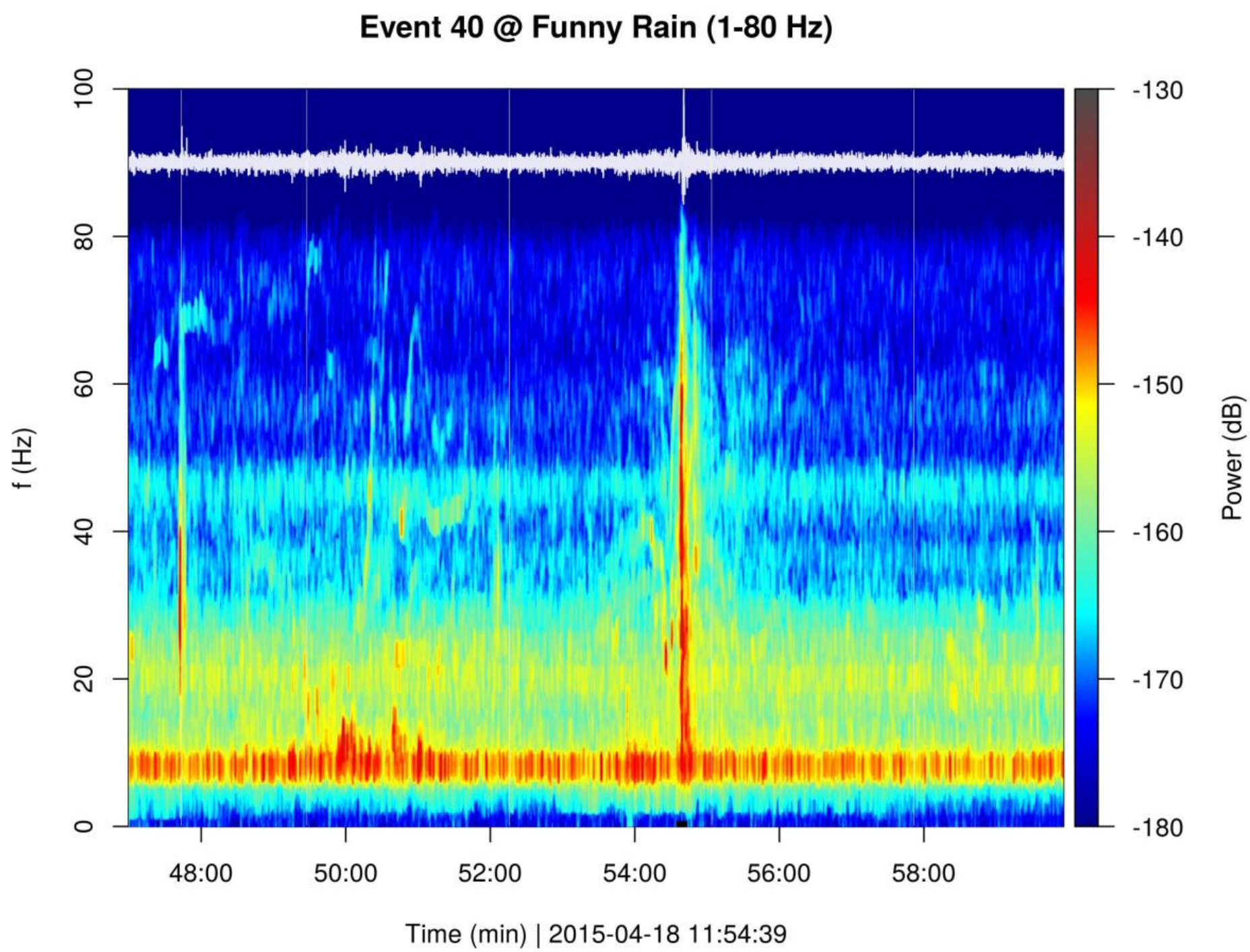


Figure 41:

Event 41 @ Funny Rain (1-80 Hz)

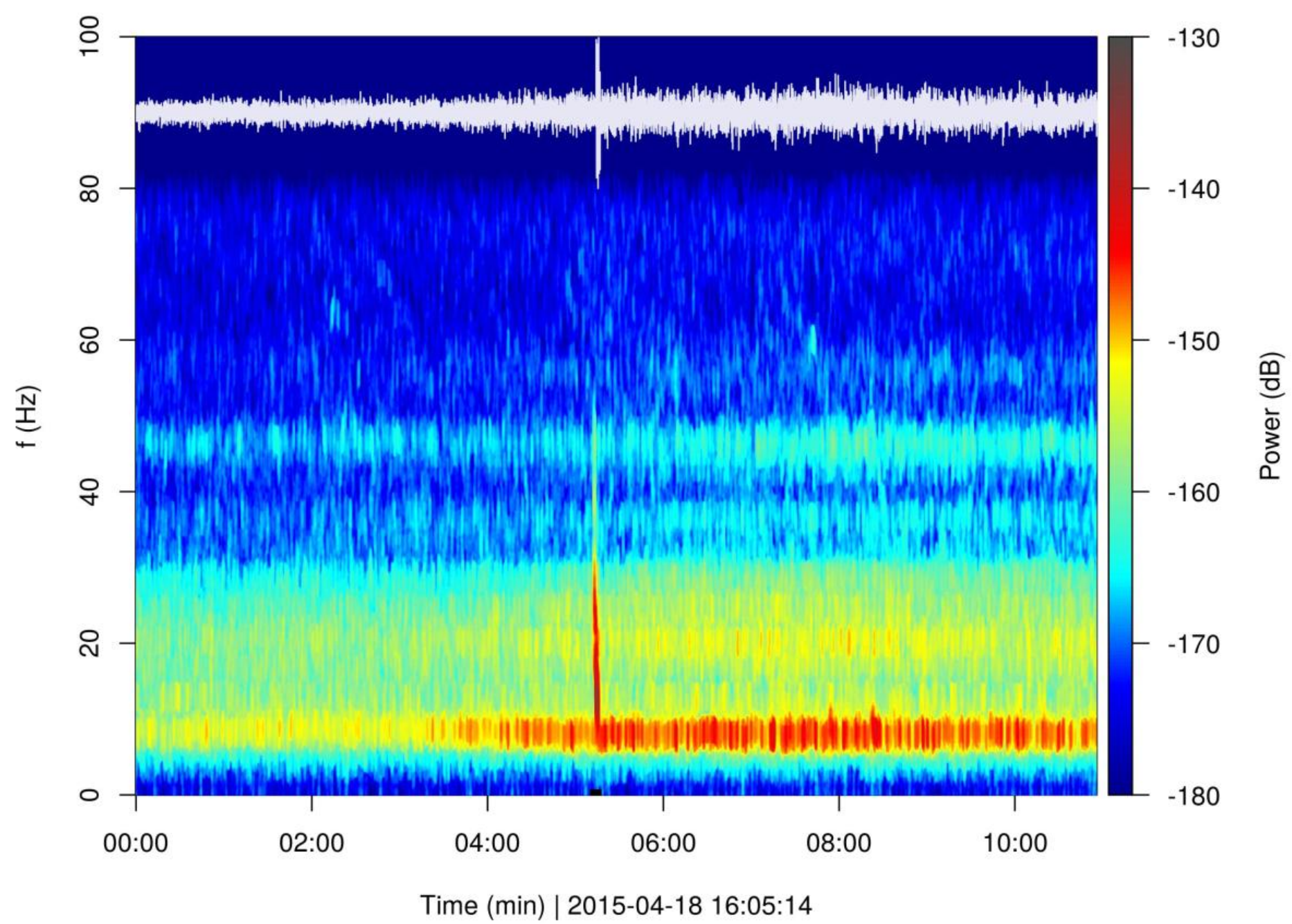


Figure 42:

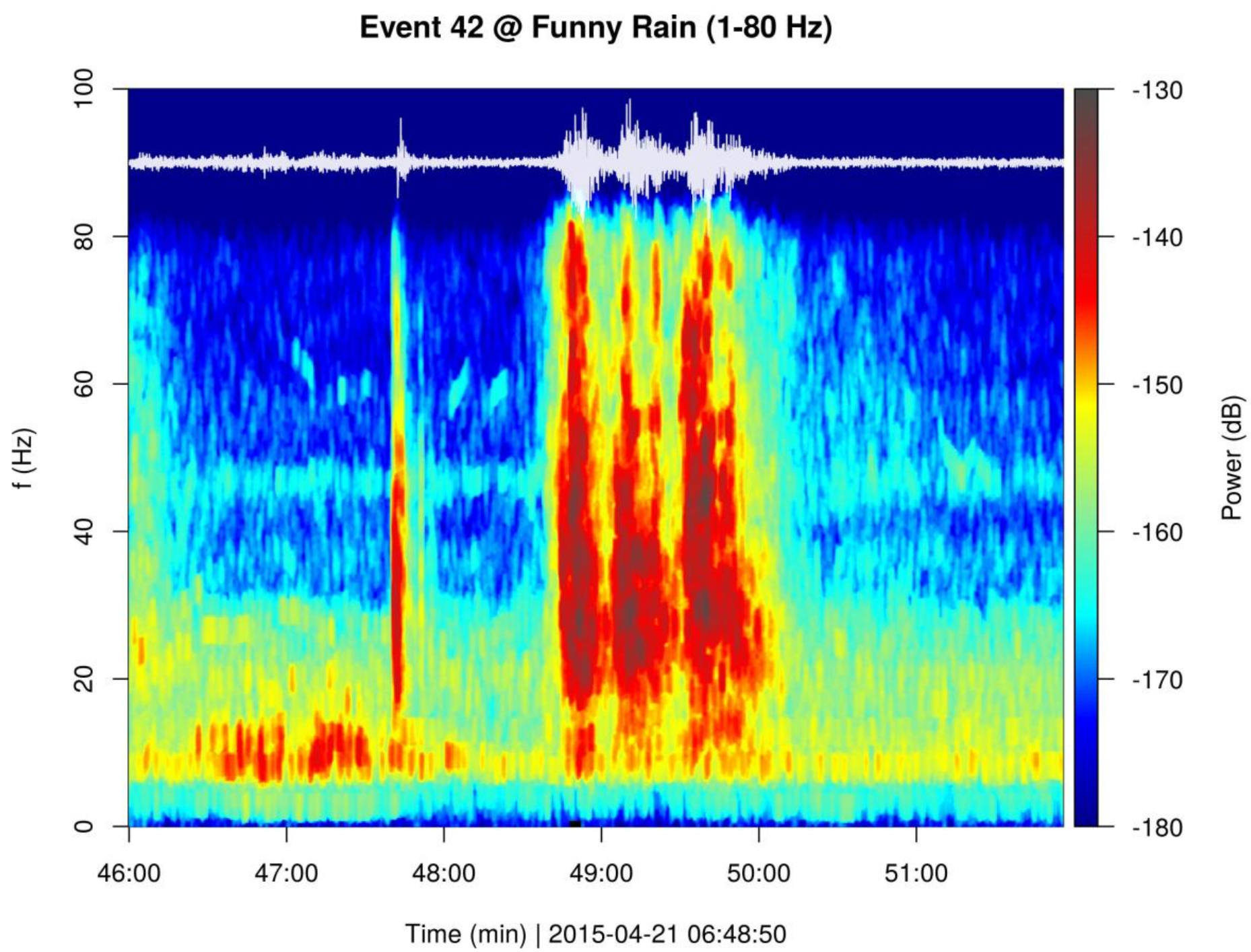


Figure 43:

Event 43 @ Funny Rain (1-80 Hz)

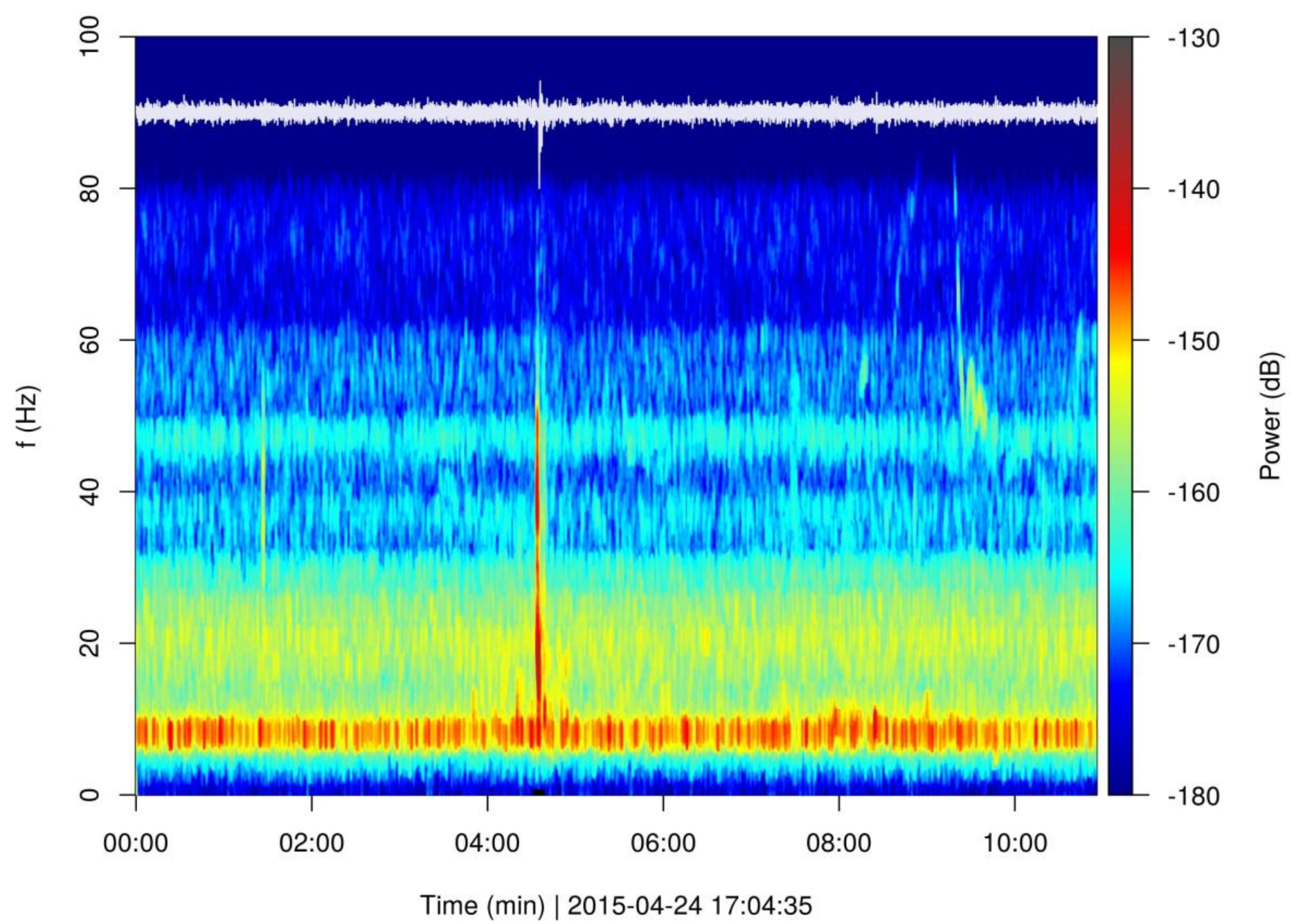


Figure 44:

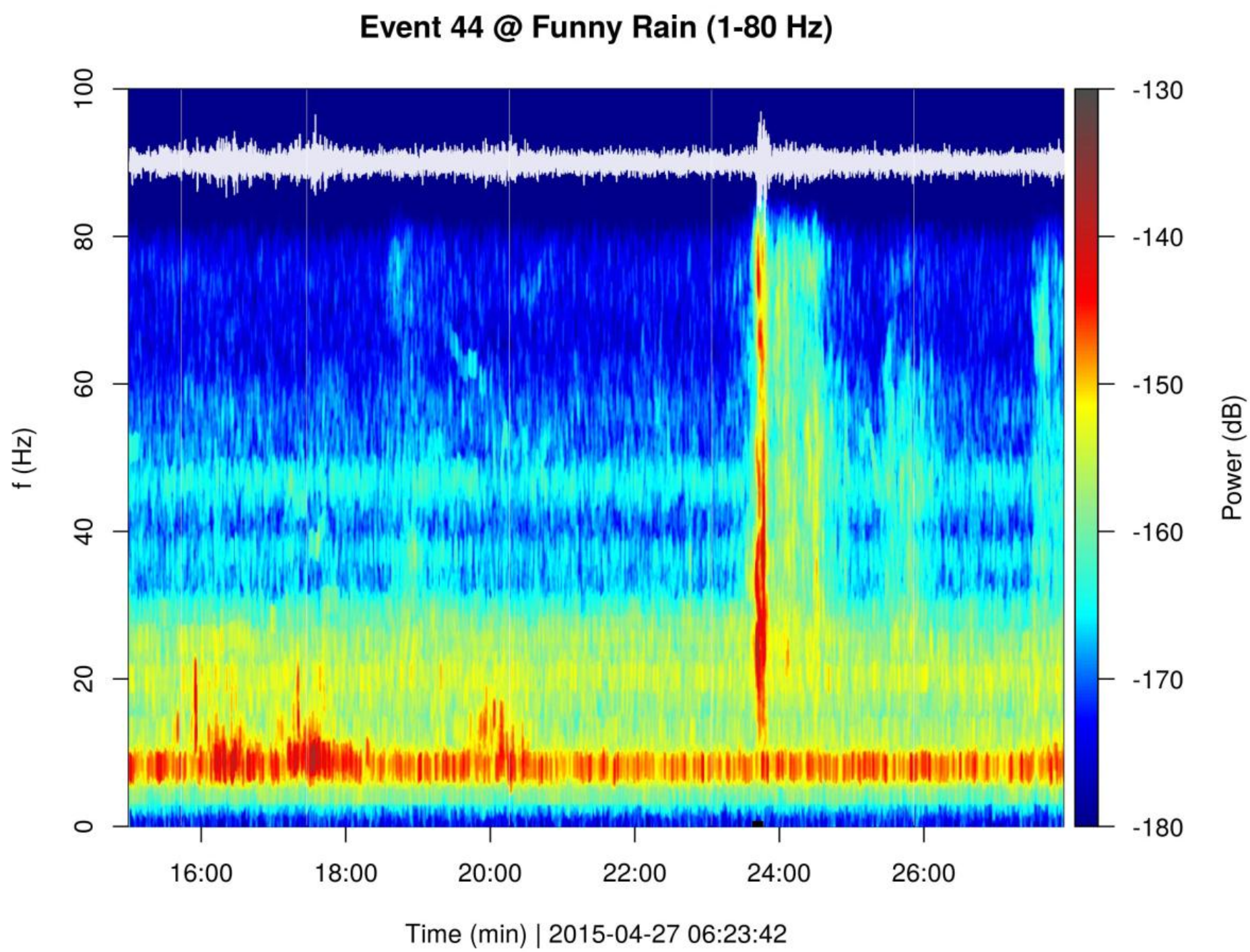


Figure 45:

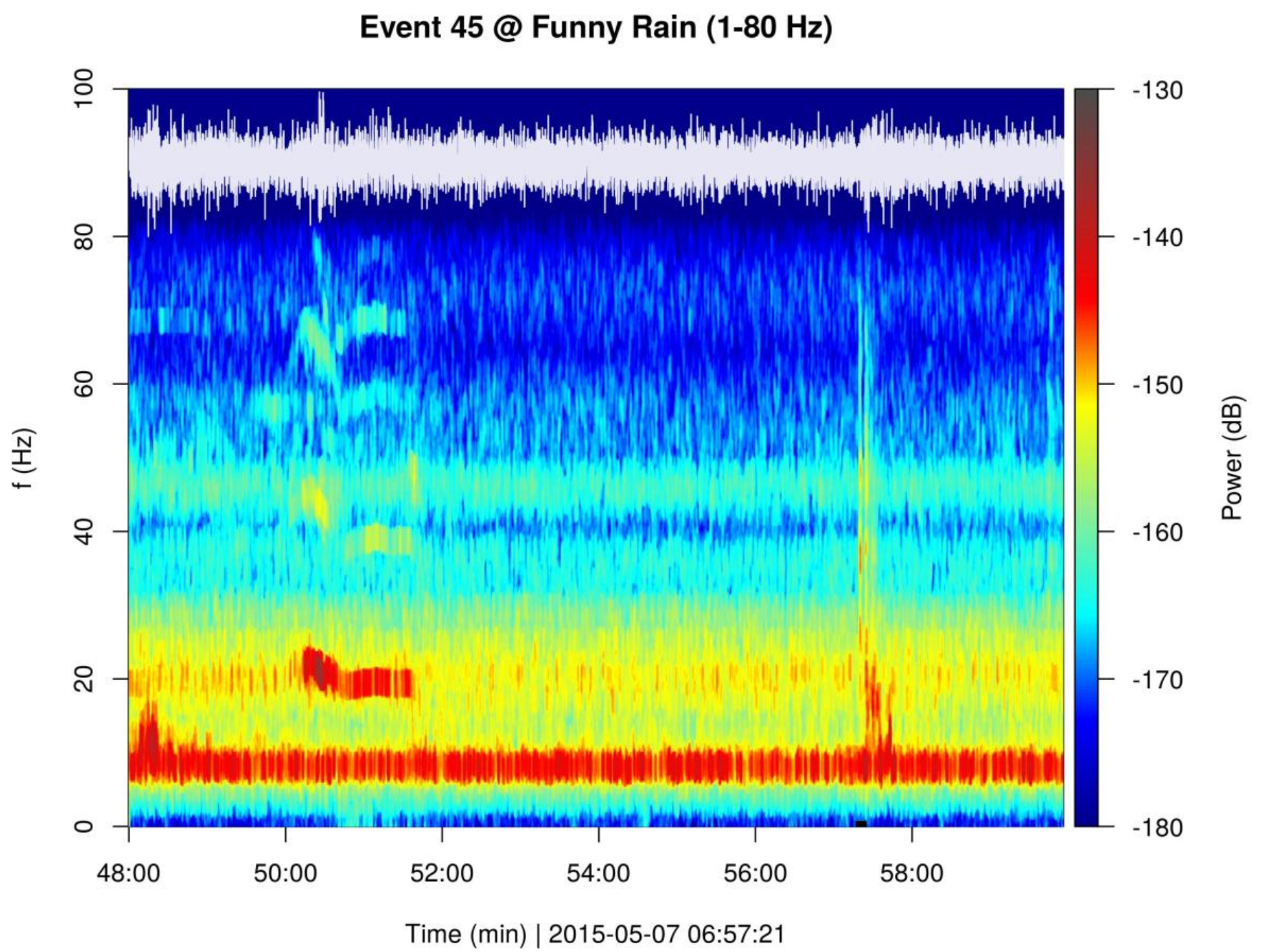


Figure 46:

Event 46 @ Funny Rain (1-80 Hz)

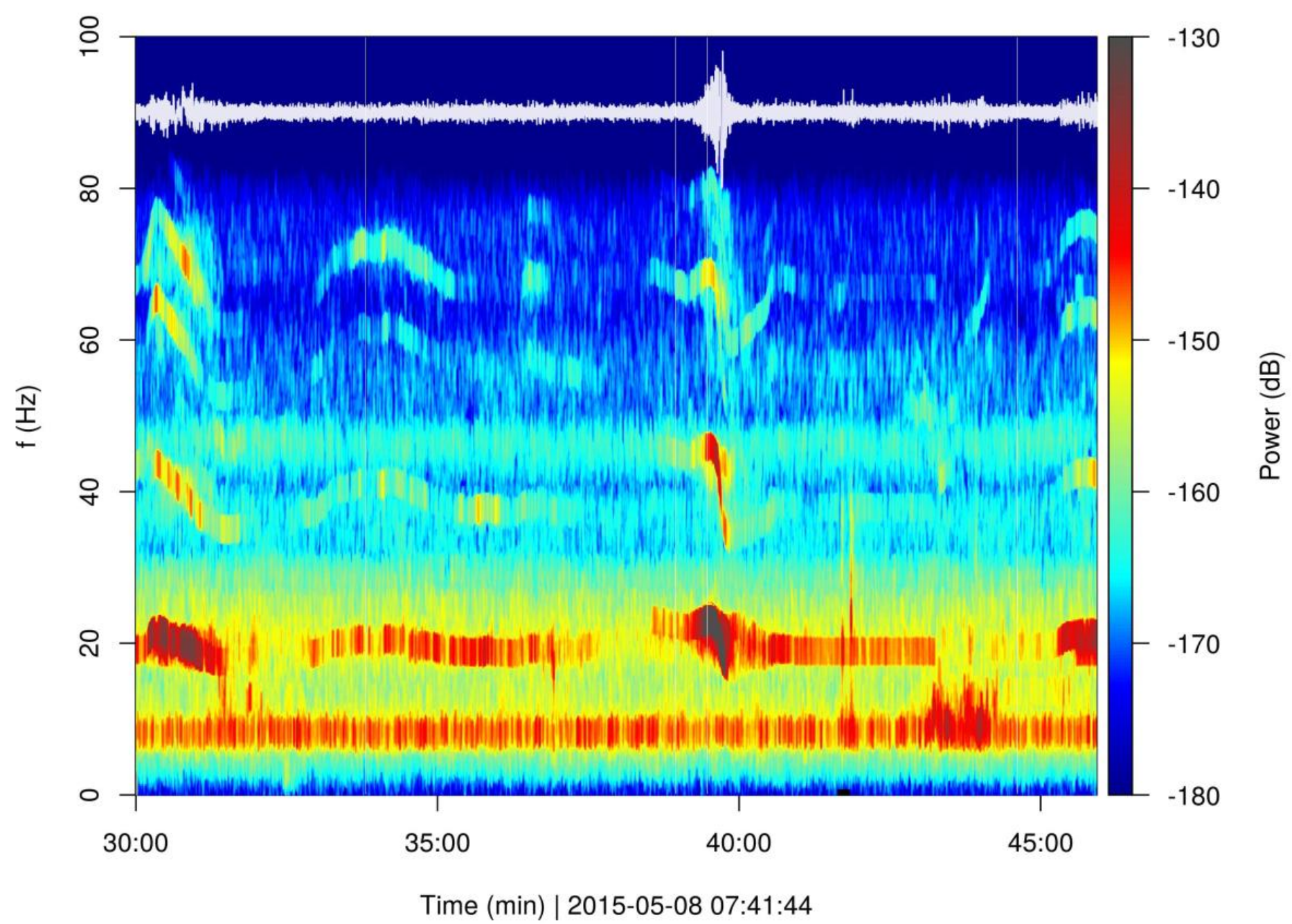


Figure 47:

Event 47 @ Funny Rain (1-80 Hz)

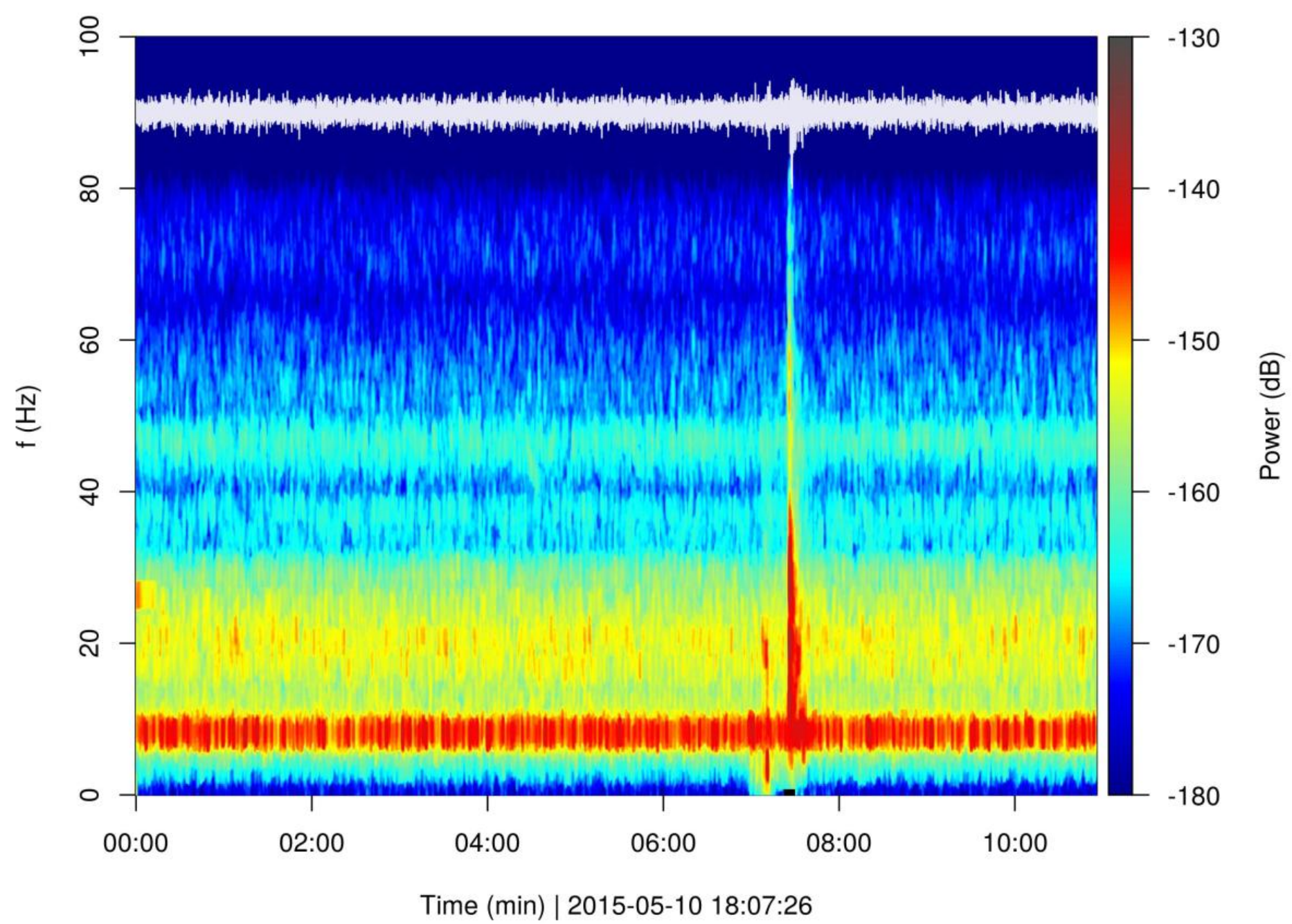


Figure 48:

Event 48 @ Funny Rain (1-80 Hz)

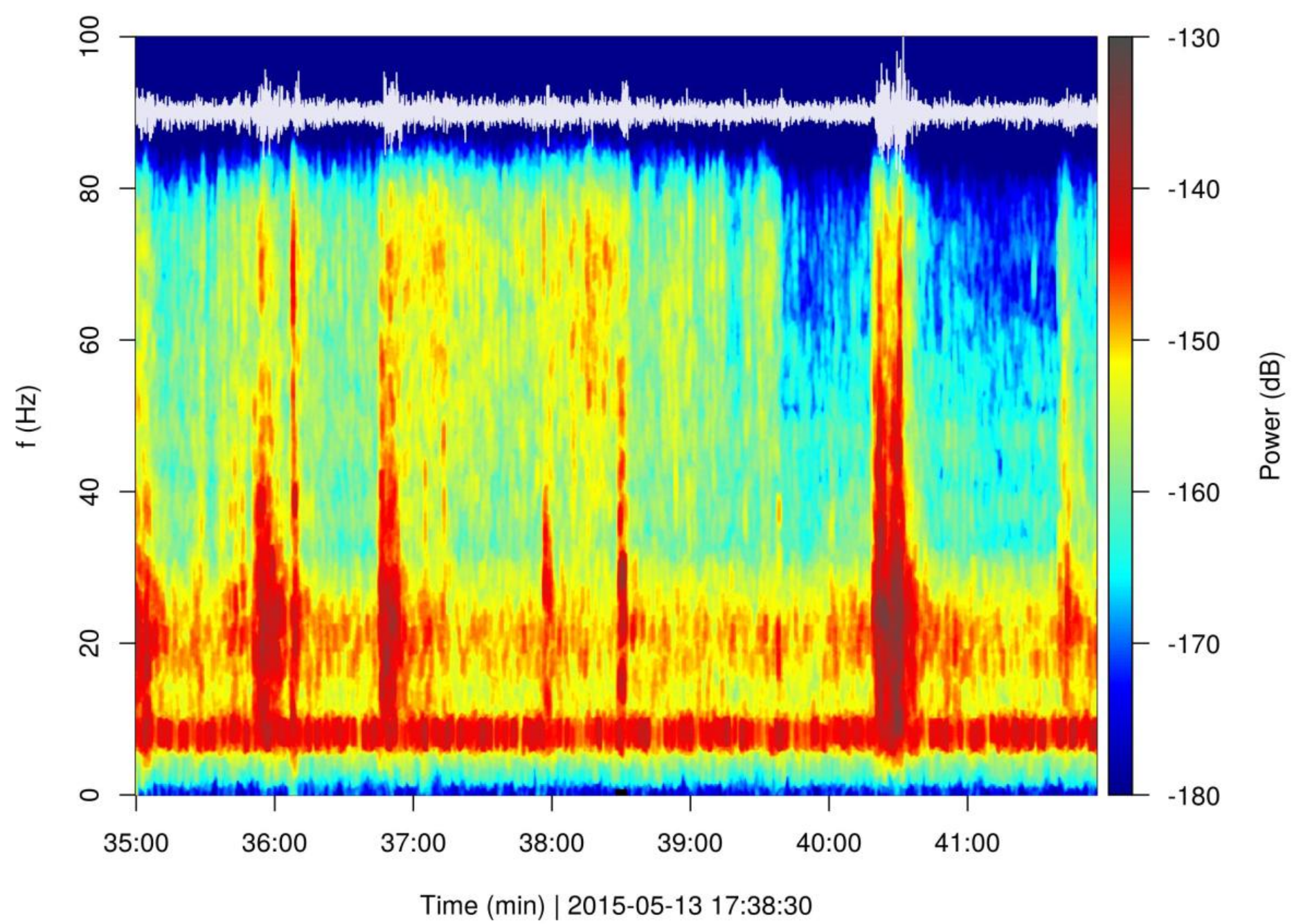


Figure 49:

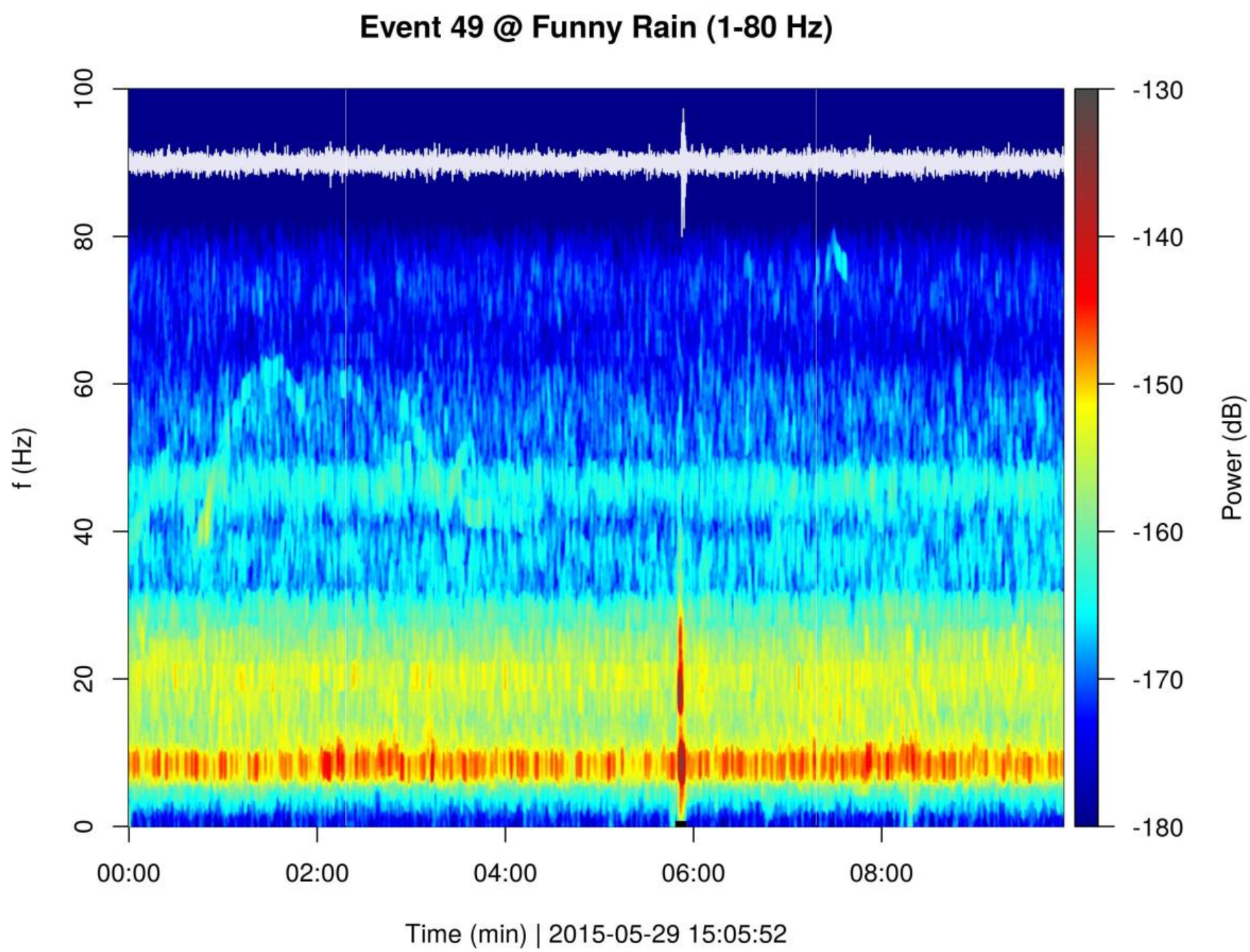


Figure 50: