Calculation of tube wave velocity in a shallow borehole using passive seismic recordings


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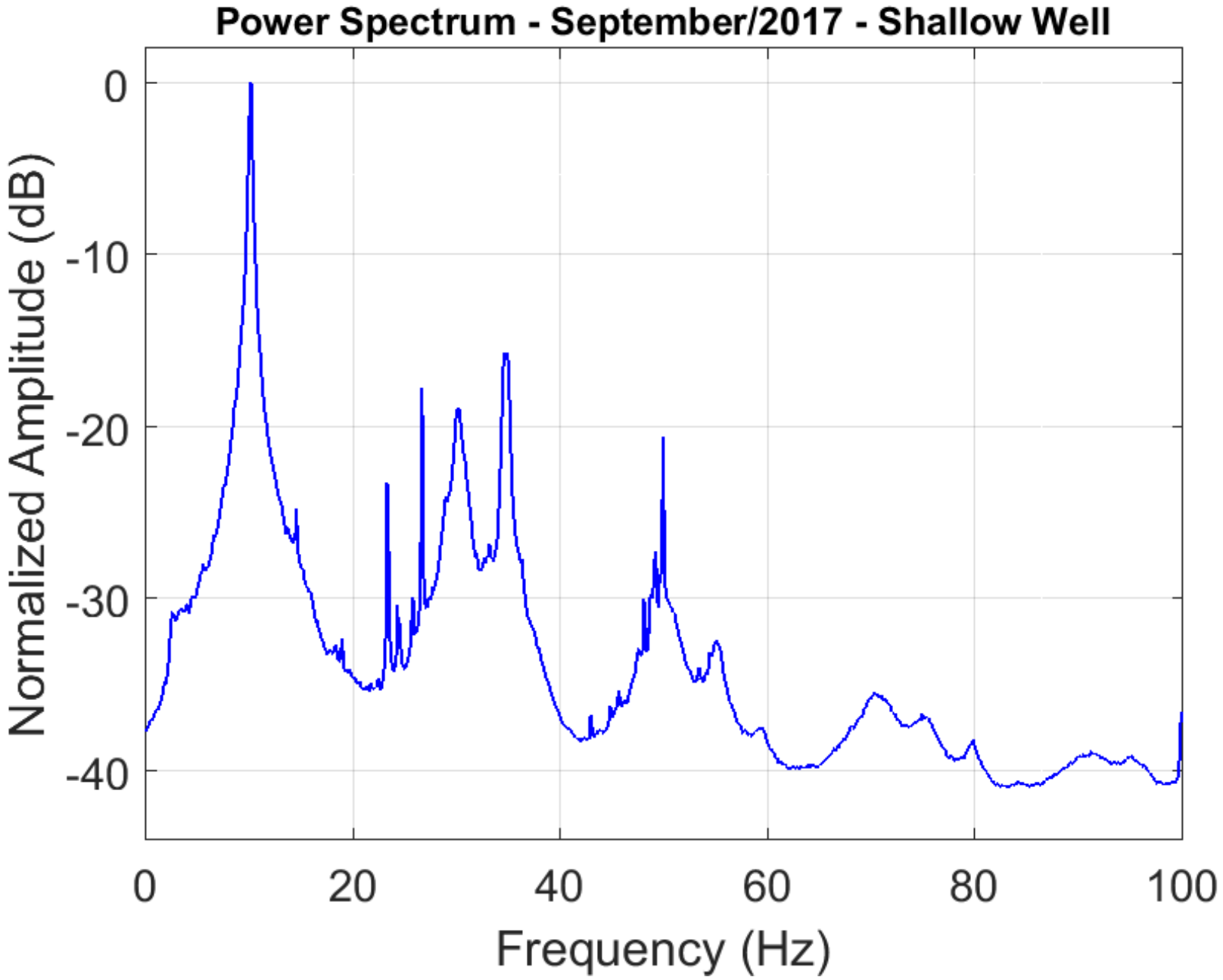
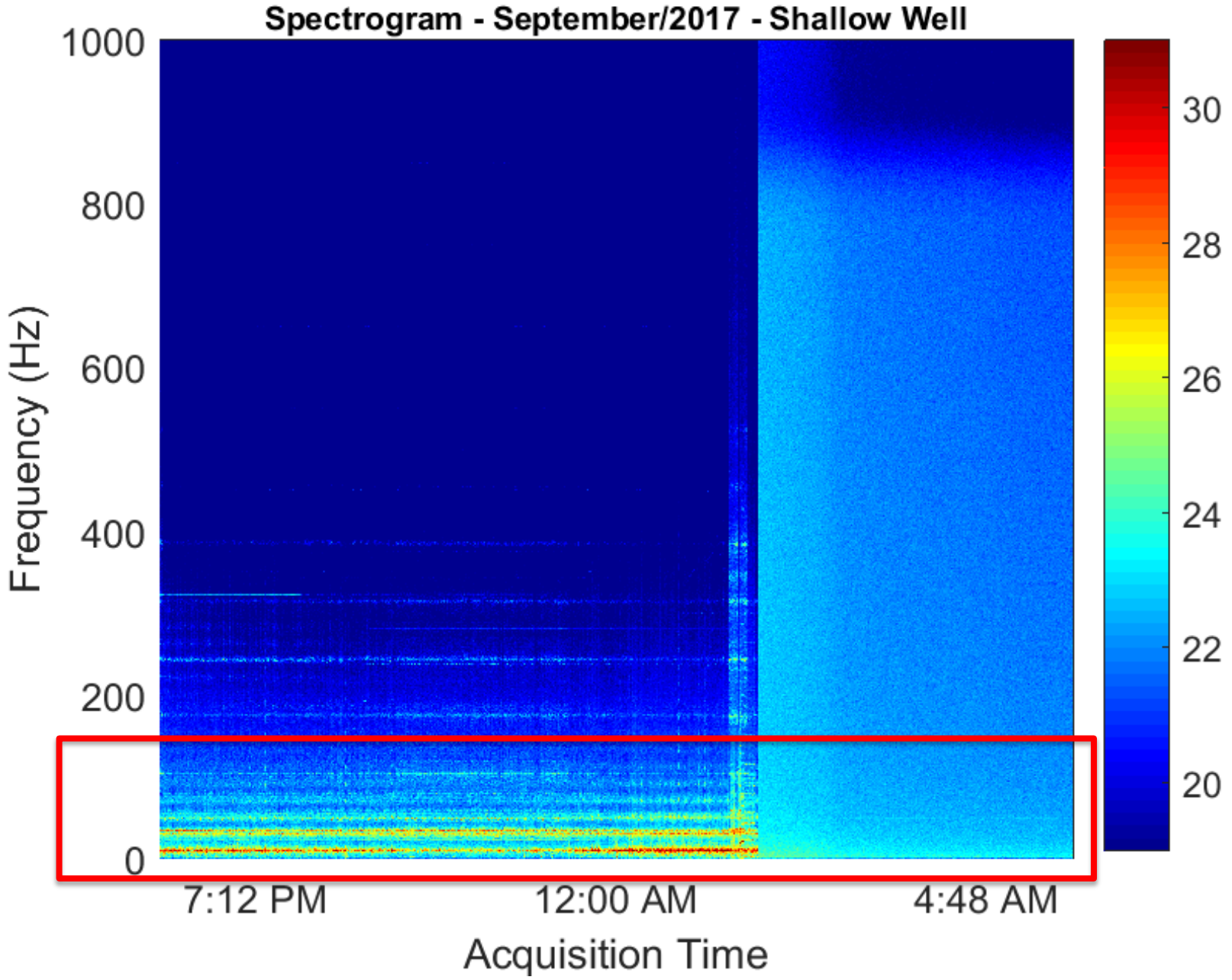
Experimental Setup – Shallow Well (1)

- 24 Hydrophones
- Sampling Frequency: 2000 Hz
- Total of 24h of recording
  - 11 SEG-Y files (10 GB)


Power Spectrum - September/2017 - Shallow Well
Normalized Amplitude (dB)
0
-10
-20
-30
-40
0
20
40
60
80
100
Frequency (Hz)


Spectrogram - September/2017 - Shallow Well
1000
800
600
400
200
0
Frequency (Hz)
7:12 PM
12:00 AM
4:48 AM
Acquisition Time
30
28
26
24
22
20

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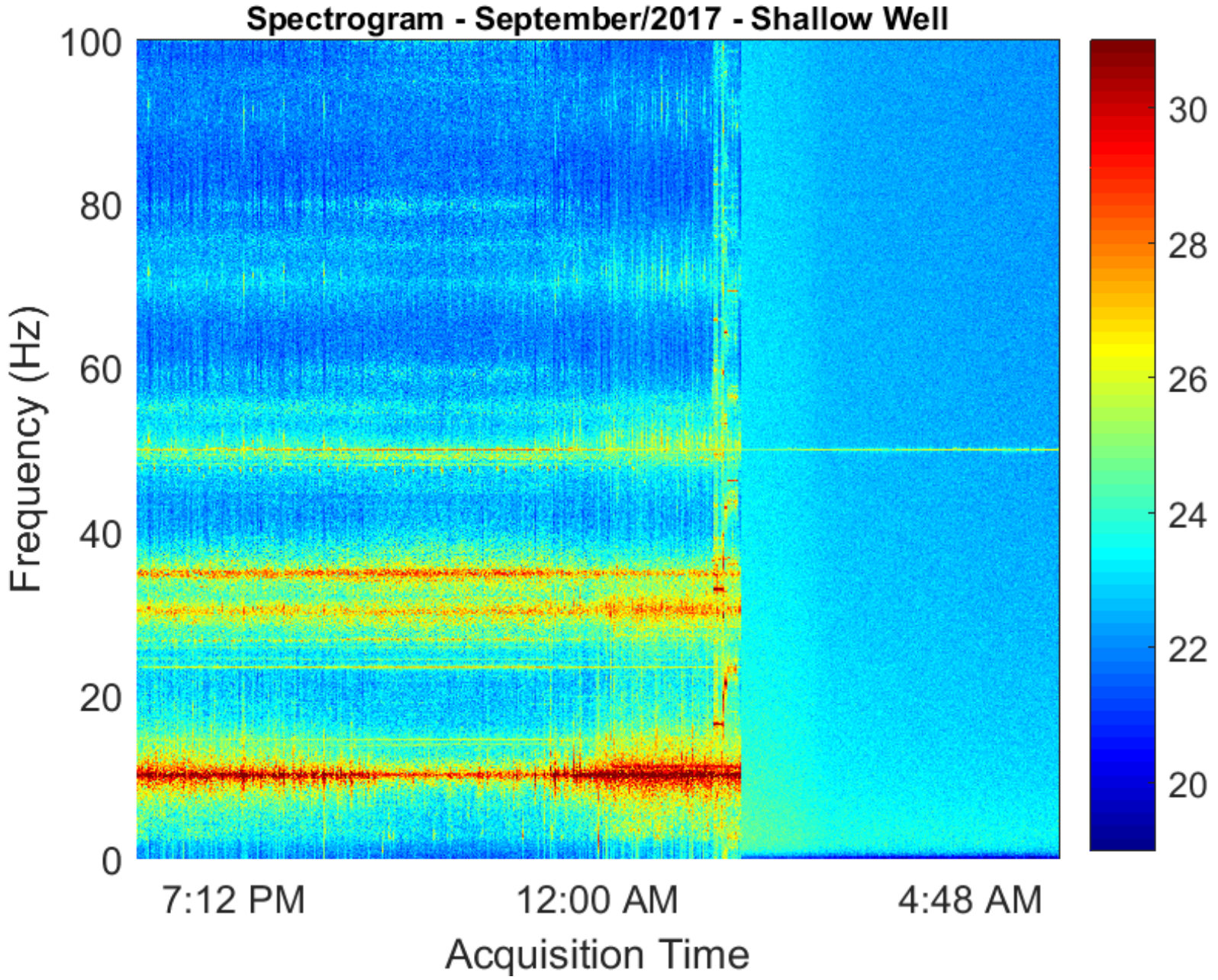
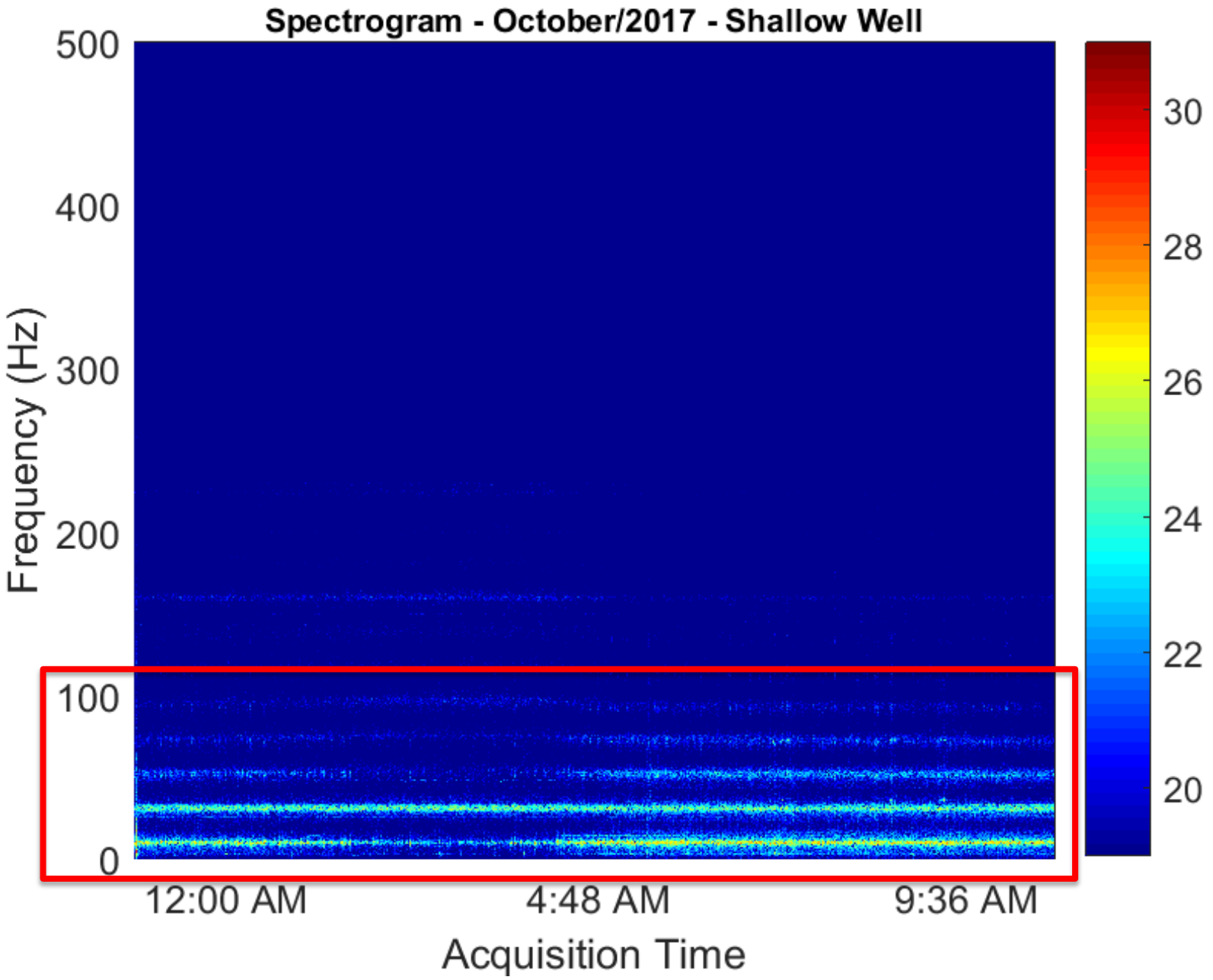

Spectrogram - September/2017 - Shallow Well
Frequency (Hz)
100
80
60
40
20
0
7:12 PM
12:00 AM
4:48 AM
Acquisition Time
30
28
26
24
22
20

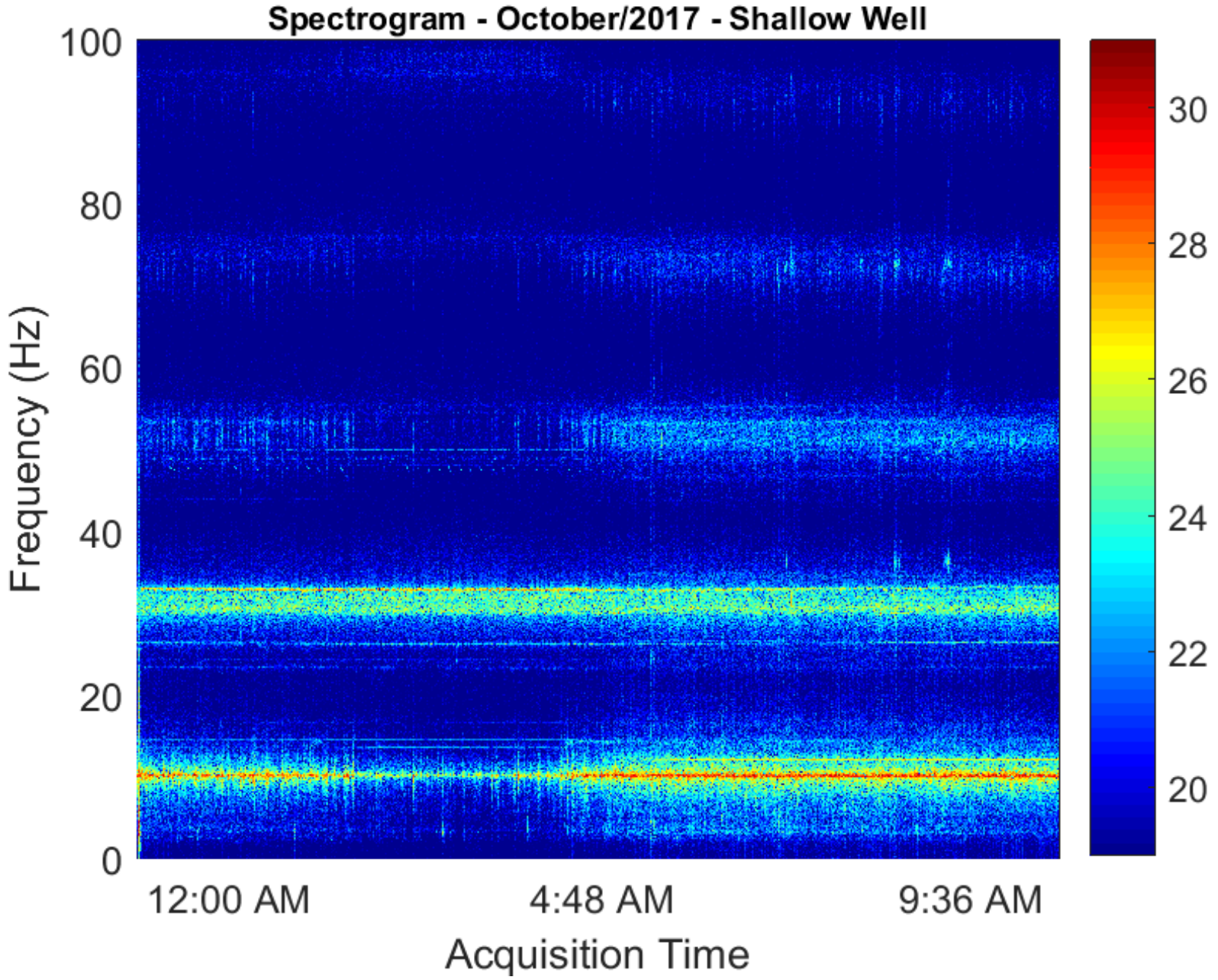
NTNU

Experimental Setup – Shallow Well (2)

- 24 Hydrophones
- Sampling Frequency: 1000 Hz
- Total of 21h of recording
  - 6 SEG-Y files (5 GB)

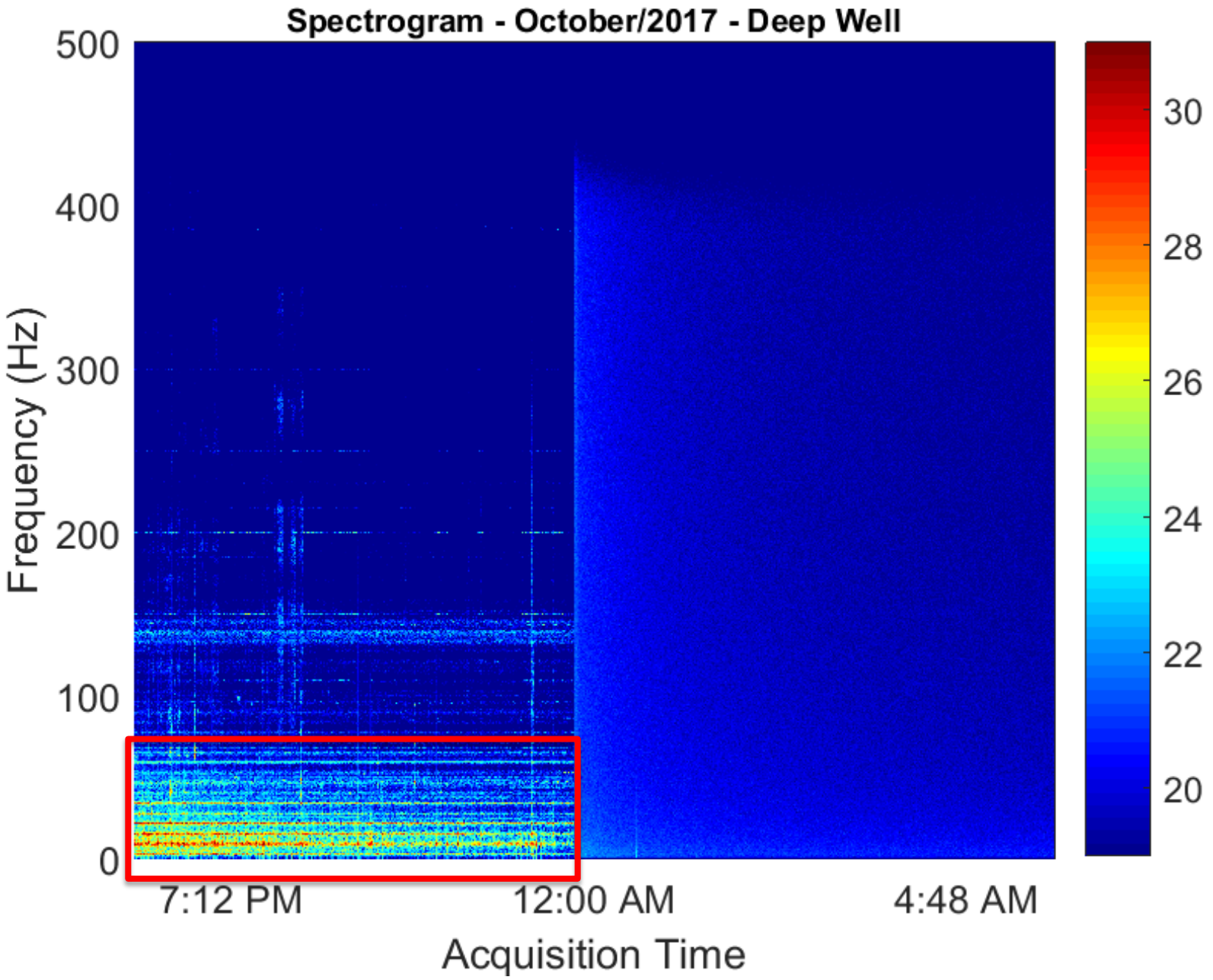

Spectrogram - October/2017 - Shallow Well
500
400
300
200
100
0
Frequency (Hz)
12:00 AM
4:48 AM
9:36 AM
Acquisition Time
30
28
26
24
22
20

NTNU

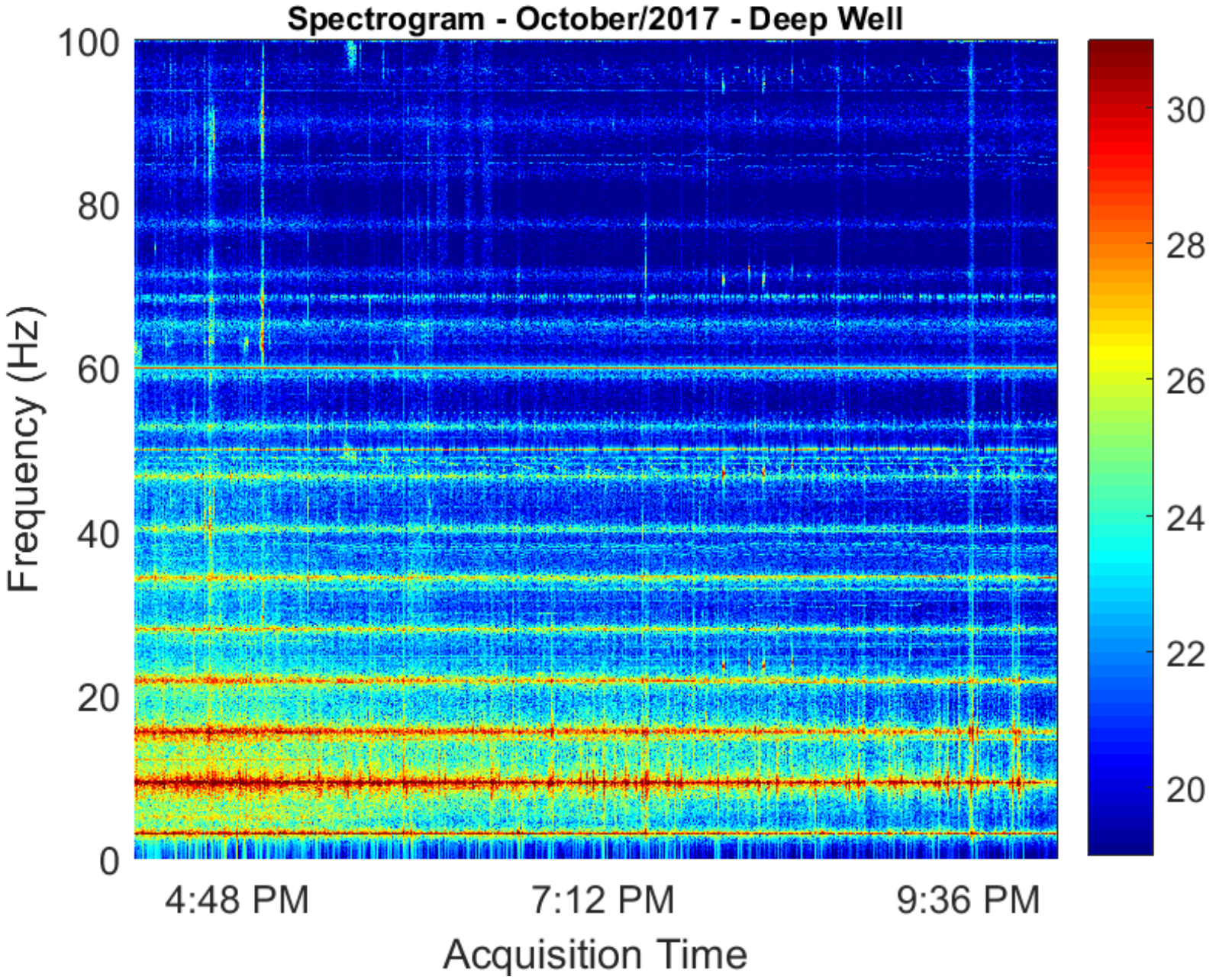

Spectrogram - October/2017 - Shallow Well
Frequency (Hz)
100
80
60
40
20
0
12:00 AM
4:48 AM
9:36 AM
Acquisition Time
30
28
26
24
22
20

Experimental Setup – Deep Well

- 24 Hydrophones (shallow part of well)
- Sampling Frequency: 1000 Hz
- Total of 22h of recording
  - 6 SEG-Y files (5.5 GB)


Spectrogram - October/2017 - Deep Well
Frequency (Hz)
500
400
300
200
100
0
7:12 PM
12:00 AM
4:48 AM
Acquisition Time
30
28
26
24
22
20

NTNU


Spectrogram - October/2017 - Deep Well
Frequency (Hz)
100
80
60
40
20
0
4:48 PM
7:12 PM
9:36 PM
Acquisition Time
30
28
26
24
22
20

Cepstrum

$$c(q) = \mathcal{F}^{-1}\left\{ \log\left(\mathcal{F}\{d(t)\} \right) \right\}$$

$D(f)$

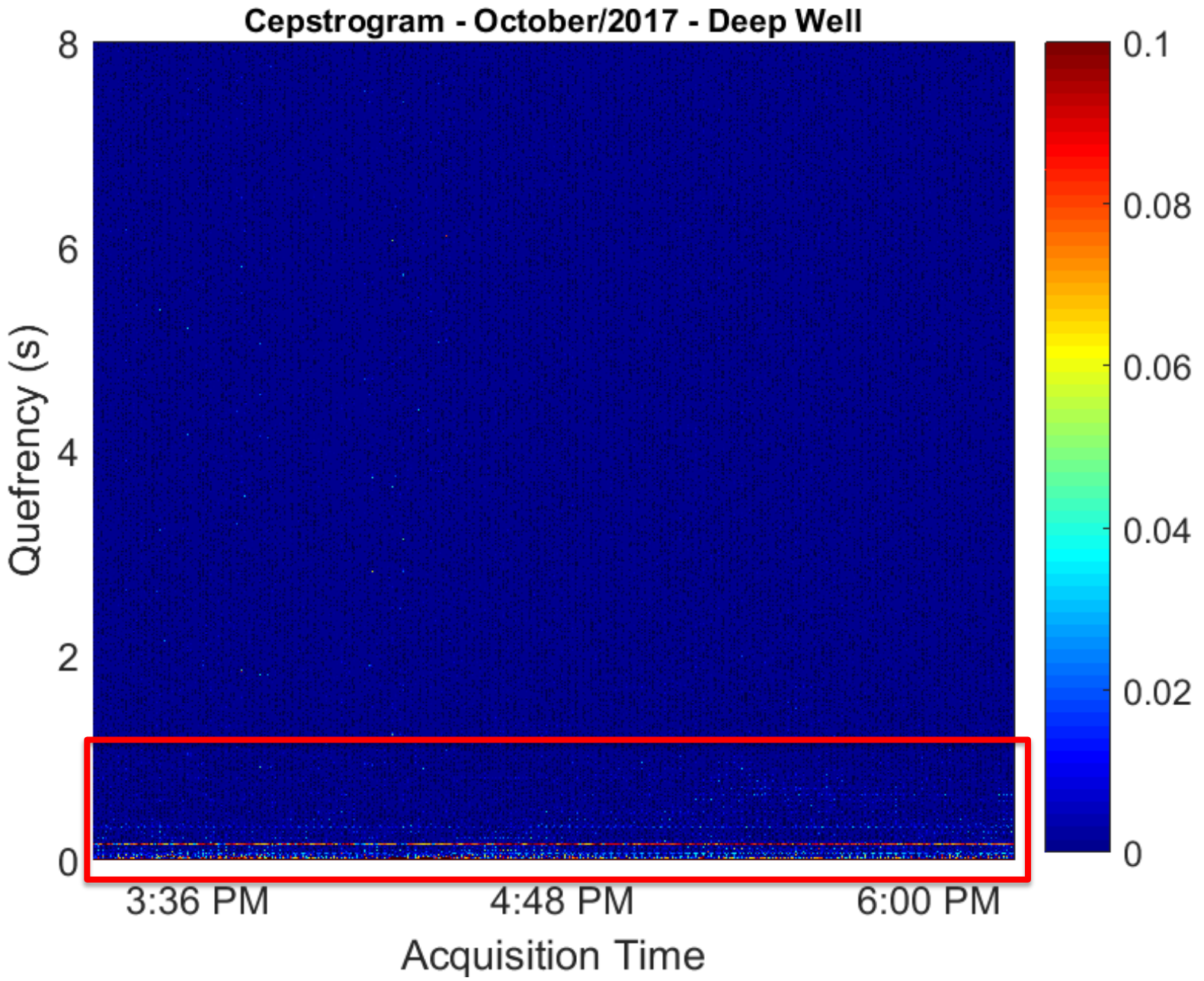
$c(q)$

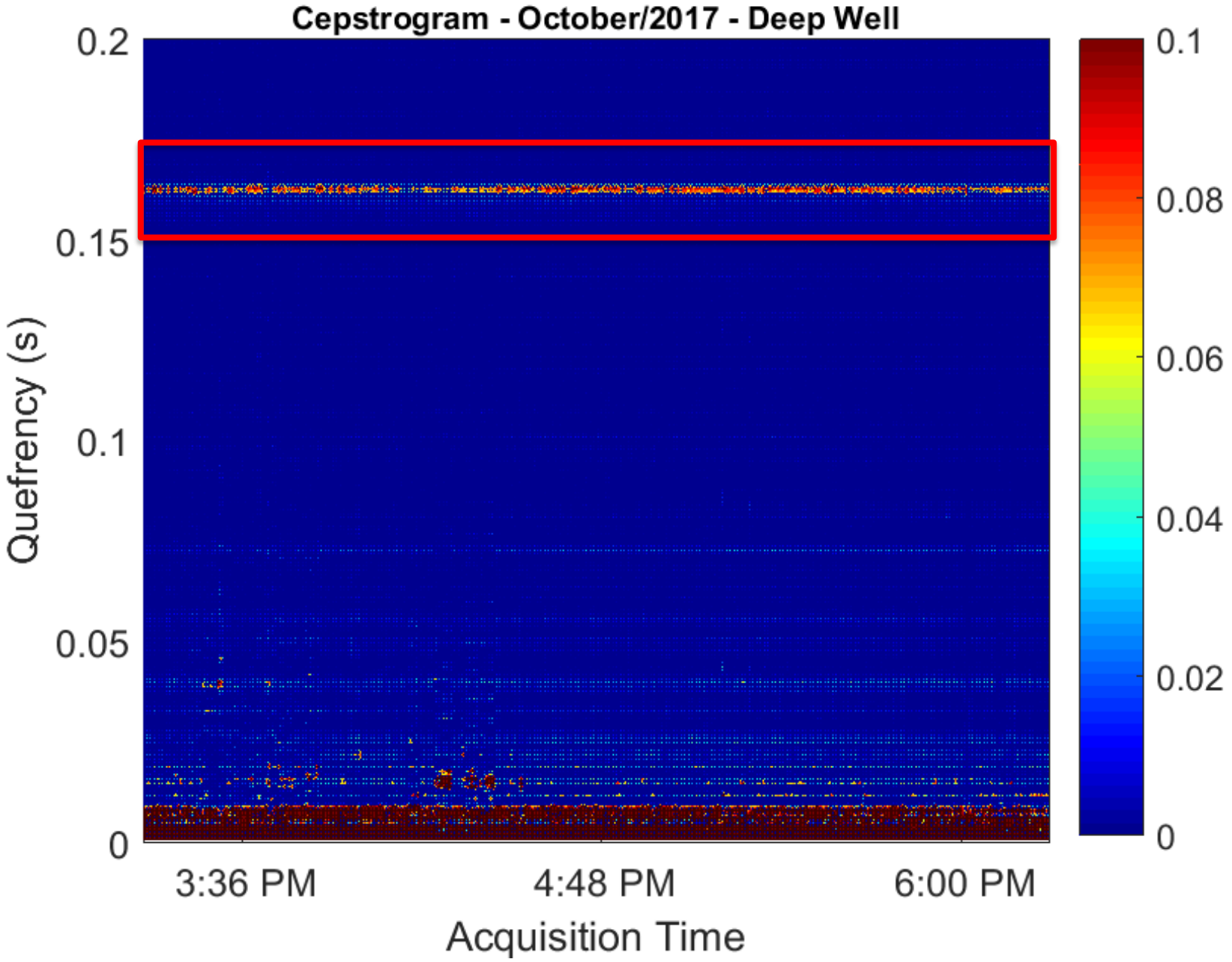
A History of the Cepstrum (Oppenheim & Schafer, 2004)

$$x(t) = d(t) + Rd(t - \tau)$$

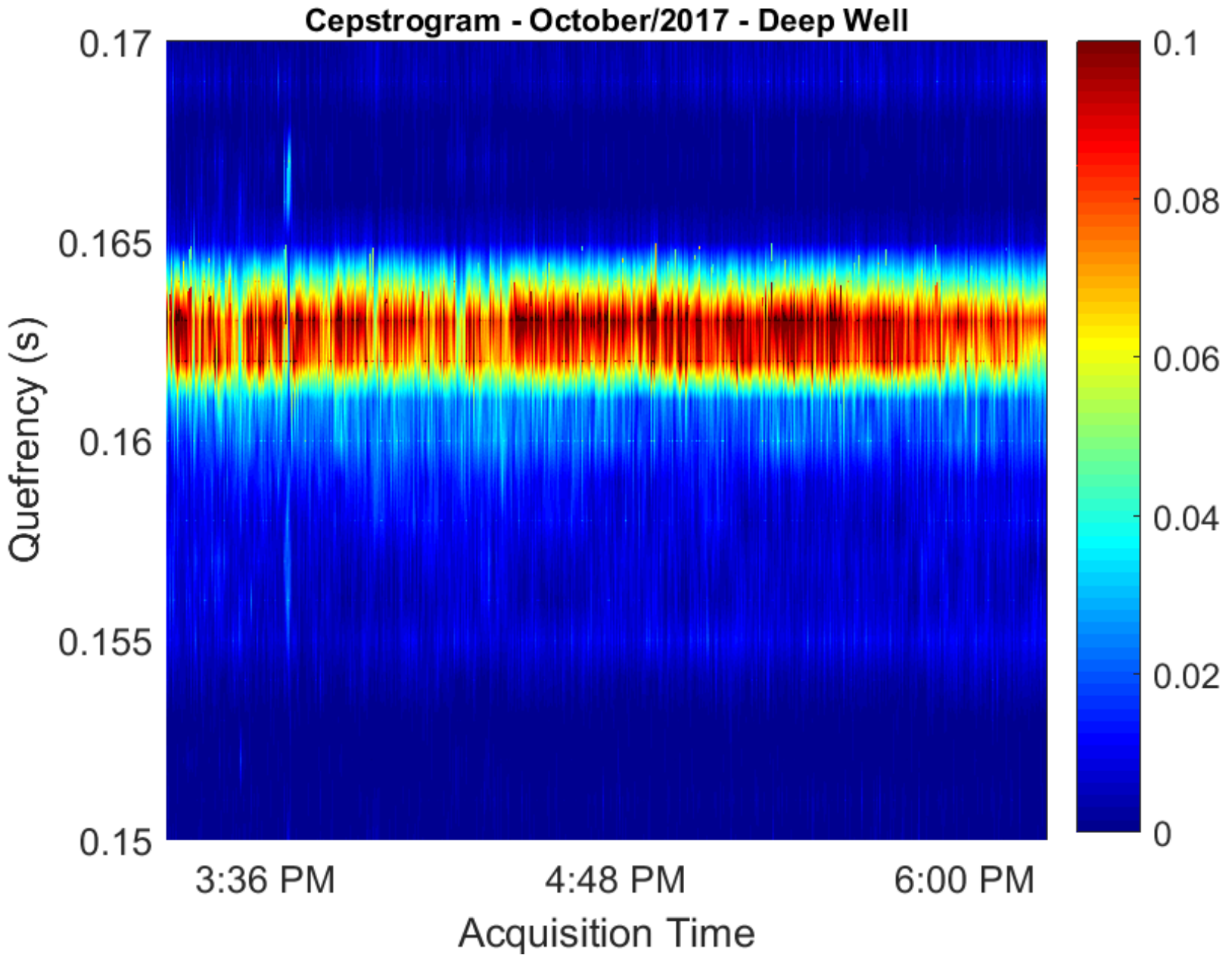
$$x(t) = d(t) + Rd(t - \tau)$$

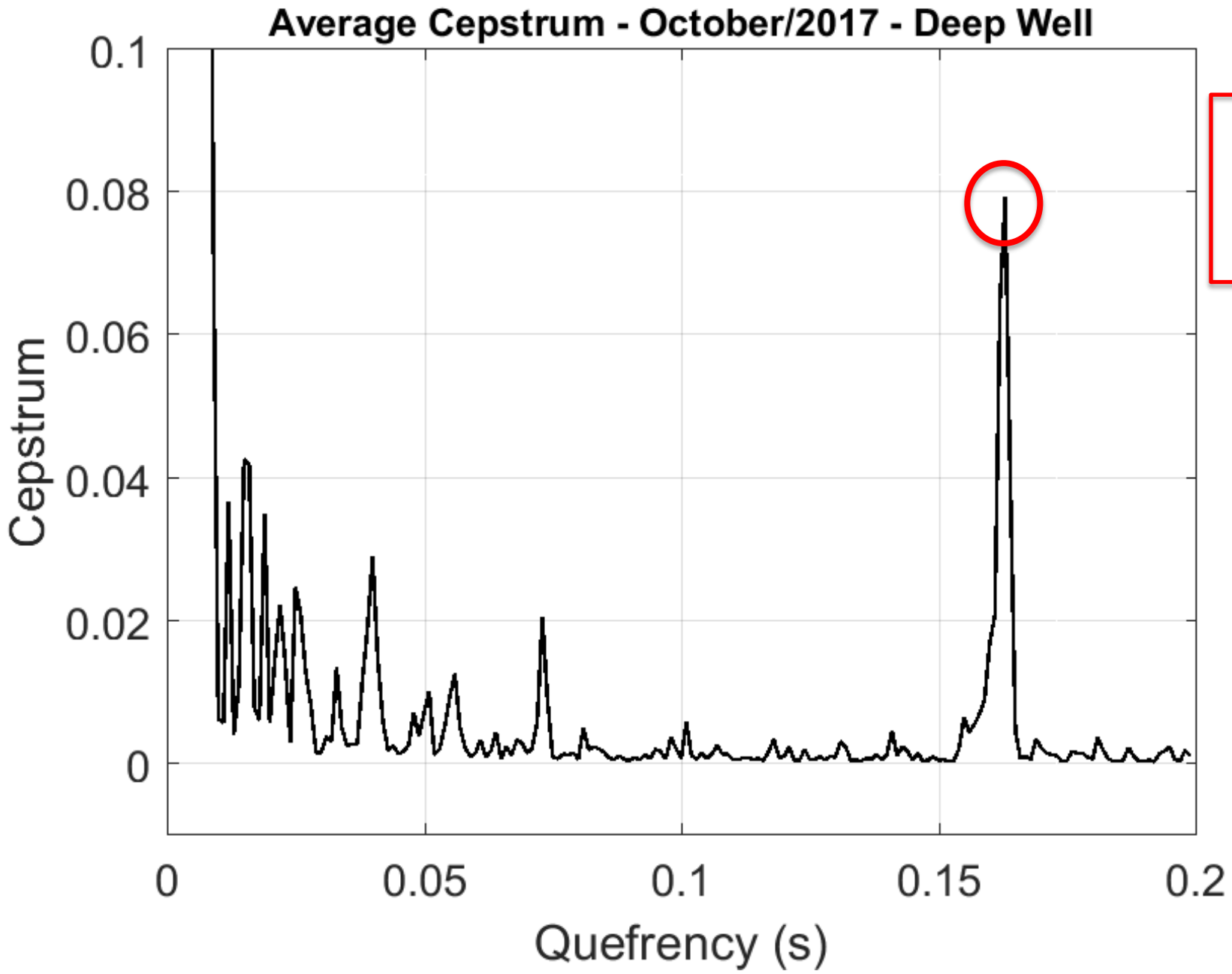
$$\tau = \frac{2L}{v}$$


Cepstrogram - October/2017 - Deep Well
Quefrency (s)
8
6
4
2
0
3:36 PM
4:48 PM
6:00 PM
Acquisition Time
0.1
0.08
0.06
0.04
0.02
0


Cepstrogram - October/2017 - Deep Well
0.2
0.15
0.1
0.05
0
Quefrency (s)
3:36 PM
4:48 PM
6:00 PM
Acquisition Time
0.1
0.08
0.06
0.04
0.02
0

NTNU

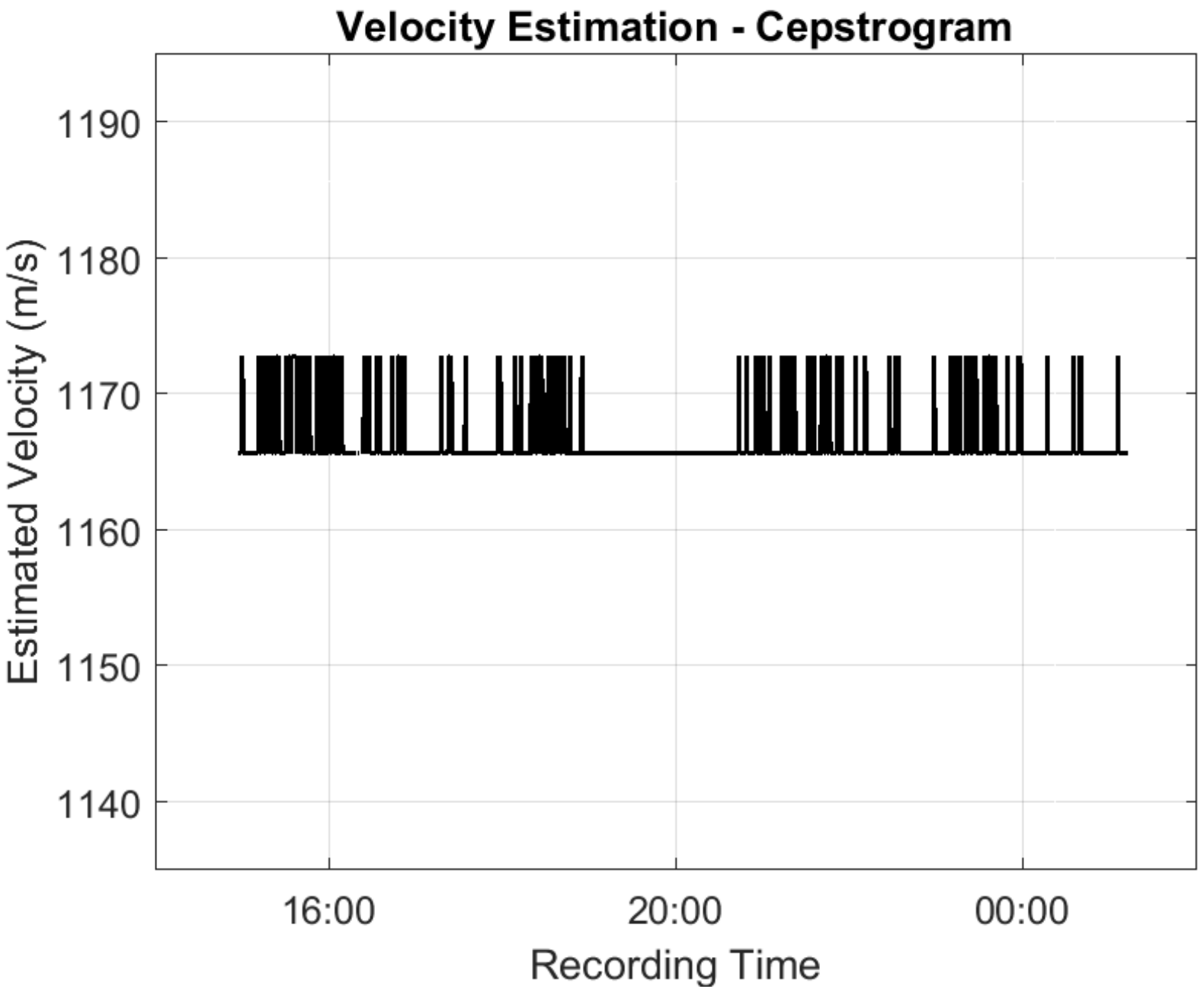

Cepstrogram - October/2017 - Deep Well
0.17
0.165
0.16
0.155
0.15
Quefrency (s)
3:36 PM
4:48 PM
6:00 PM
Acquisition Time
0.1
0.08
0.06
0.04
0.02
0

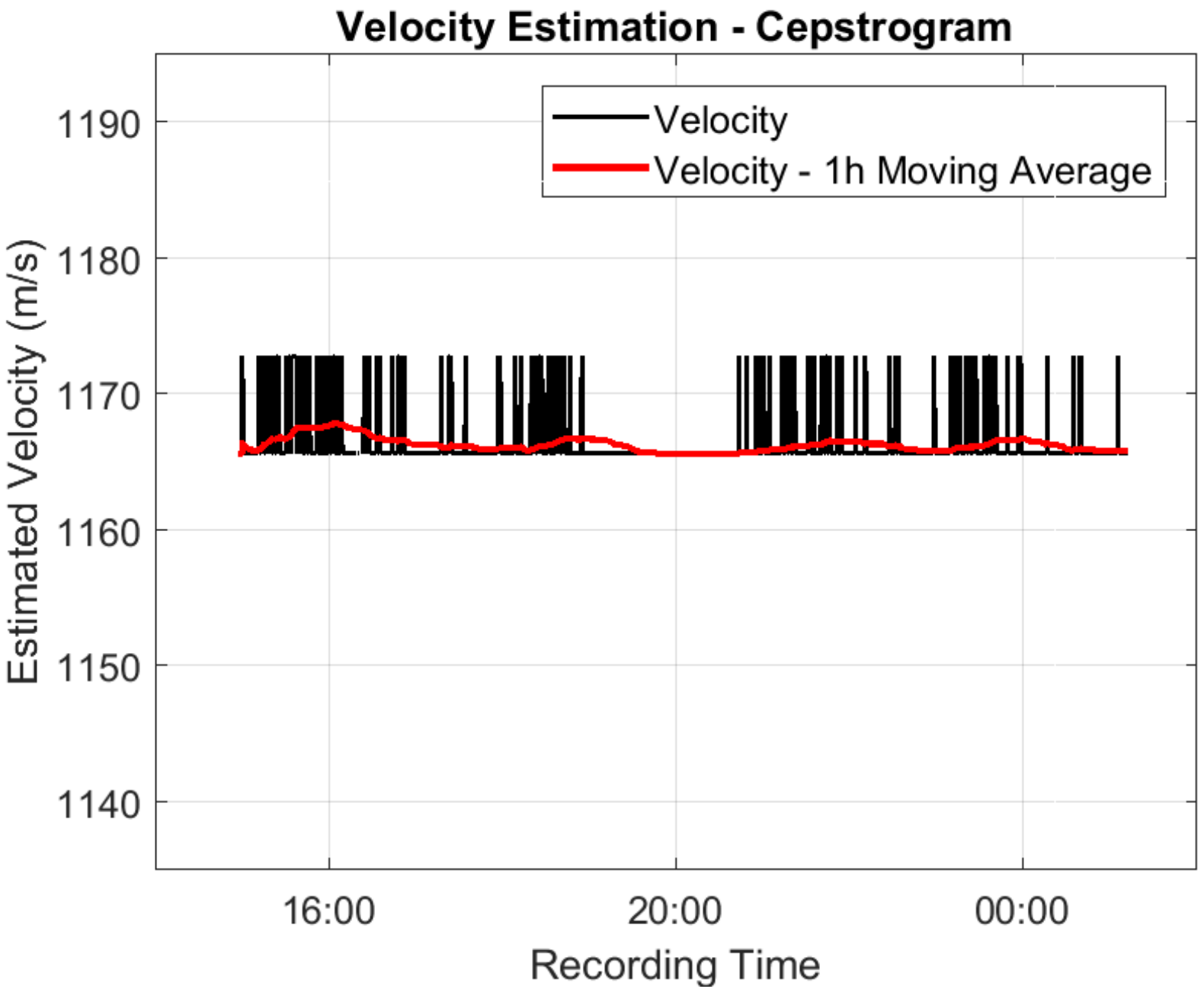


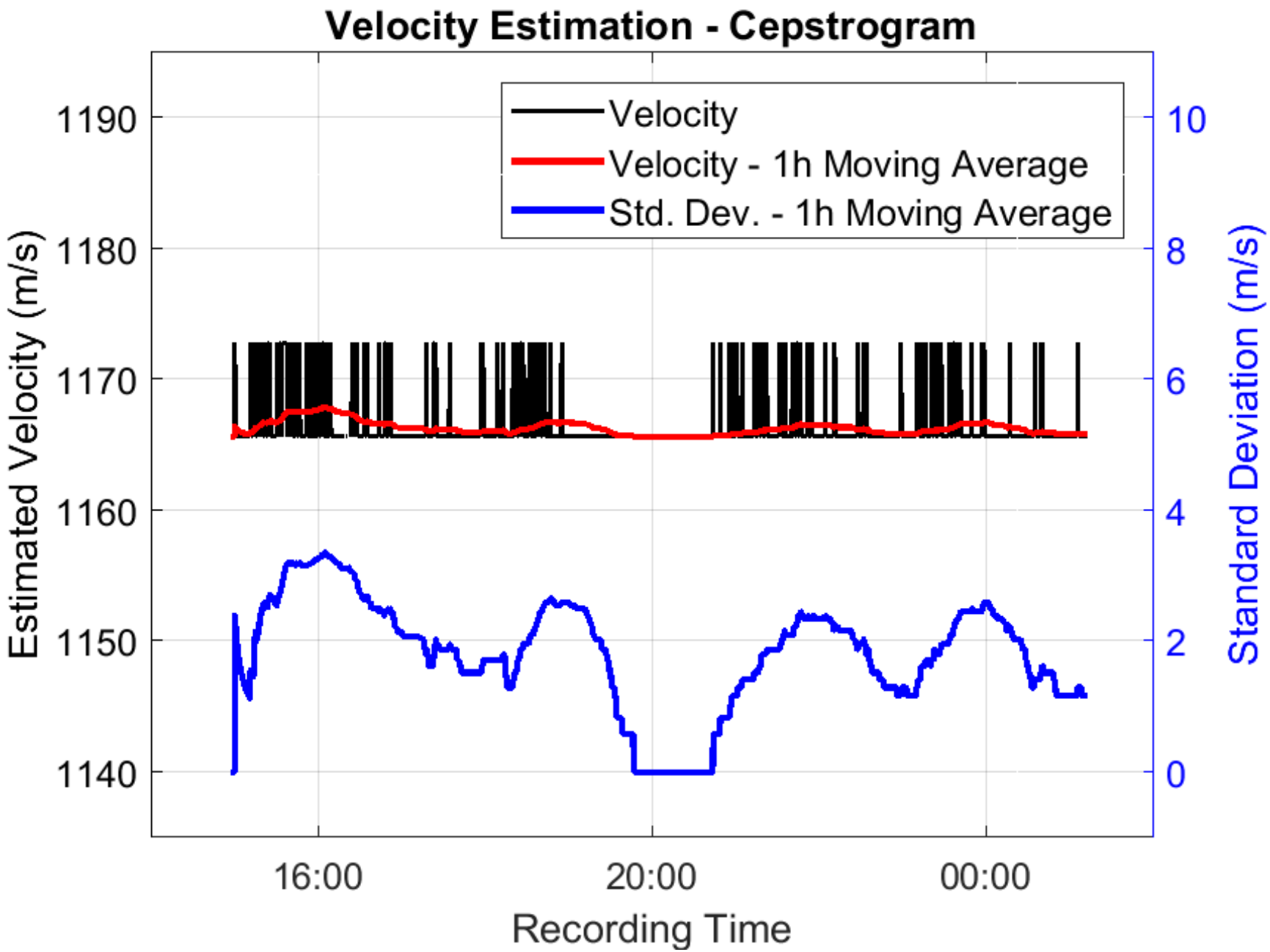
$\tau = 0.163$ s

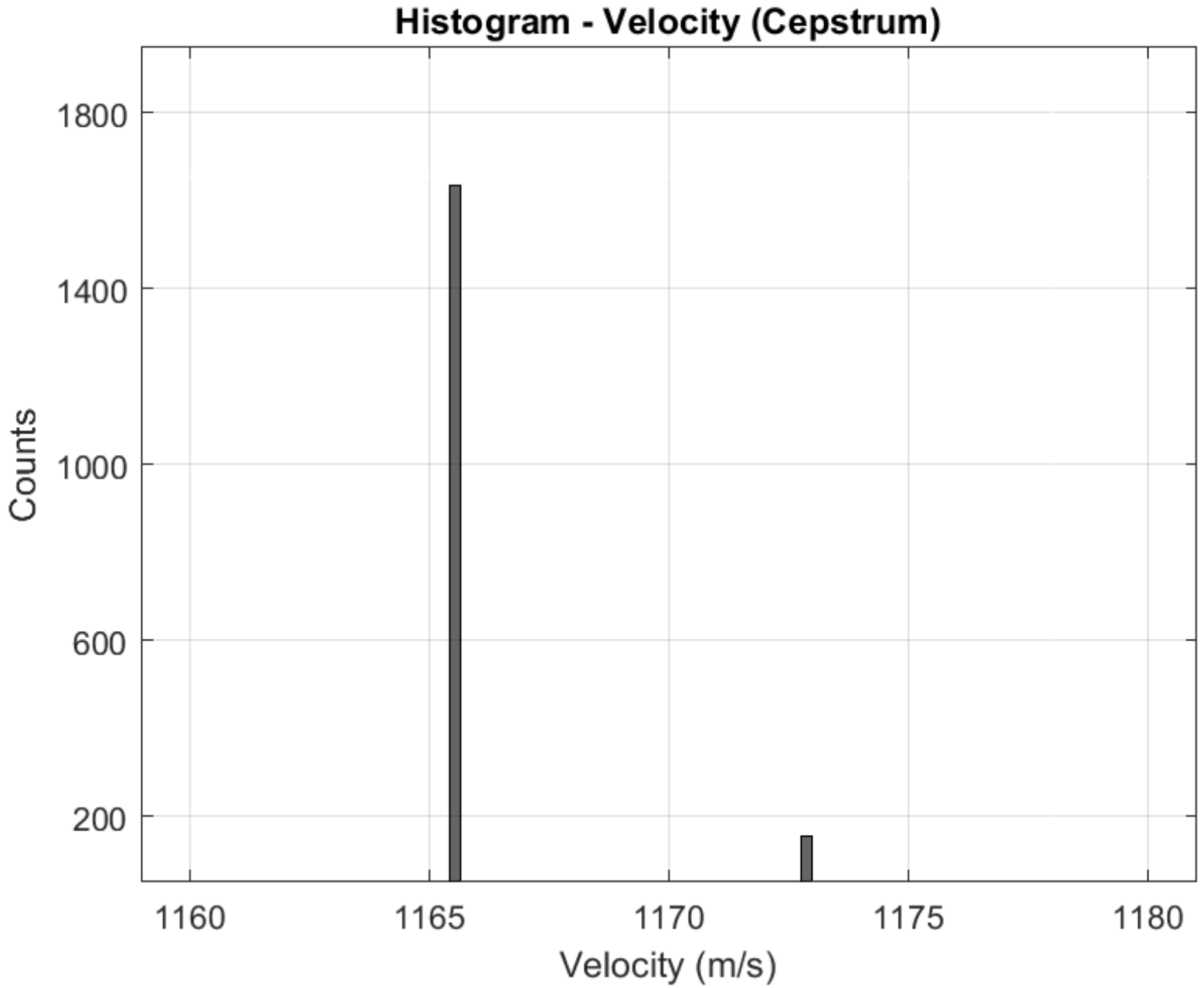
L =95 m

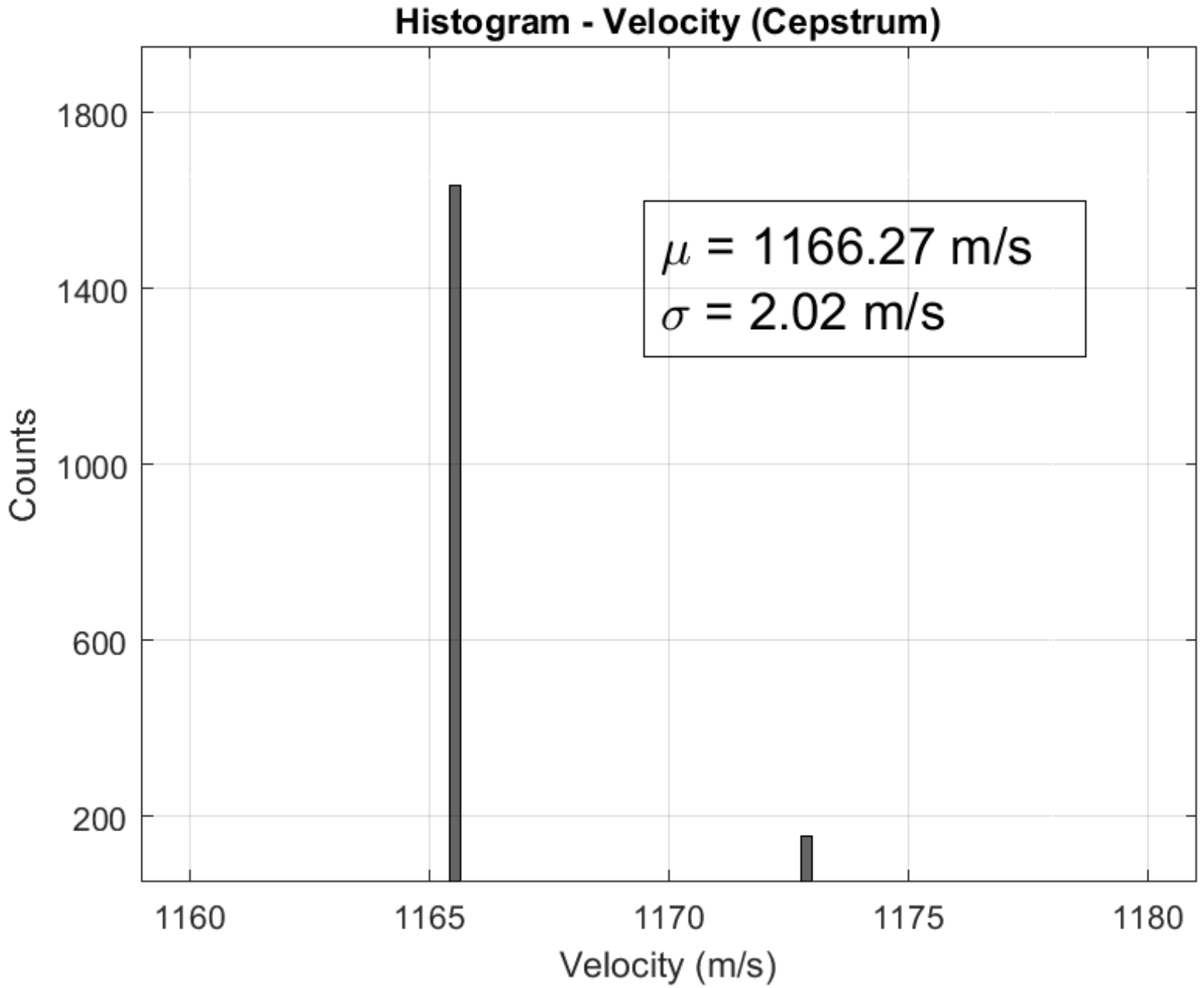
$v = \frac{2L}{\tau} = 1165$ m/s

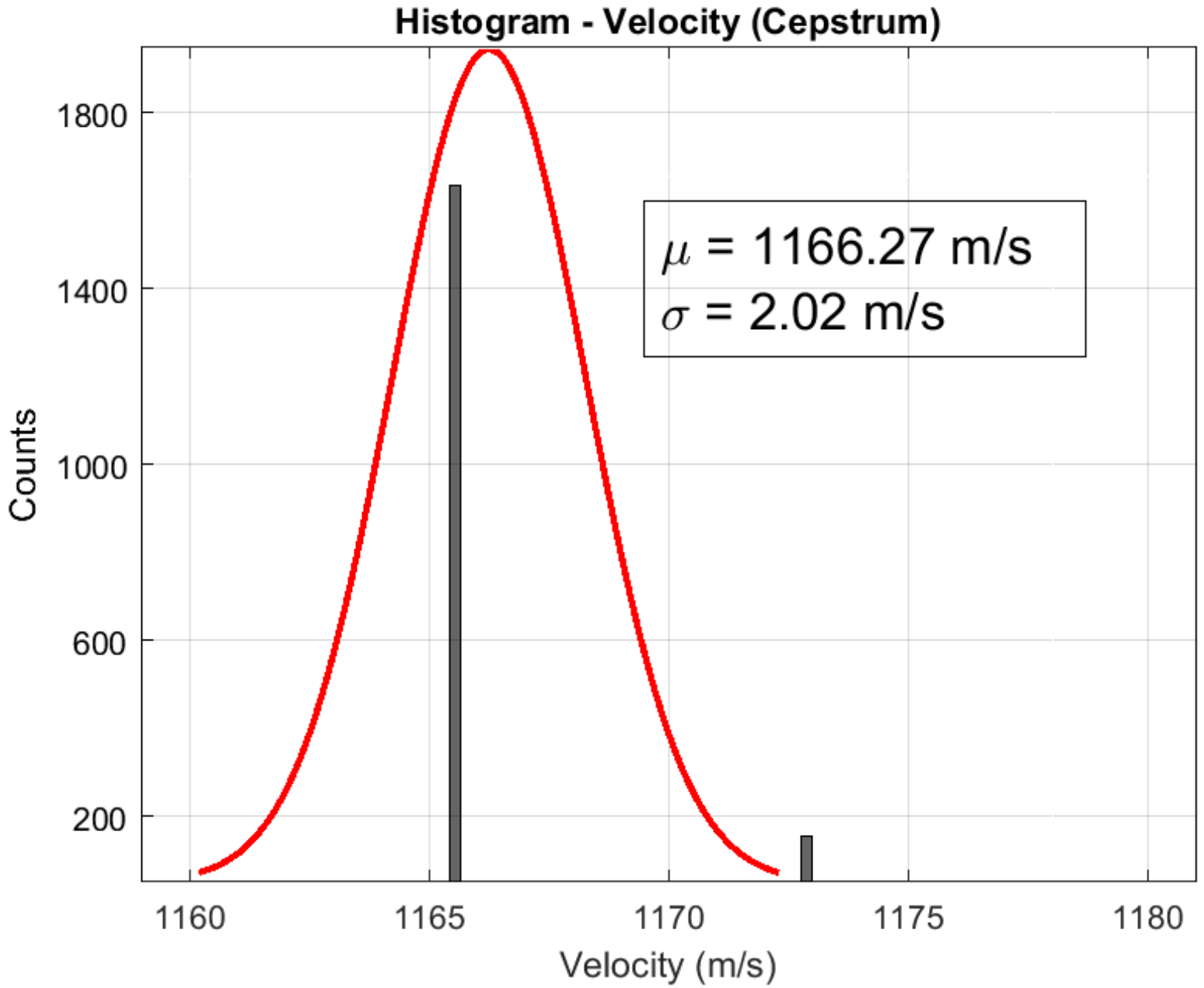

Velocity Estimation - Cepstrogram
Estimated Velocity (m/s)
1190
1180
1170
1160
1150
1140
16:00
20:00
00:00
Recording Time

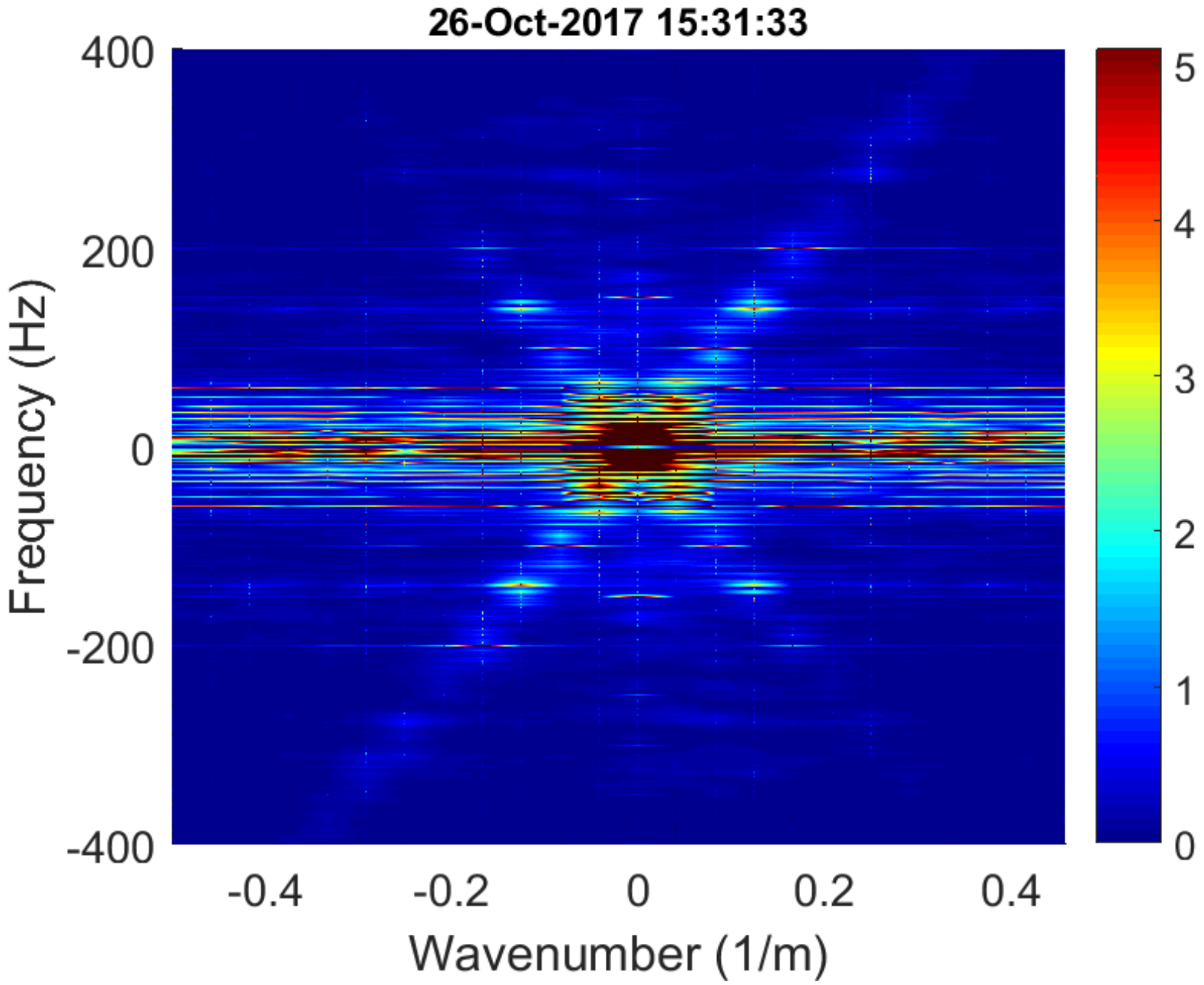

Velocity Estimation - Cepstrogram
Velocity
Velocity - 1h Moving Average
Estimated Velocity (m/s)
1190
1180
1170
1160
1150
1140
16:00
20:00
00:00
Recording Time

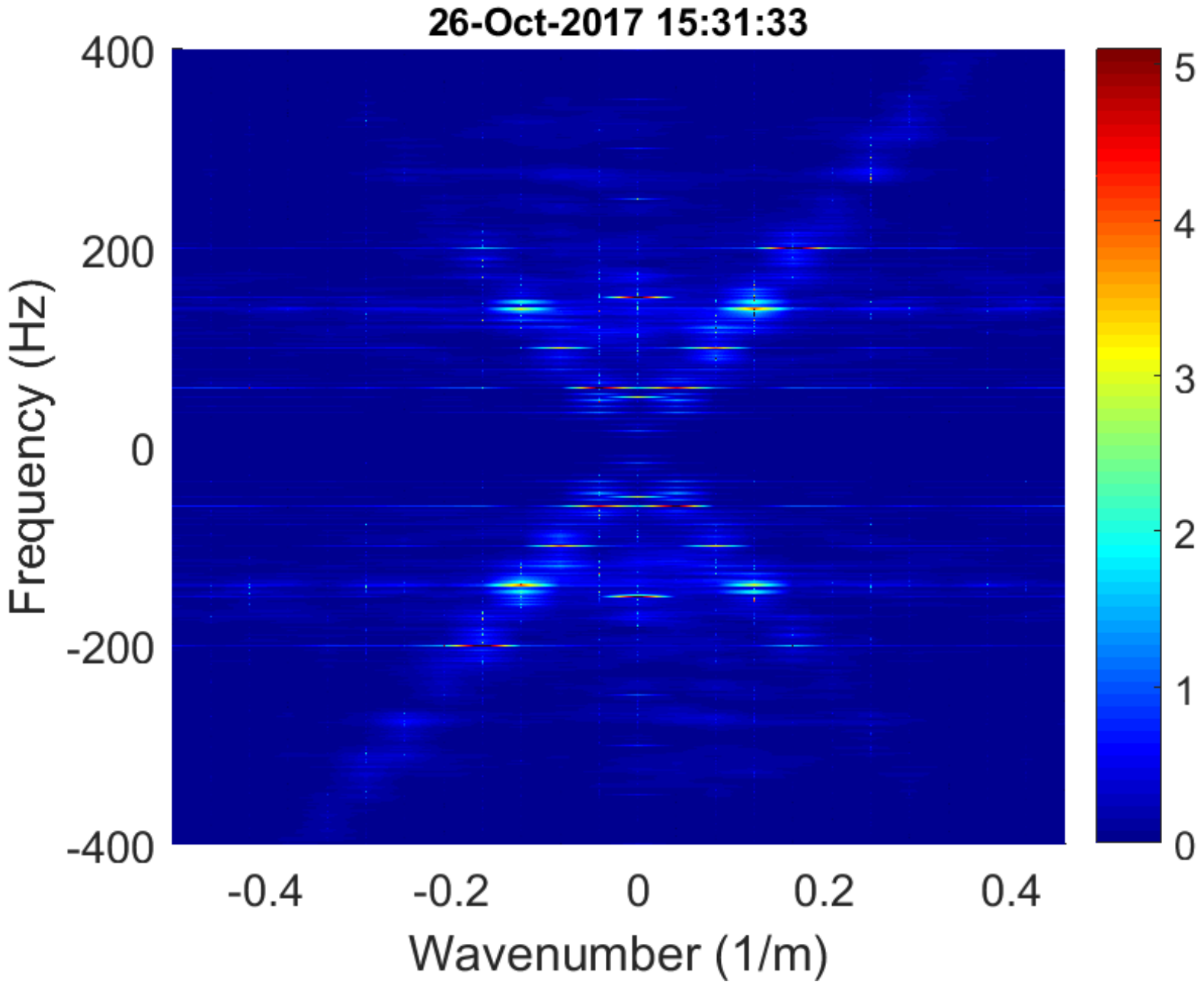

Velocity Estimation - Cepstrogram
Velocity
Velocity - 1h Moving Average
Std. Dev. - 1h Moving Average
Estimated Velocity (m/s)
Standard Deviation (m/s)
1190
1180
1170
1160
1150
1140
10
8
6
4
2
0
16:00
20:00
00:00
Recording Time

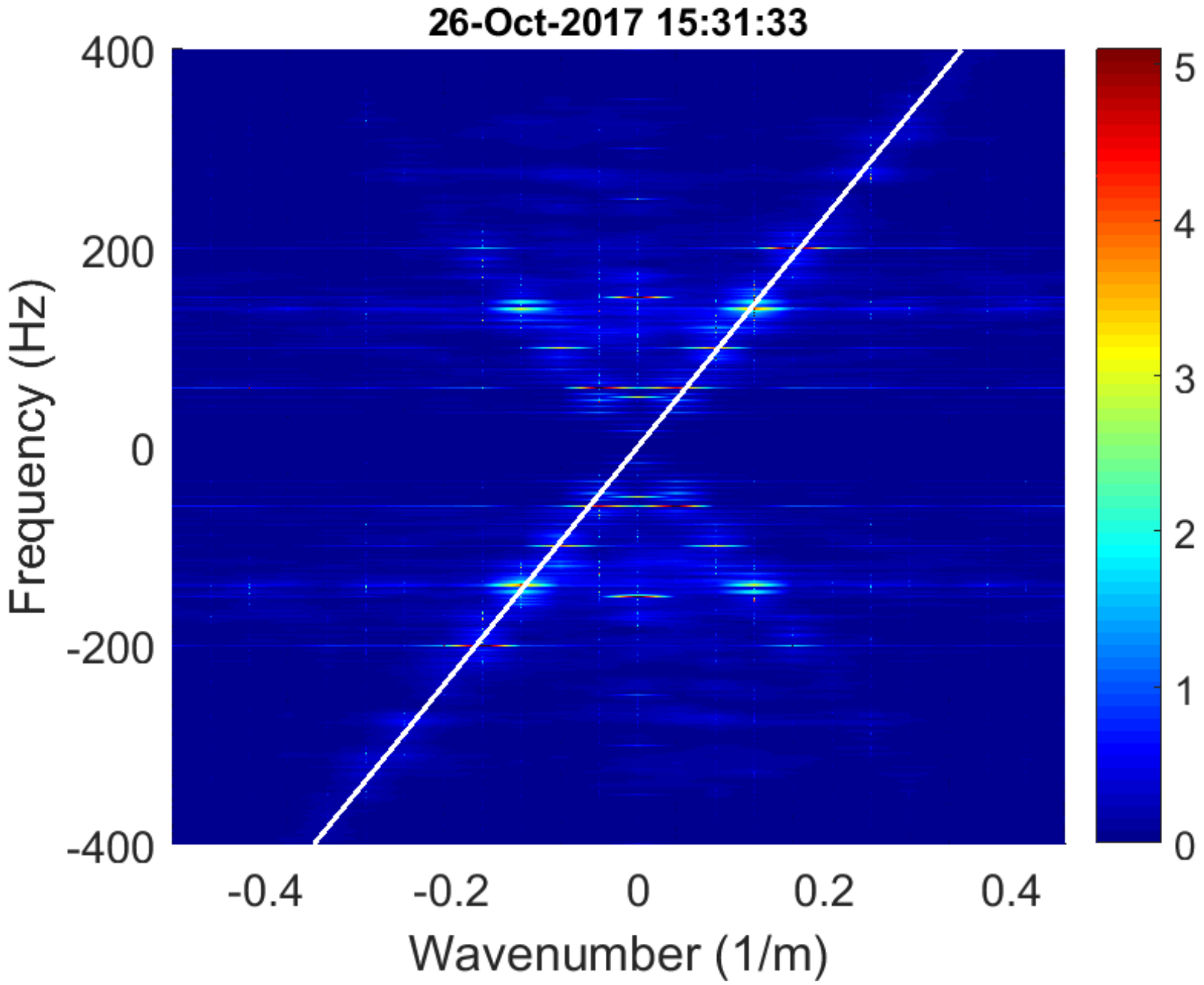

Histogram - Velocity (Cepstrum)
Counts
1800
1400
1000
600
200
1160
1165
1170
1175
1180
Velocity (m/s)

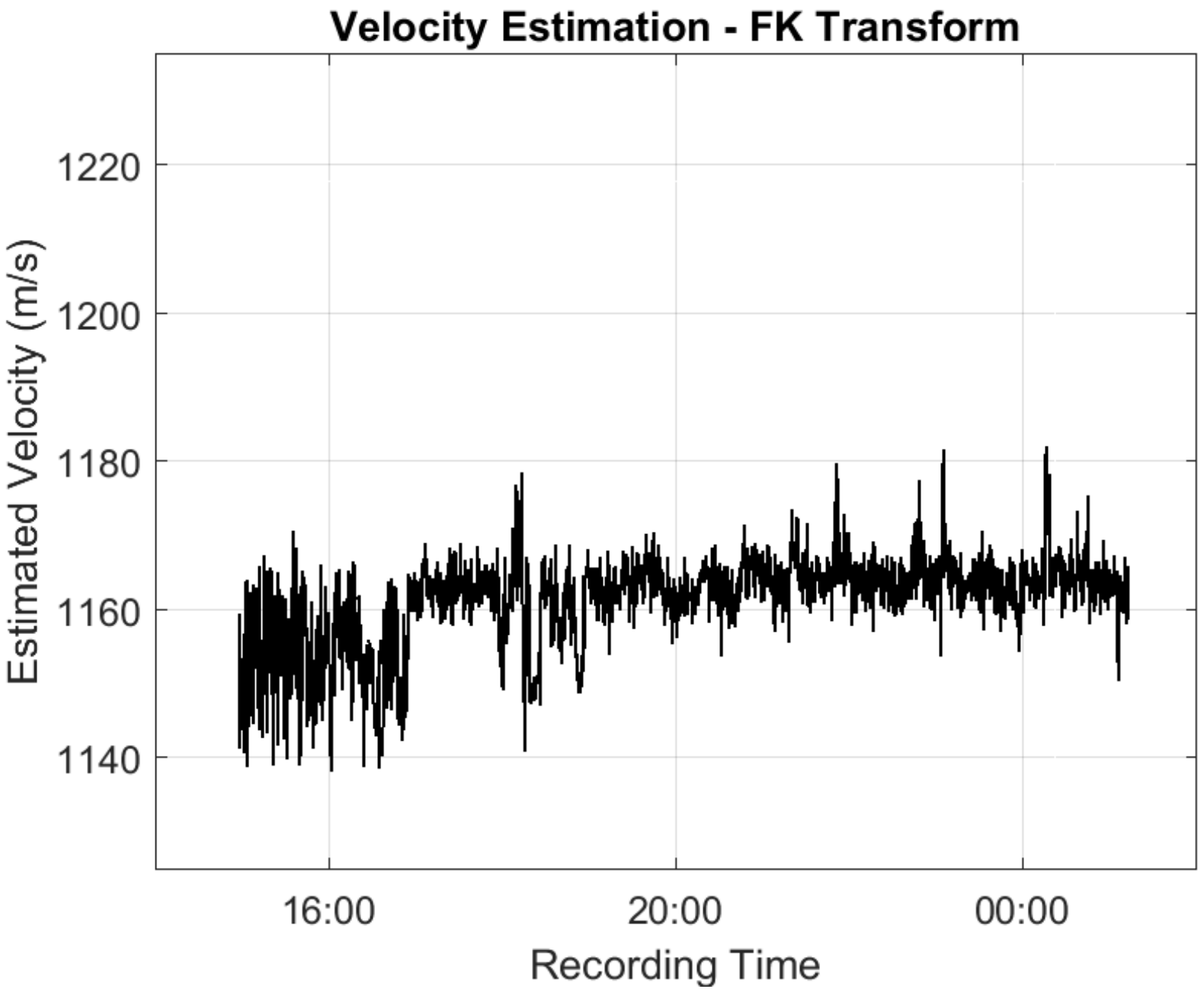

Histogram - Velocity (Cepstrum)
1800
1400
1000
600
200
Counts
μ = 1166.27 m/s
σ = 2.02 m/s
1160
1165
1170
1175
1180
Velocity (m/s)

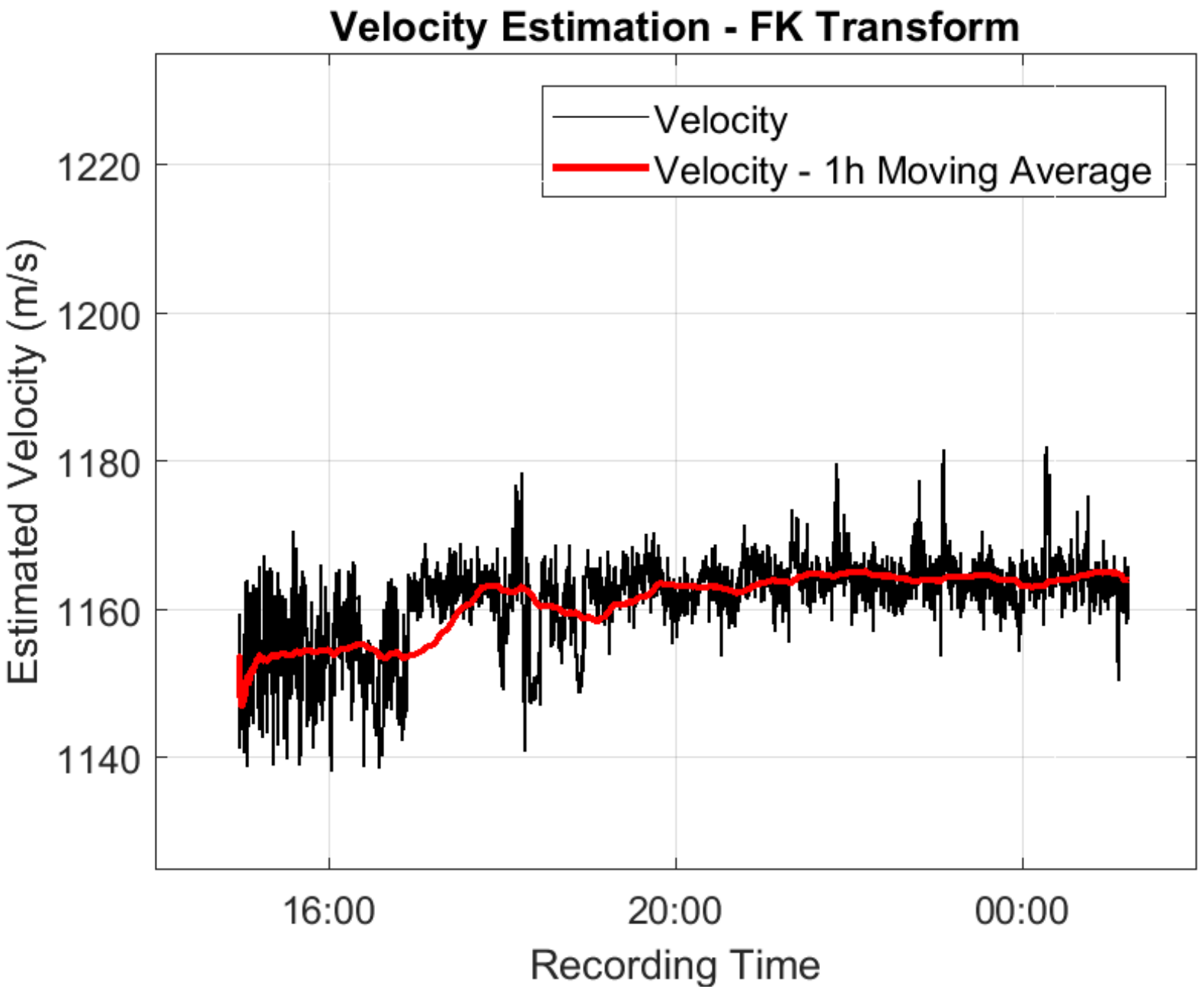

Histogram - Velocity (Cepstrum)
1800
1400
1000
600
200
Counts
μ = 1166.27 m/s
σ = 2.02 m/s
1160
1165
1170
1175
1180
Velocity (m/s)

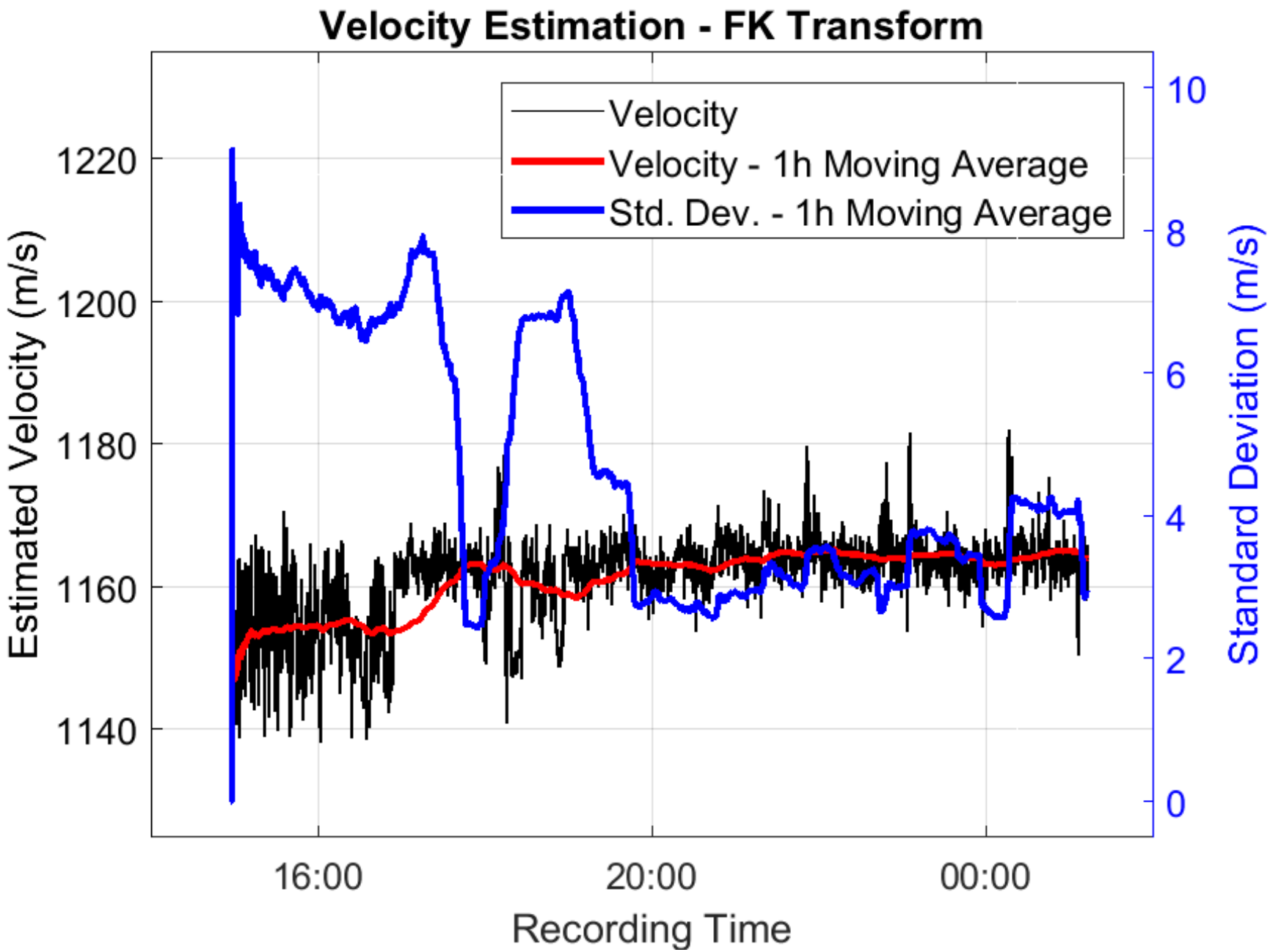

26-Oct-2017 15:31:33
400
200
0
-200
-400
Frequency (Hz)
-0.4
-0.2
0
0.2
0.4
Wavenumber (1/m)
5
4
3
2
1
0

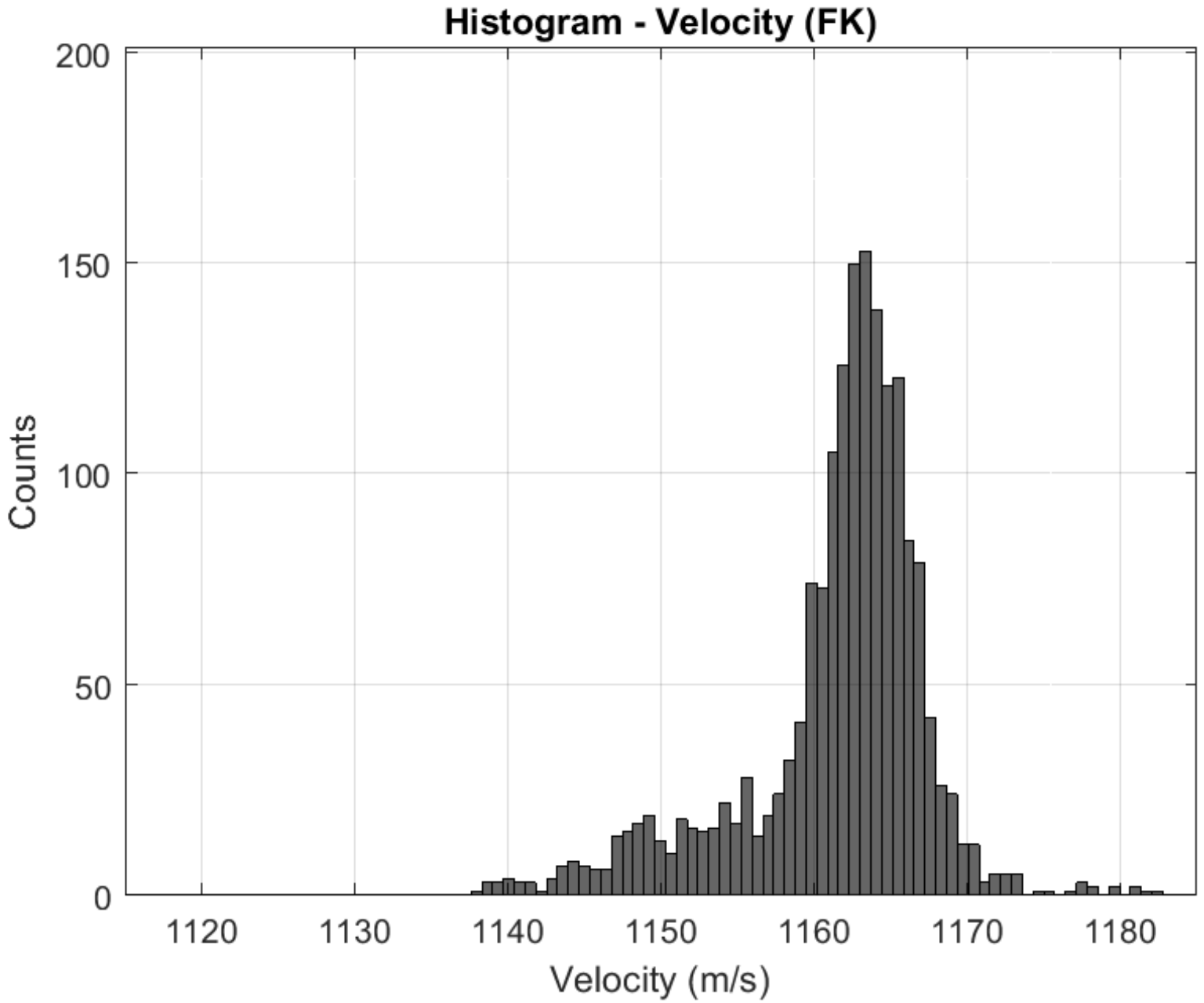

26-Oct-2017 15:31:33
400
200
0
-200
-400
Frequency (Hz)
-0.4
-0.2
0
0.2
0.4
Wavenumber (1/m)
5
4
3
2
1
0

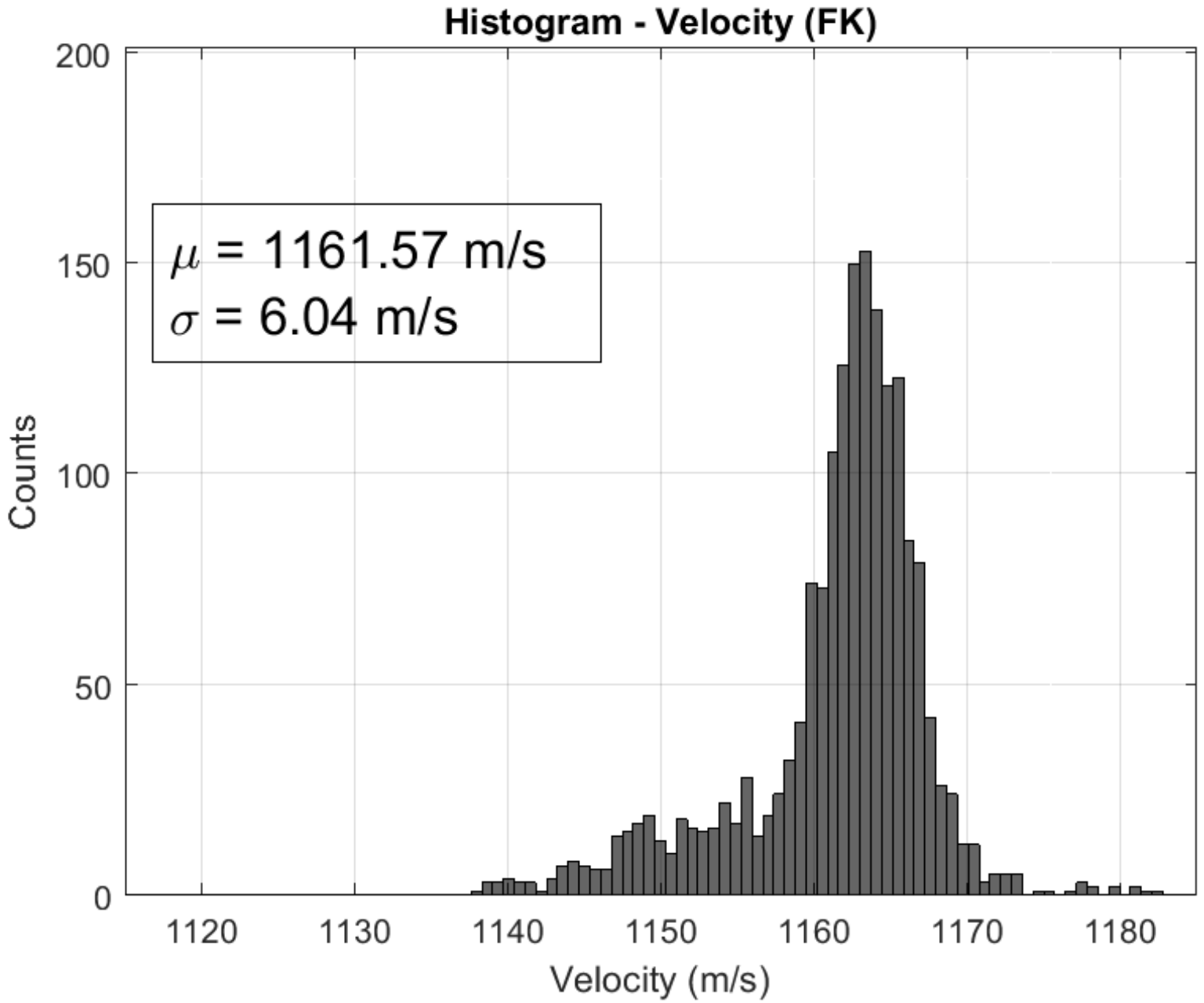

26-Oct-2017 15:31:33
400
200
0
-200
-400
Frequency (Hz)
-0.4
-0.2
0
0.2
0.4
Wavenumber (1/m)
5
4
3
2
1
0

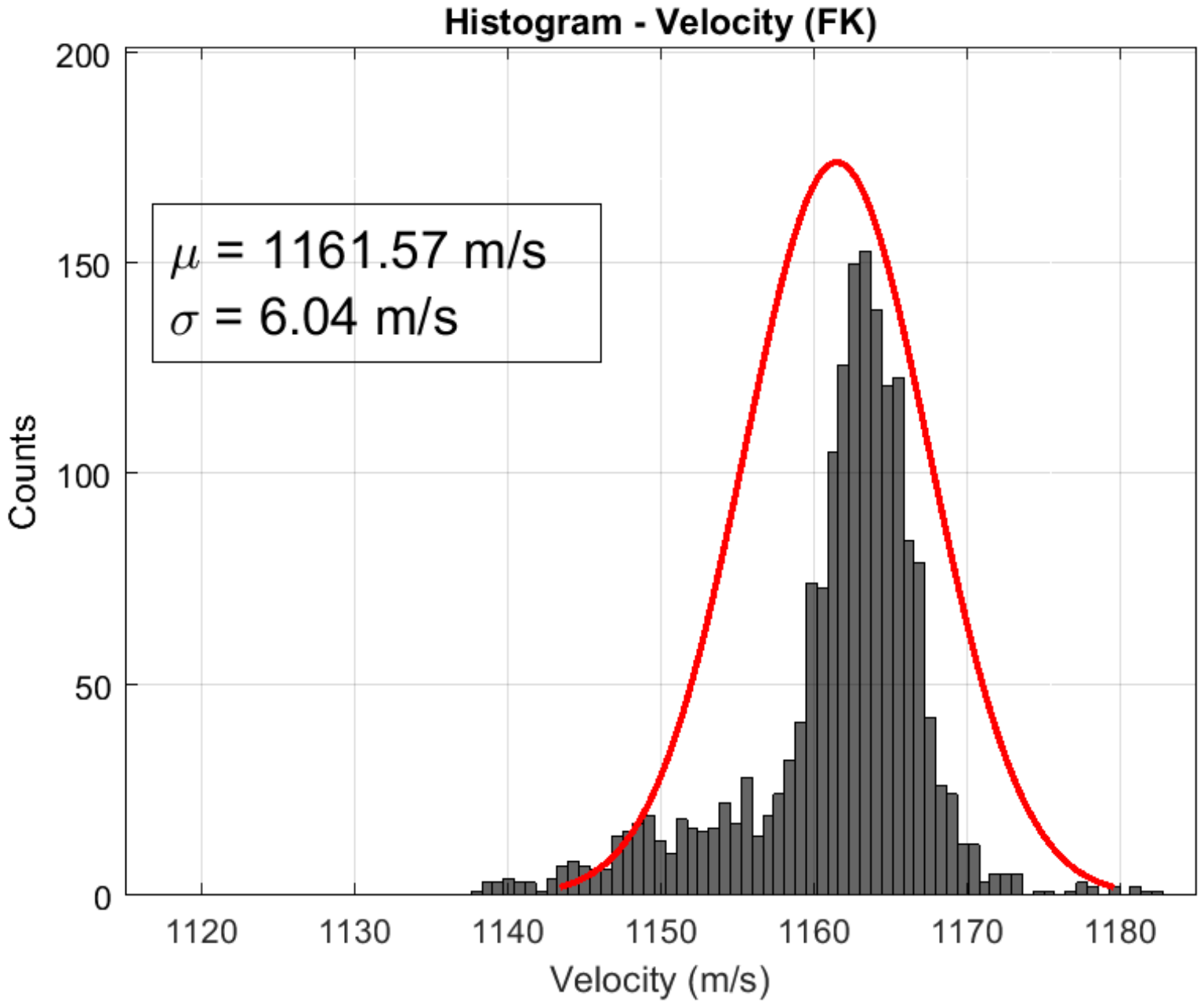

Velocity Estimation - FK Transform
Estimated Velocity (m/s)
1220
1200
1180
1160
1140
16:00
20:00
00:00
Recording Time


Velocity Estimation - FK Transform
Velocity
Velocity - 1h Moving Average
1220
1200
1180
1160
1140
Estimated Velocity (m/s)
16:00
20:00
00:00
Recording Time


Velocity Estimation - FK Transform
Velocity
Velocity - 1h Moving Average
Std. Dev. - 1h Moving Average
Estimated Velocity (m/s)
Standard Deviation (m/s)
1220
1200
1180
1160
1140
10
8
6
4
2
0
16:00
20:00
00:00
Recording Time


Histogram - Velocity (FK)
Counts
200
150
100
50
0
1120
1130
1140
1150
1160
1170
1180
Velocity (m/s)


Histogram - Velocity (FK)
μ = 1161.57 m/s
σ = 6.04 m/s
Counts
Velocity (m/s)
0
50
100
150
200
1120
1130
1140
1150
1160
1170
1180


Histogram - Velocity (FK)
μ = 1161.57 m/s
σ = 6.04 m/s
Counts
Velocity (m/s)
0
50
100
150
200
1120
1130
1140
1150
1160
1170
1180

Data Storage

- 100 sensors, 1000 Hz sampling
  - 10^5 samples/s
  - 10^5 x 60 x 60 x 24 = 8.64 x 10^9 samples/day
  - 8.64 x 10^9 samples/day x 4 bytes/sample = 35 GB/day
  - Over 1 TB/month

- Data can be discarded after velocity estimation… But we didn't!

Conclusions

- Passive data can be used to estimate tube wave velocity
  - Less precise than experiments with active source
  - Local (F-K domain) x Average (Cepstrum)
  - Results not so good for the shallow borehole
- Workflow can be easily automated
- No need for large data storage
- Next test: Distributed Acoustic Sensors (DAS)

Acknowledgments