Ground Water Level Change due to Earthquake using Time-Frequency Analysis and Hilbert-Huang Transform

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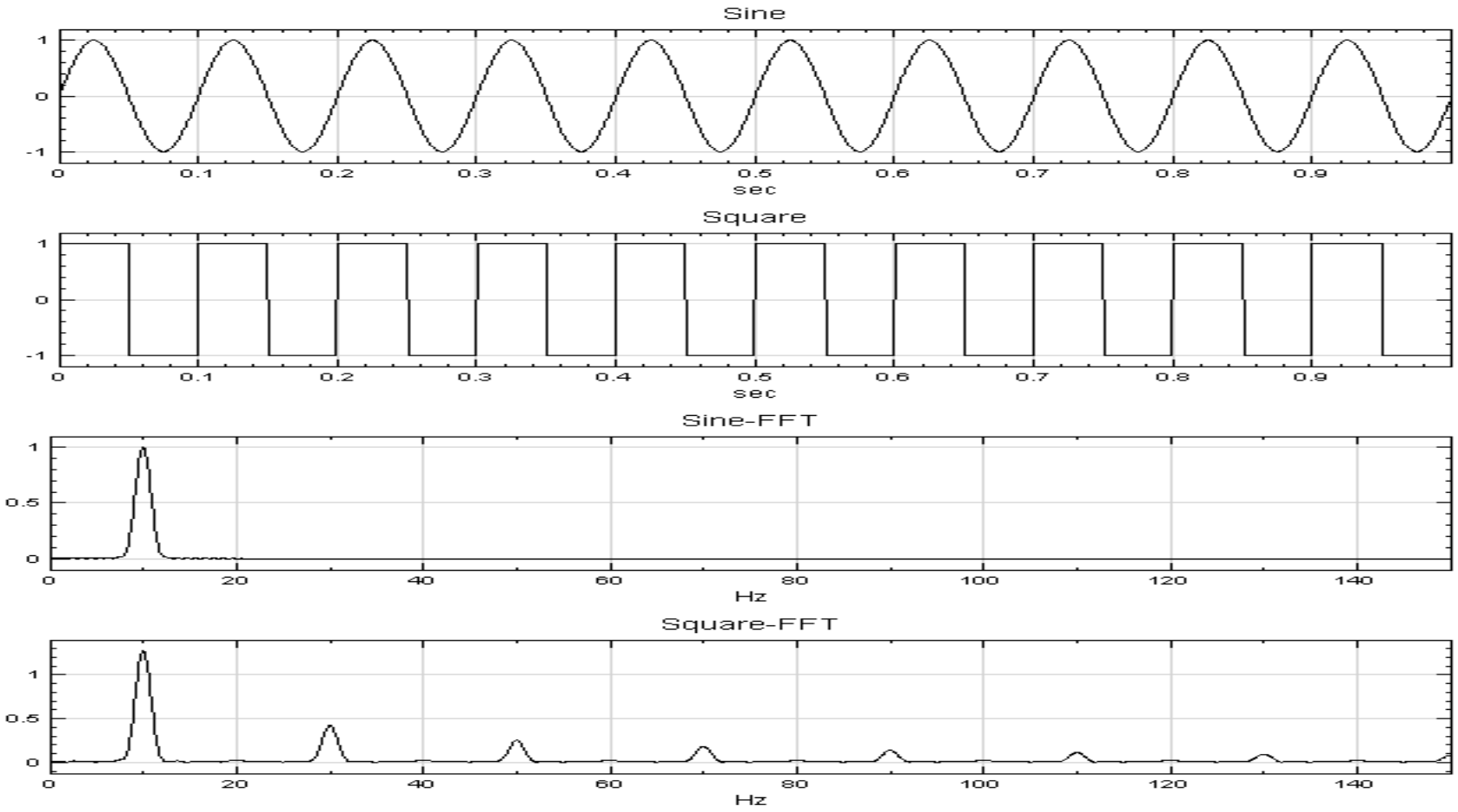
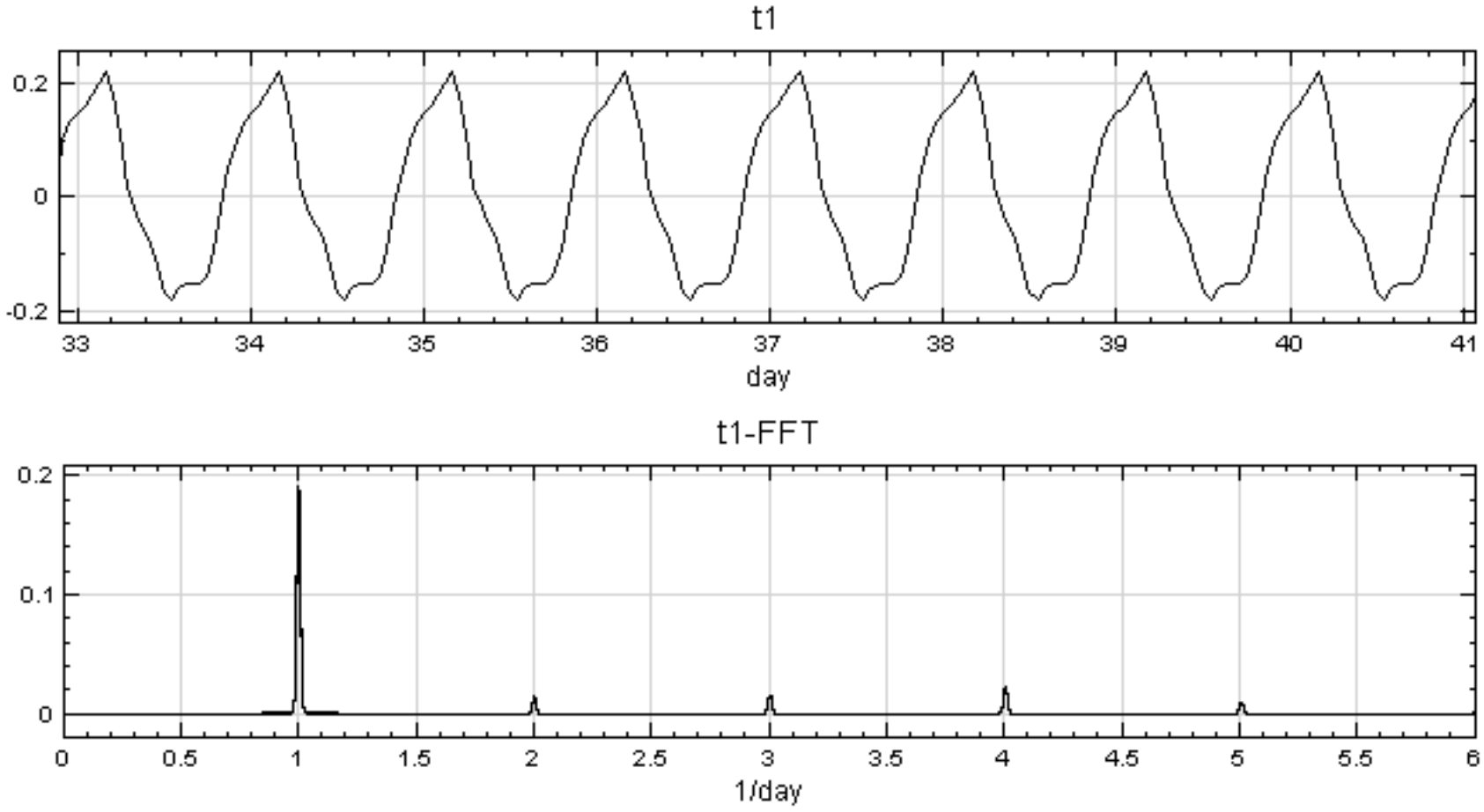
Contents

- Time-Frequency Analysis
- Single Frequency and Harmonics
- Diurnal/Semi-Diurnal Tide Separation using EMD
- Missing Harmonics: a Precursor to Earthquake?
- Body Tide
- Oscillation of GWL: Another Precursor to Earthquake?
- Summary

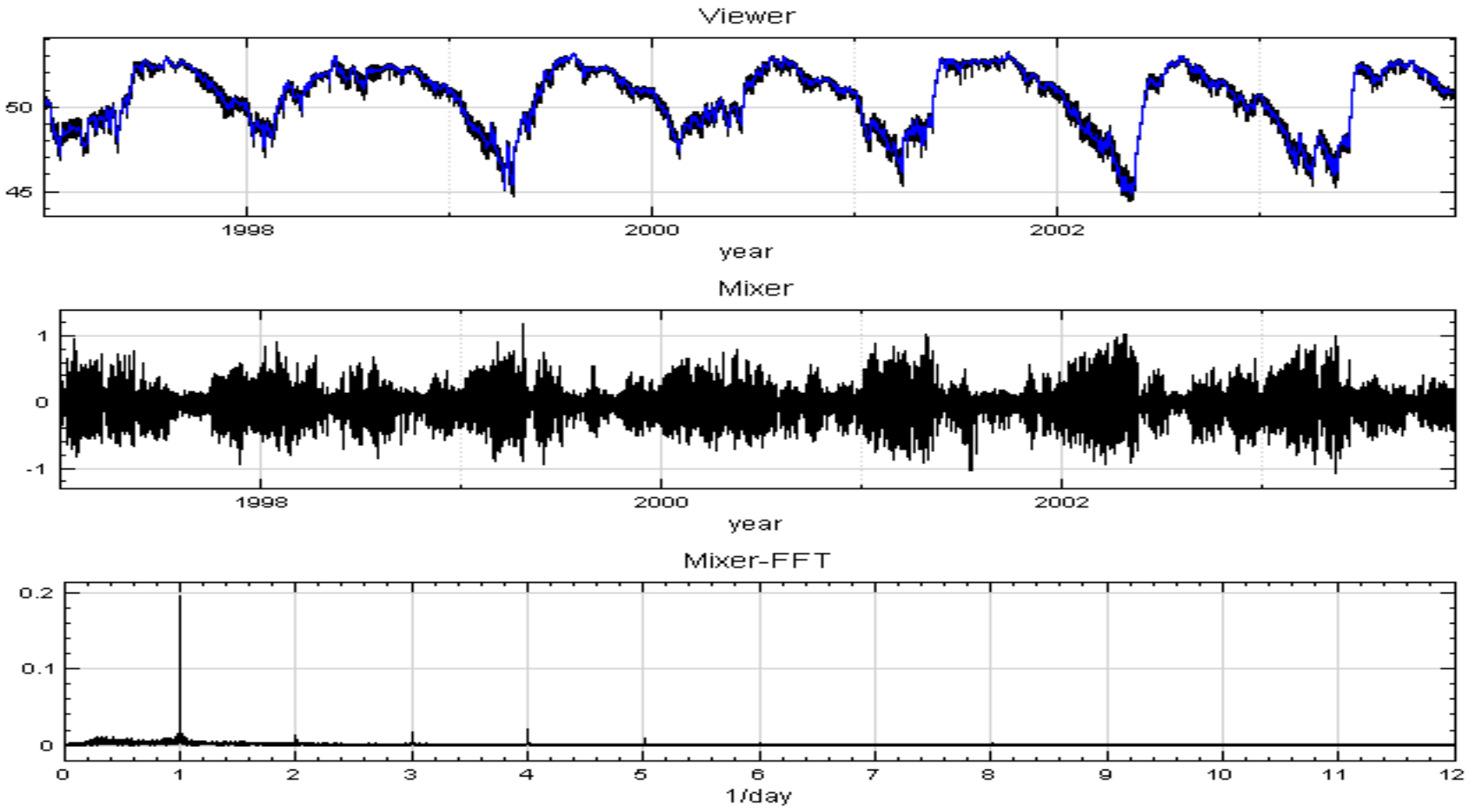
Single Frequency and Harmonics



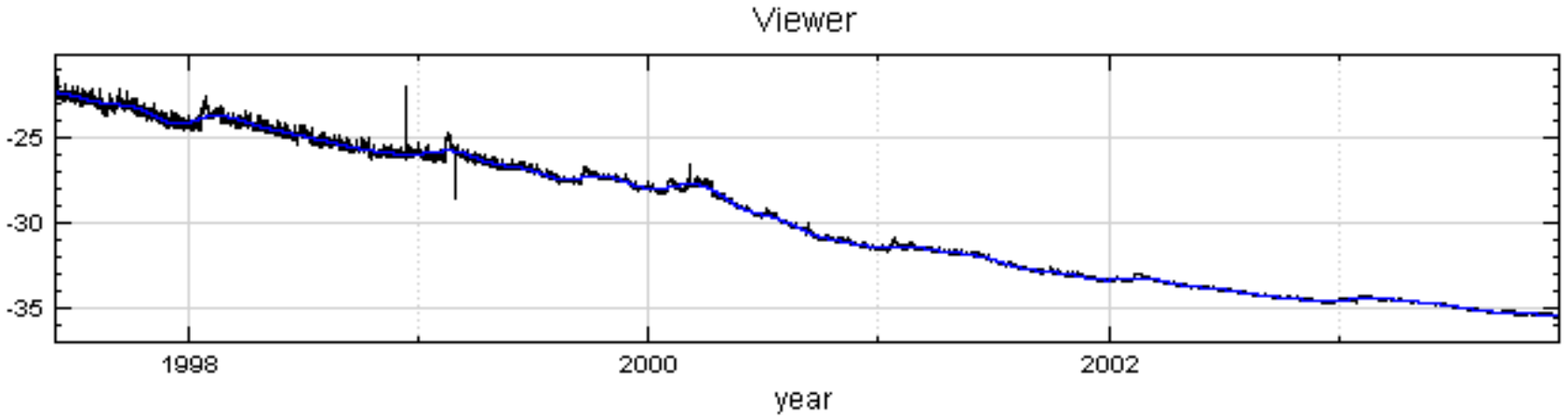
Spectrum of 美濃(1)

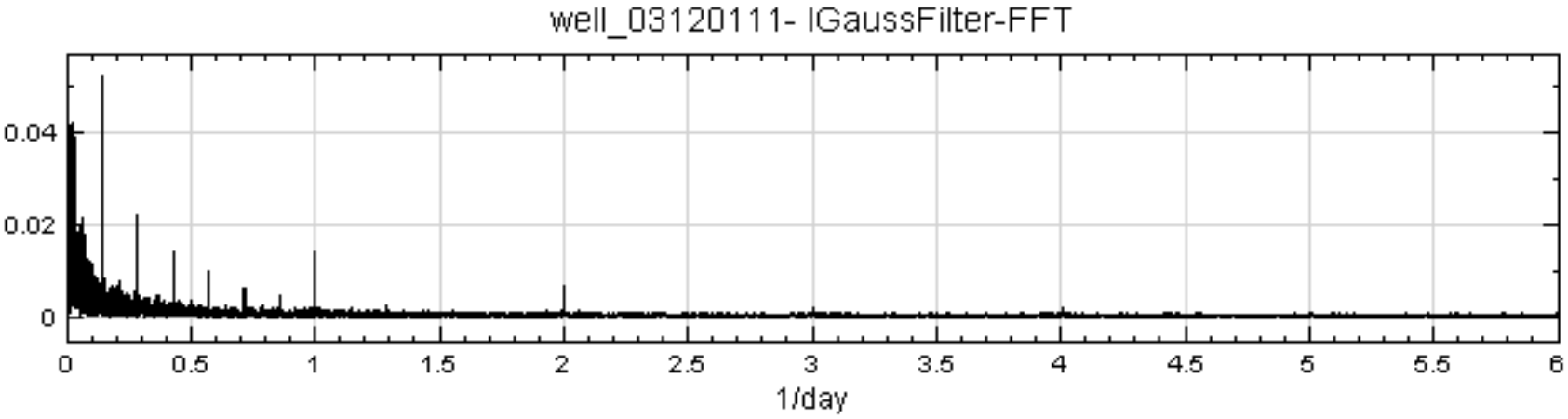


美濃(1)

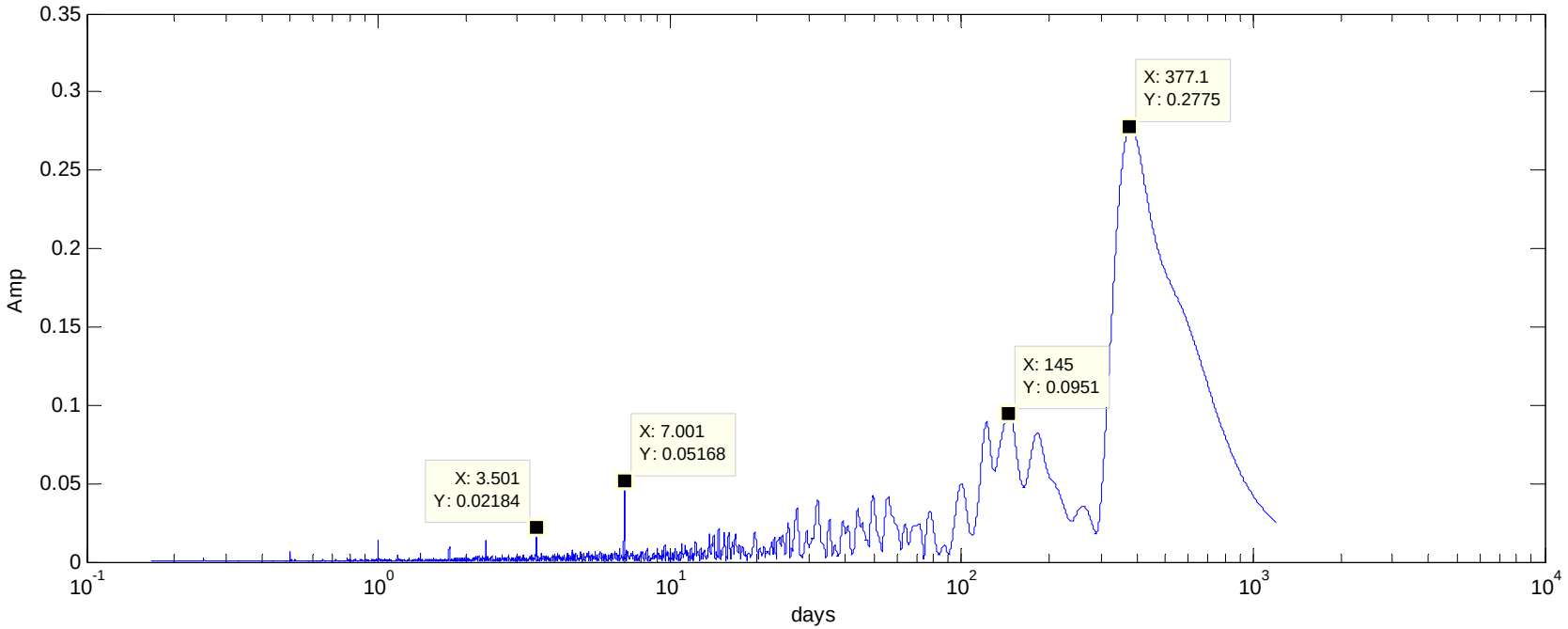

Viewer
50
45
1998
2000
2002
year
Mixer
1
0
-1
1998
2000
2002
year
Mixer-FFT
0.2
0.1
0
0
1
2
3
4
5
6
7
8
9
10
11
12
1/day

樹林(1)

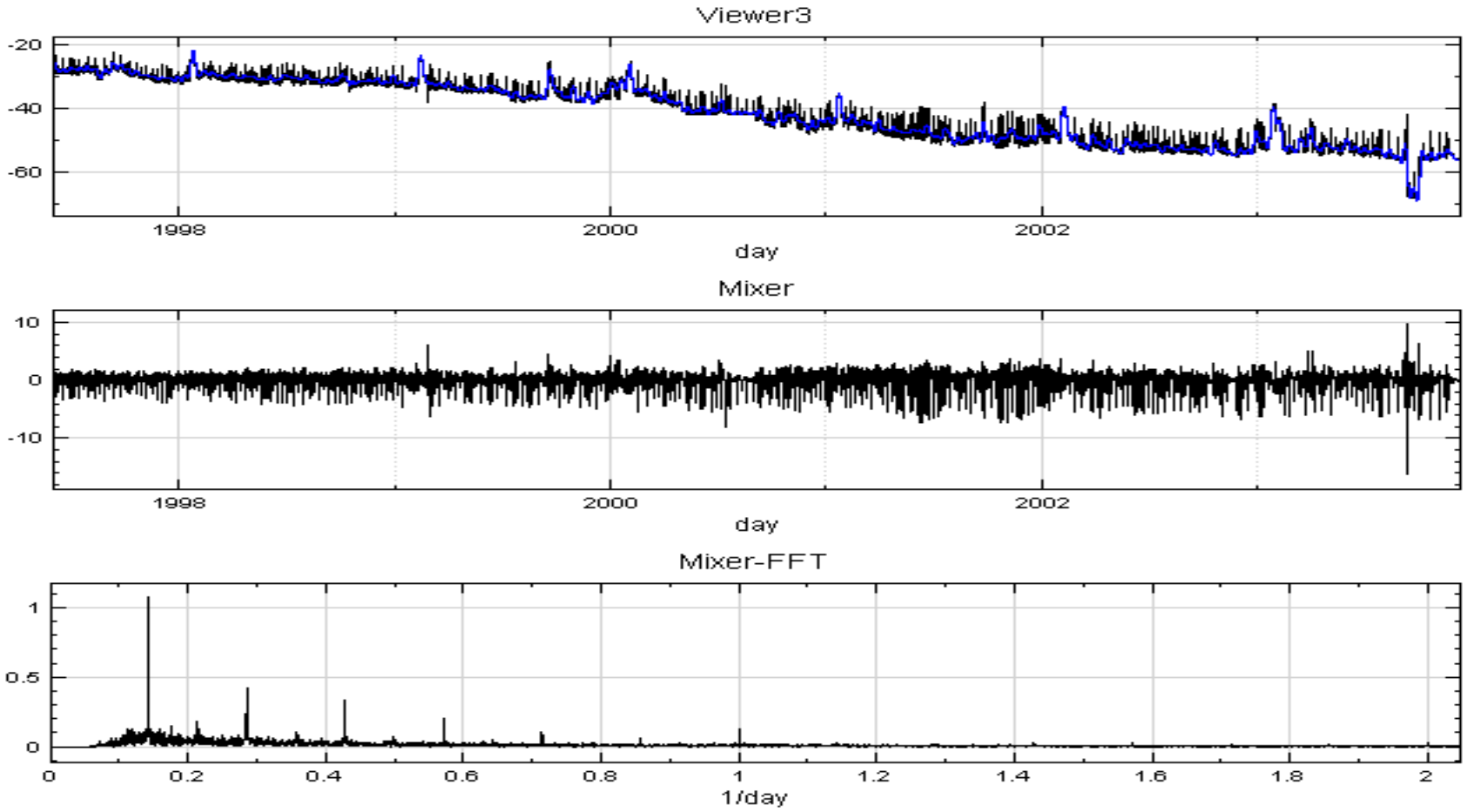

Viewer
-25
-30
-35
1998
2000
2002
year


well_03120111- IGaussFilter-FFT
0.04
0.02
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
1/day

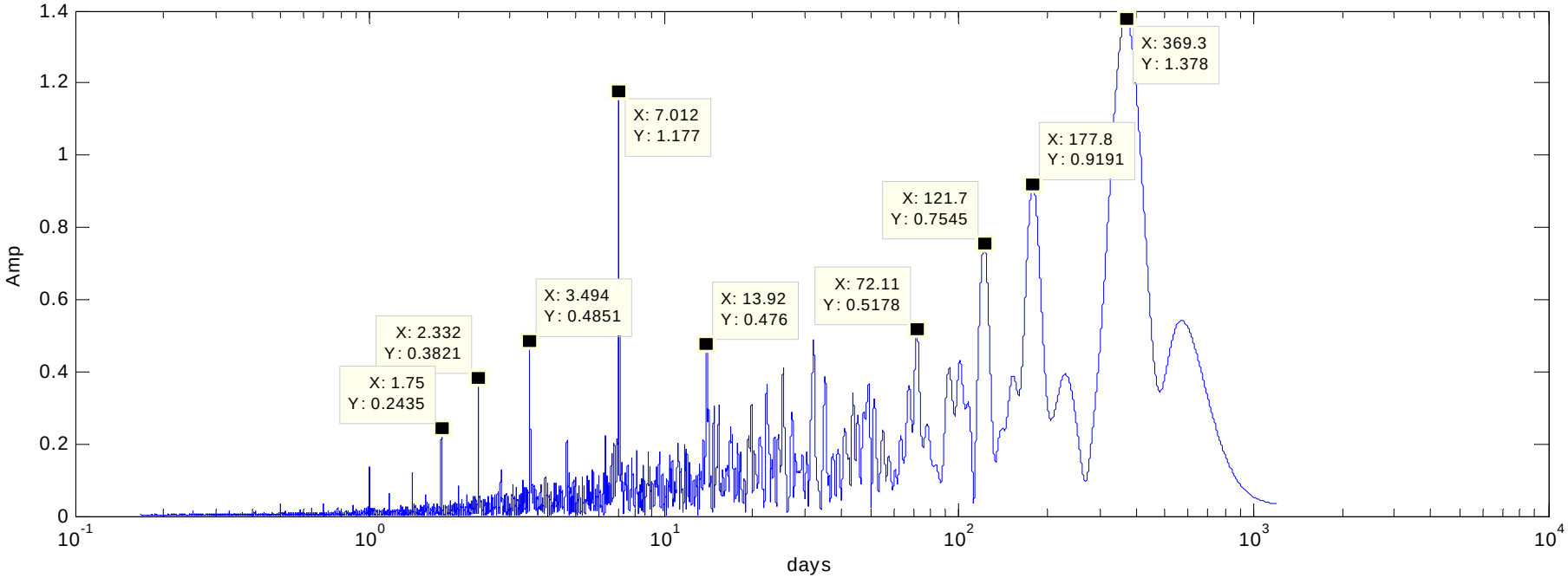
Spectrum of Ground Water Level (樹林1)



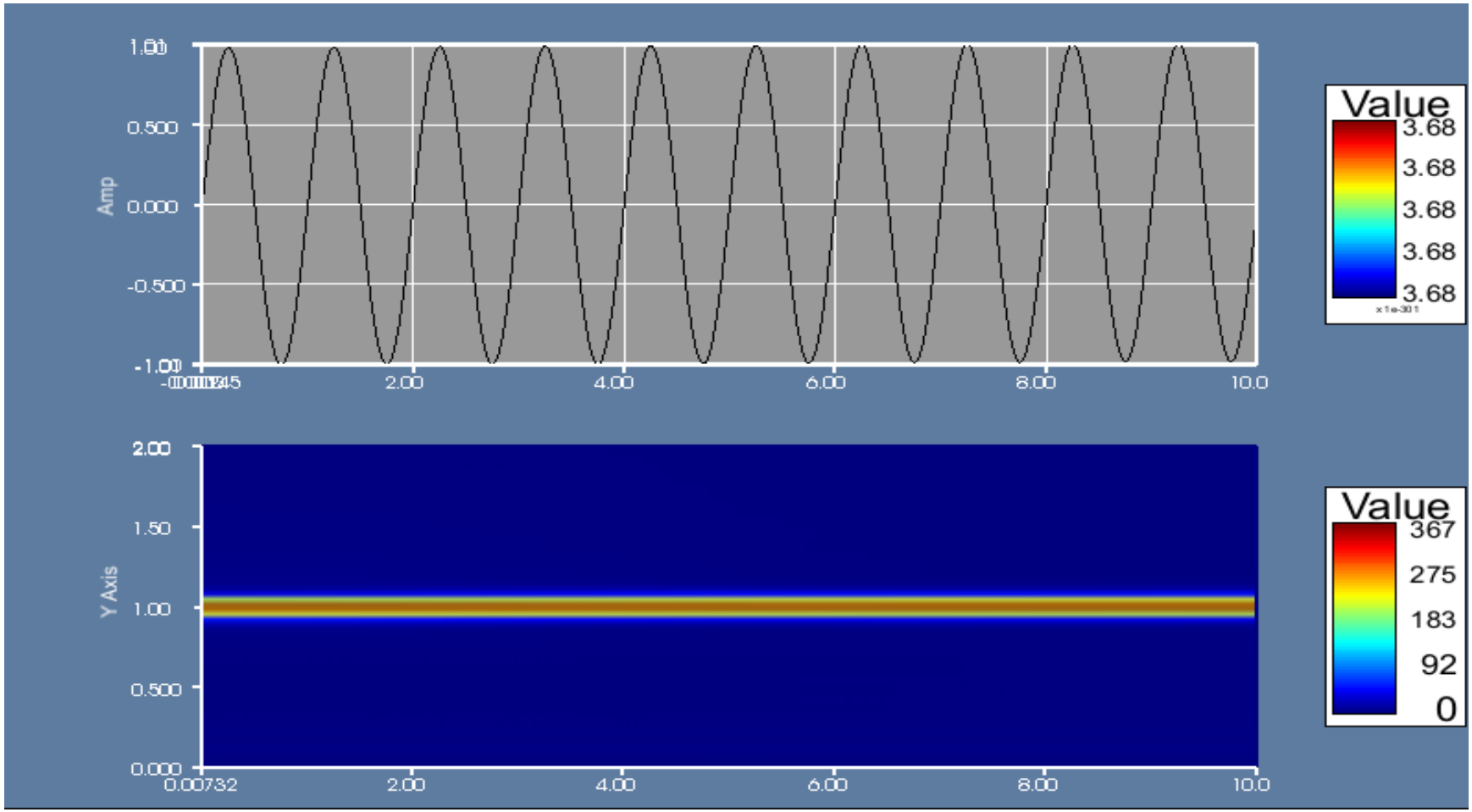
樹林(2)


Viewer3
-20
-40
-60
1998
2000
2002
day
Mixer
10
0
-10
1998
2000
2002
day
Mixer-FFT
1
0.5
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
1/day

Spectrum of Ground Water Level (樹林2)



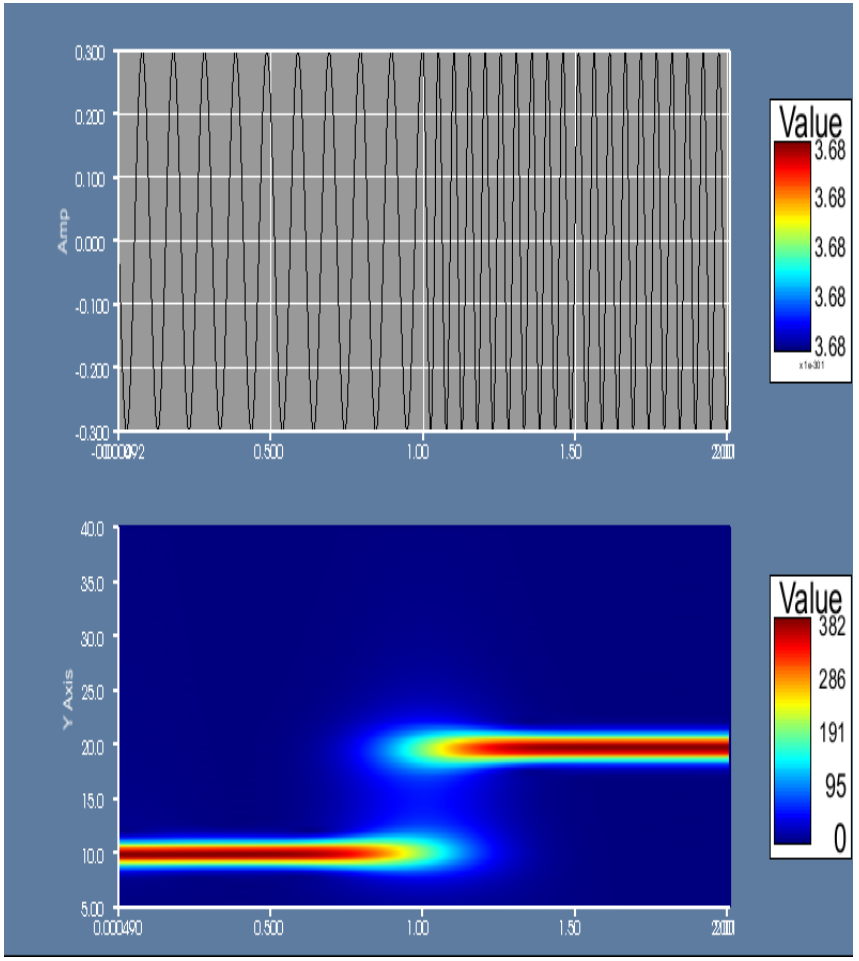
TF Plot: Single frequency



TF Plot: Change of frequency

- Signal with abrupt change of frequency.

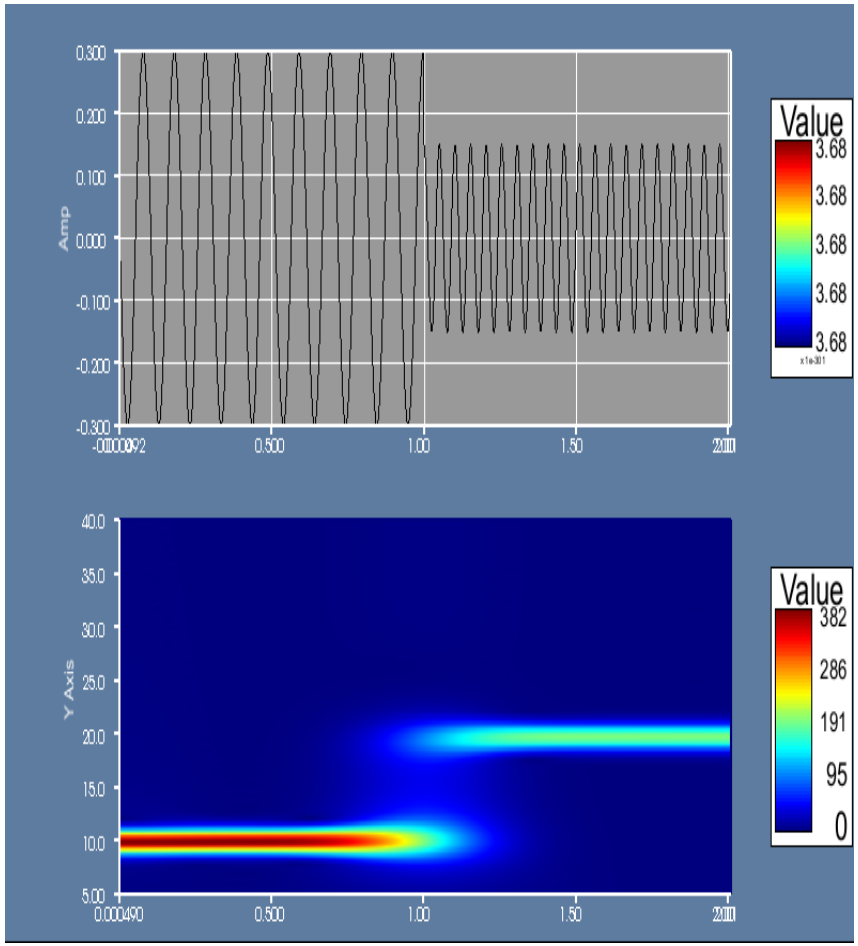
$$x(t) = \begin{cases} 0.30\cos(2\times 10\pi t) & ,0 \le t < 1 \\ 0.30\cos(2\times 20\pi t) & ,1 \le t < 2 \end{cases}$$



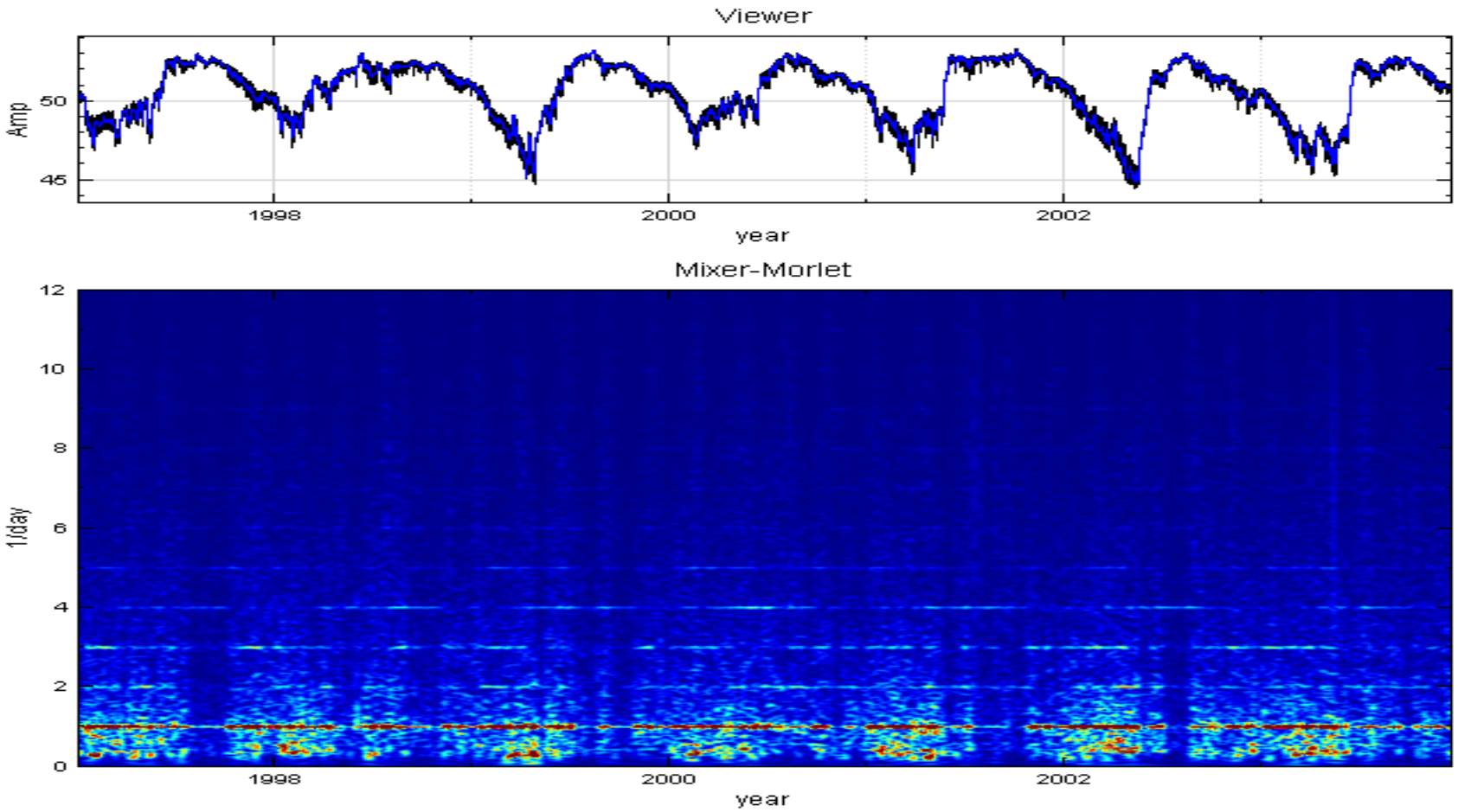
TF Plot: Change of frequency and amplitude

- Signal with abrupt change of frequency and amplitude

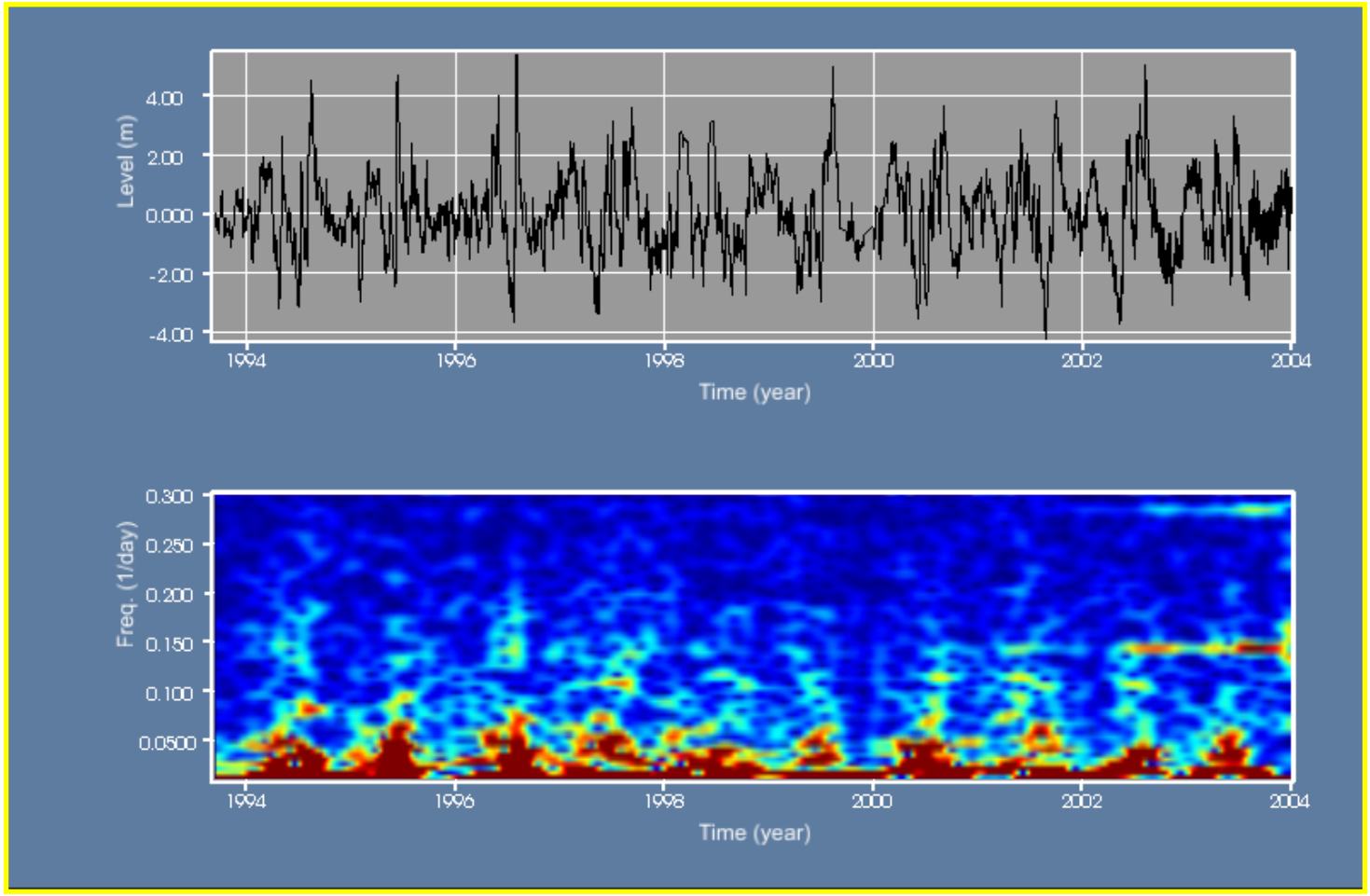
$$x(t) = \begin{cases} 0.30\cos(2\times 10\pi t) & ,0 \le t < 1 \\ 0.15\cos(2\times 20\pi t) & ,1 \le t < 2 \end{cases}$$



TF Plot of 美濃(1)



Abnormal Pumping



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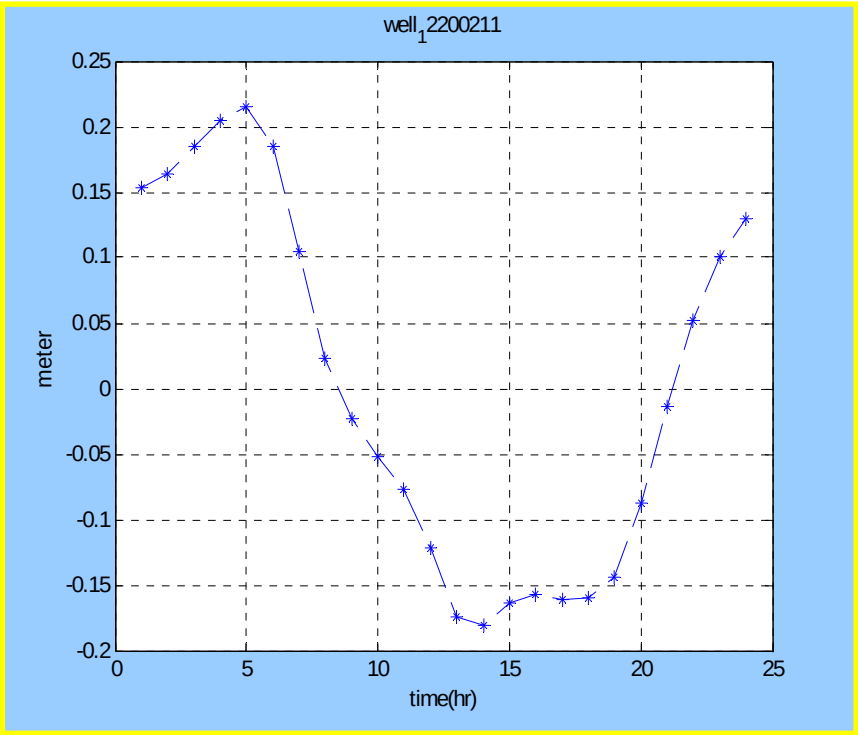
Time-Frequency Analysis in Visual Signal

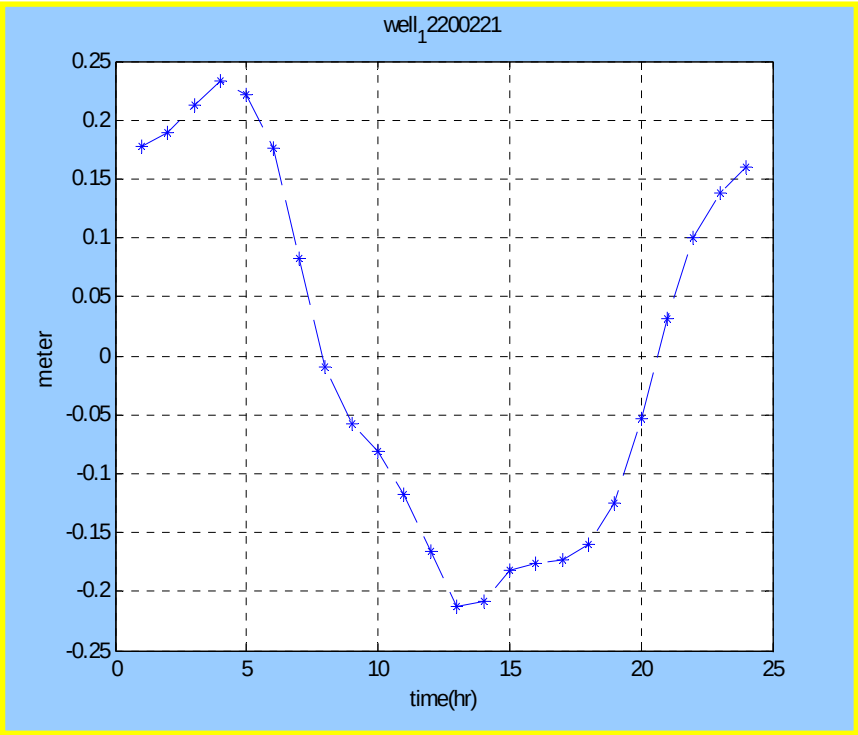
	Fourier Transform	STFT	**Morlet / Enhanced Morlet***	Hilbert Transform	**HHT***
Instantaneous frequency	n/a	distribution	**distribution**	Single value	**Discrete values**
Frequency change with time	no	yes	**yes**	yes	**yes**
Frequency resolution	good	ok	**ok/good**	good	**good**
Adaptive base	no	no	**no**	n/a	**yes**
Handling non-linear effect	n/a	no	**no**	yes	**yes**

*Algorithm used in this study

Average Daily Variation of GWL in Agriculture Region

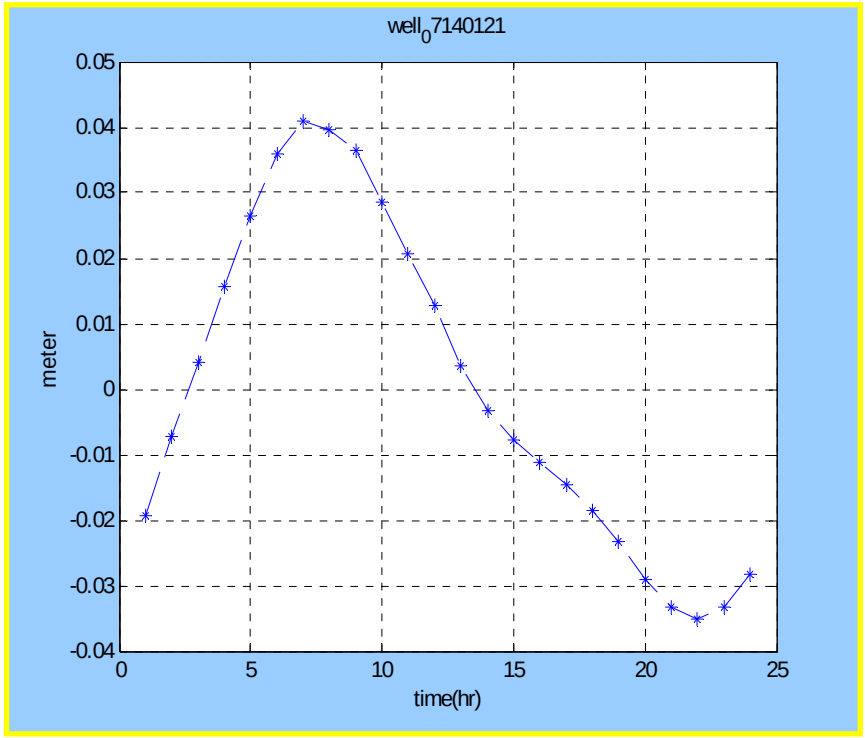


美濃(1)



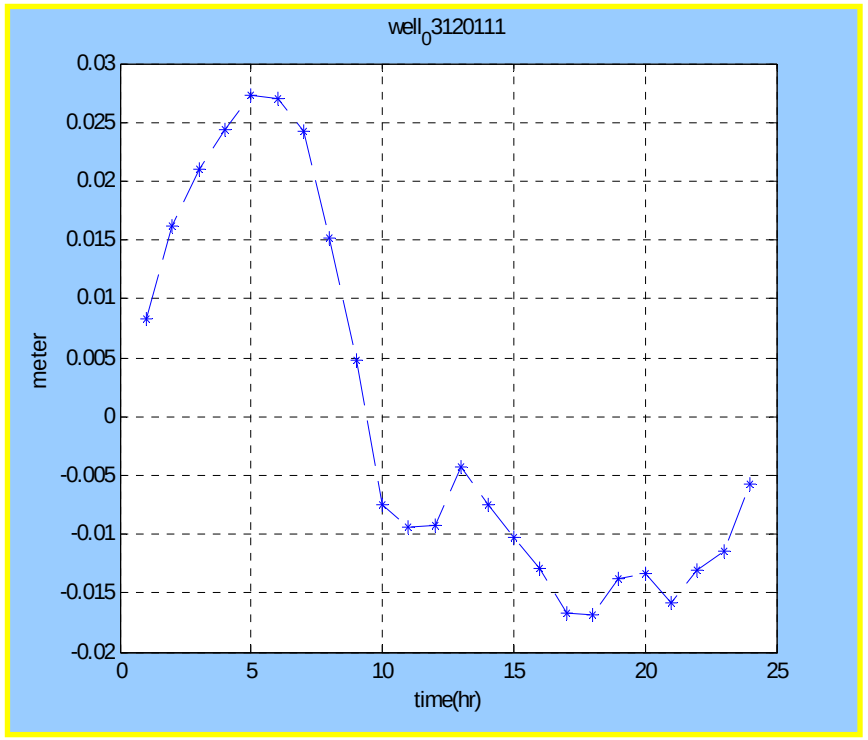
美濃(2)

Average Daily Variation of GWL in Industrial Region

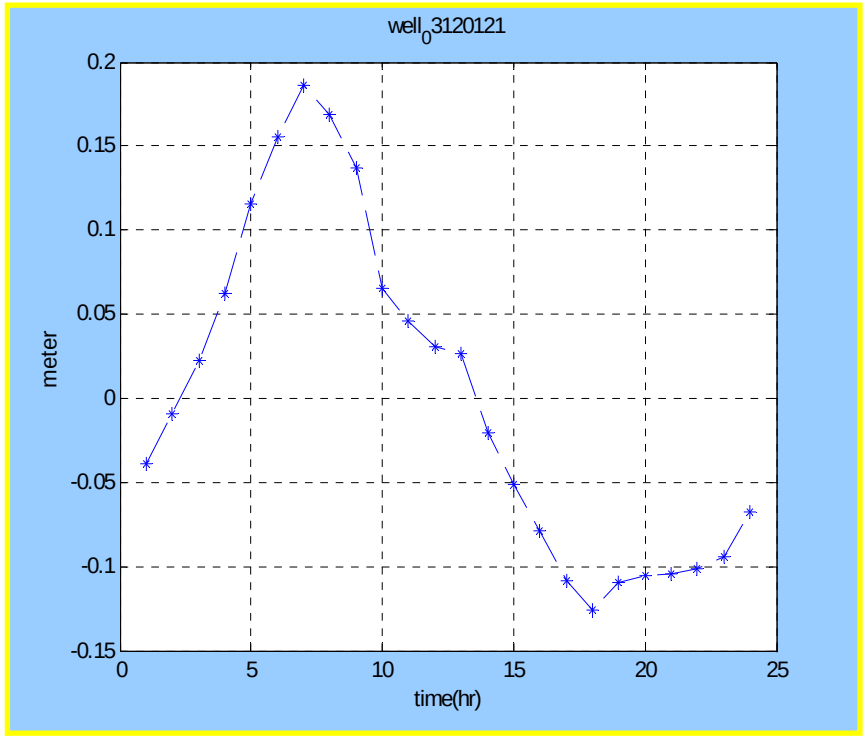


彰化・好修 (2)

Average Daily Variation of GWL in Mixed Region

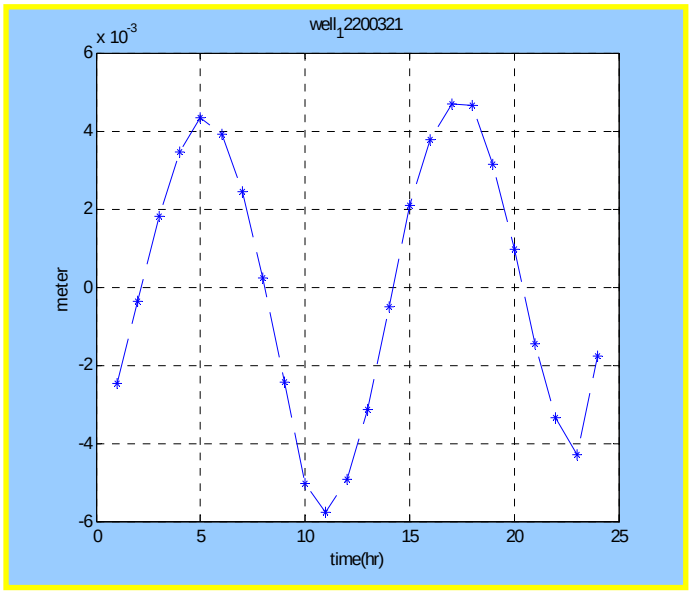


桃園樹林 (1)

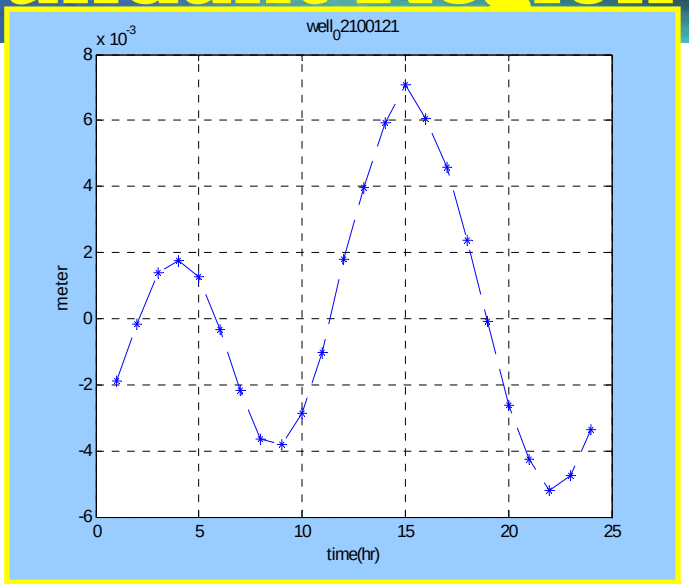


桃園樹林 (2)

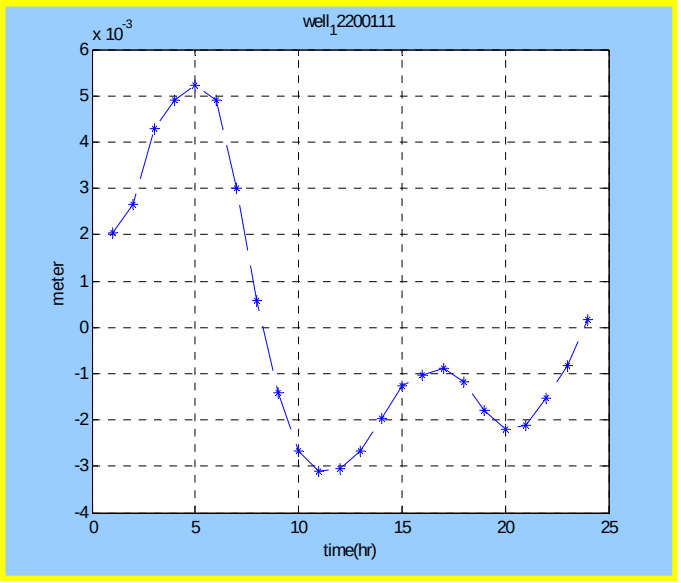
Average Daily Variation of GWL in Recharge Abundant Region



吉洋人工湖

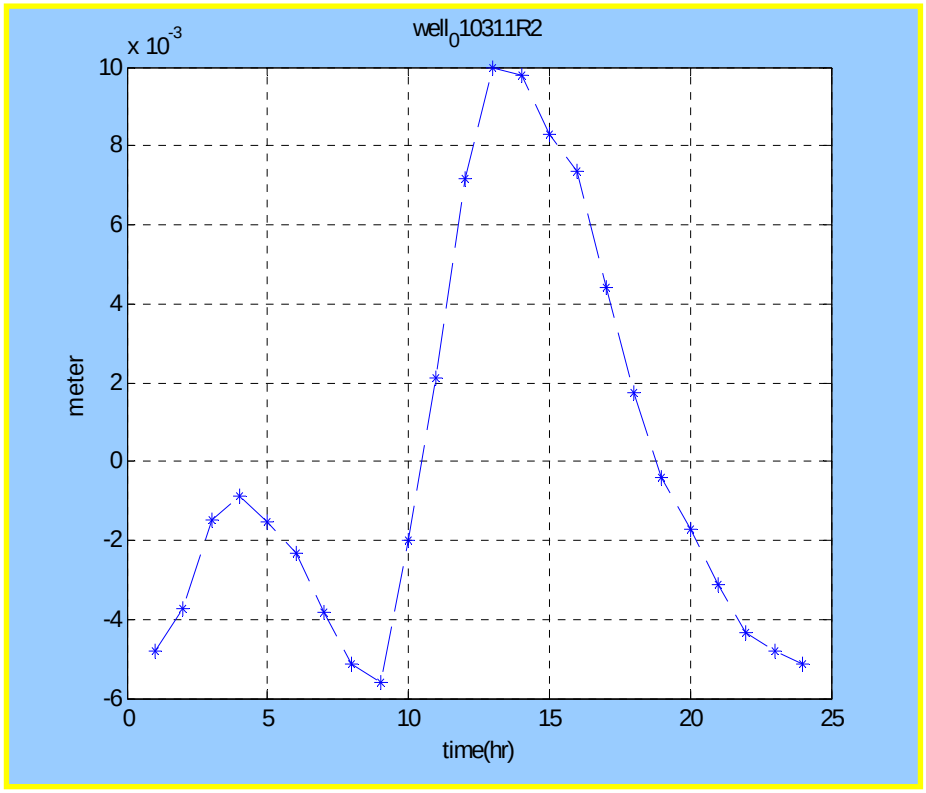


吉洋工作站



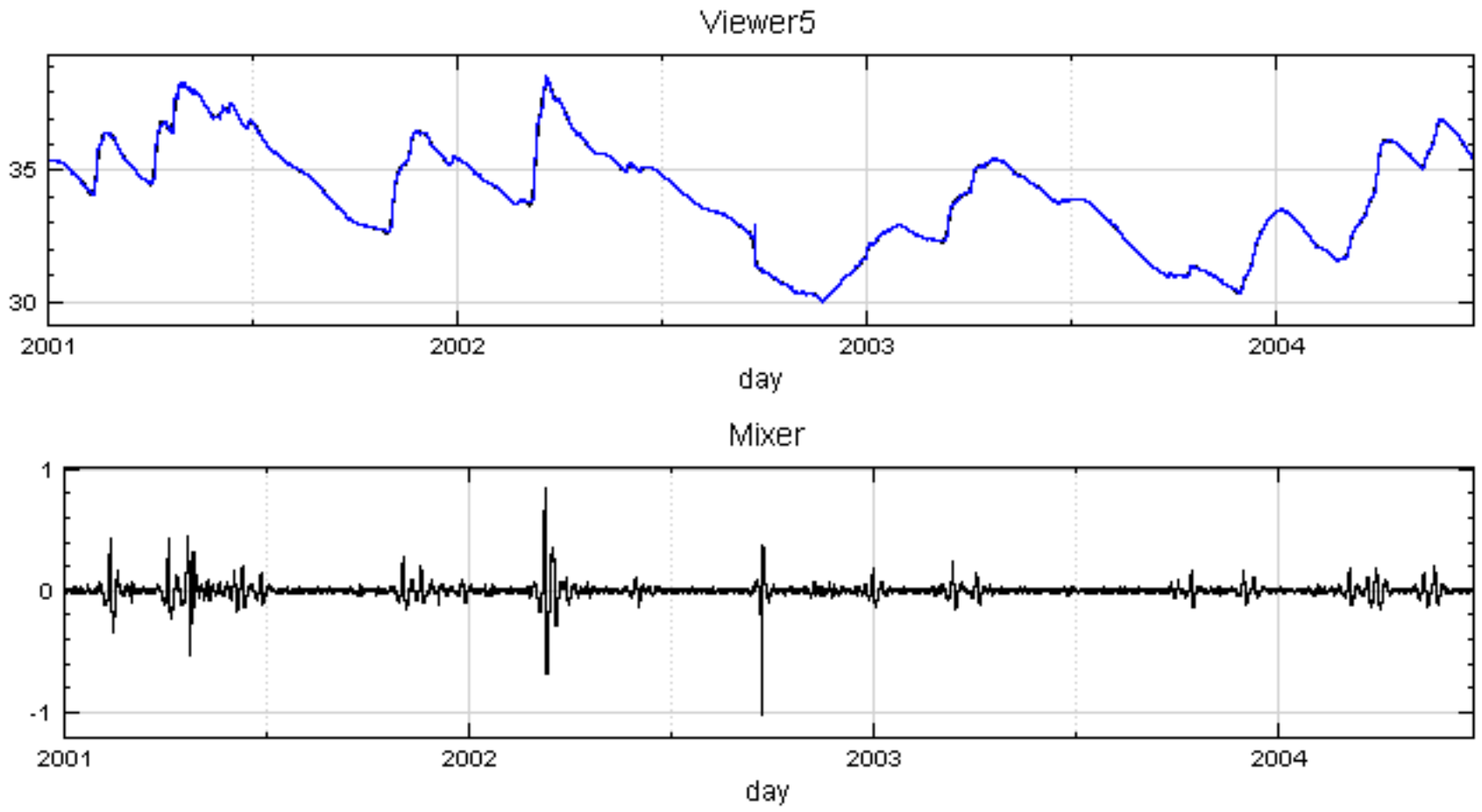
宜蘭・大隱

Average Daily Variation of GWL in Region without Pumping

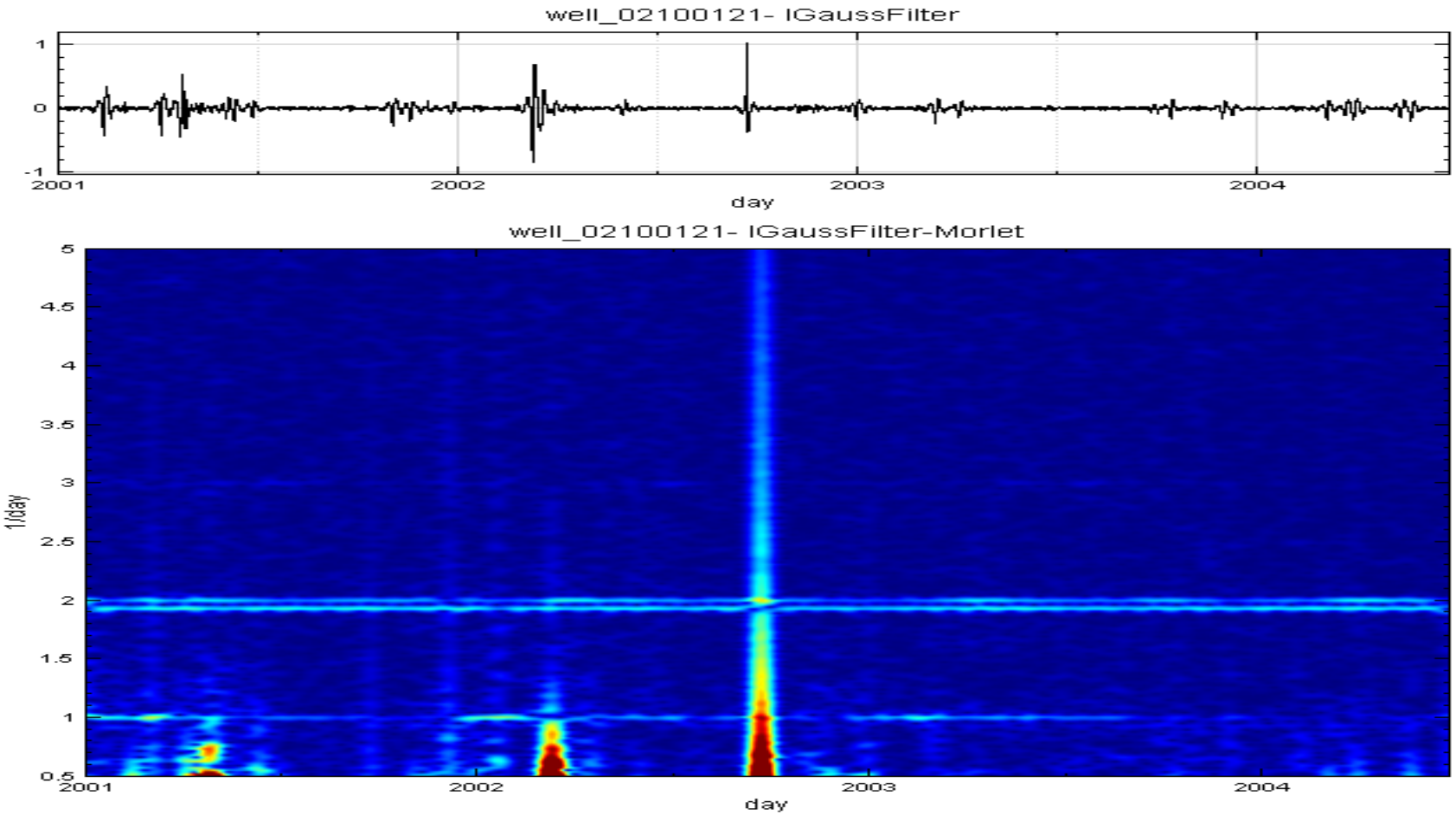


中和 **Well, Taipei**

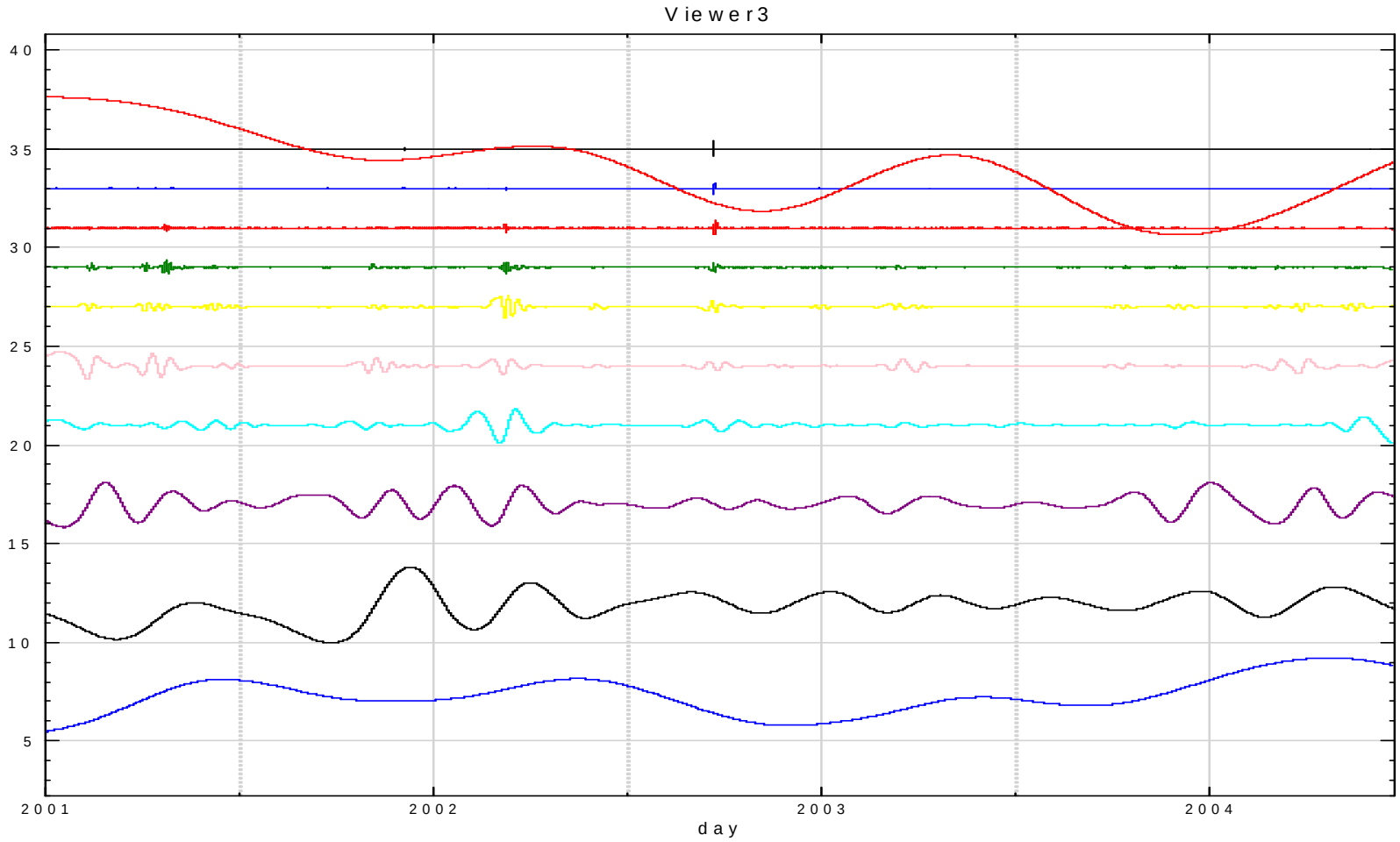
宜蘭大隱


Viewer5
35
30
2001
2002
2003
2004
day
Mixer
1
0
-1
2001
2002
2003
2004
day

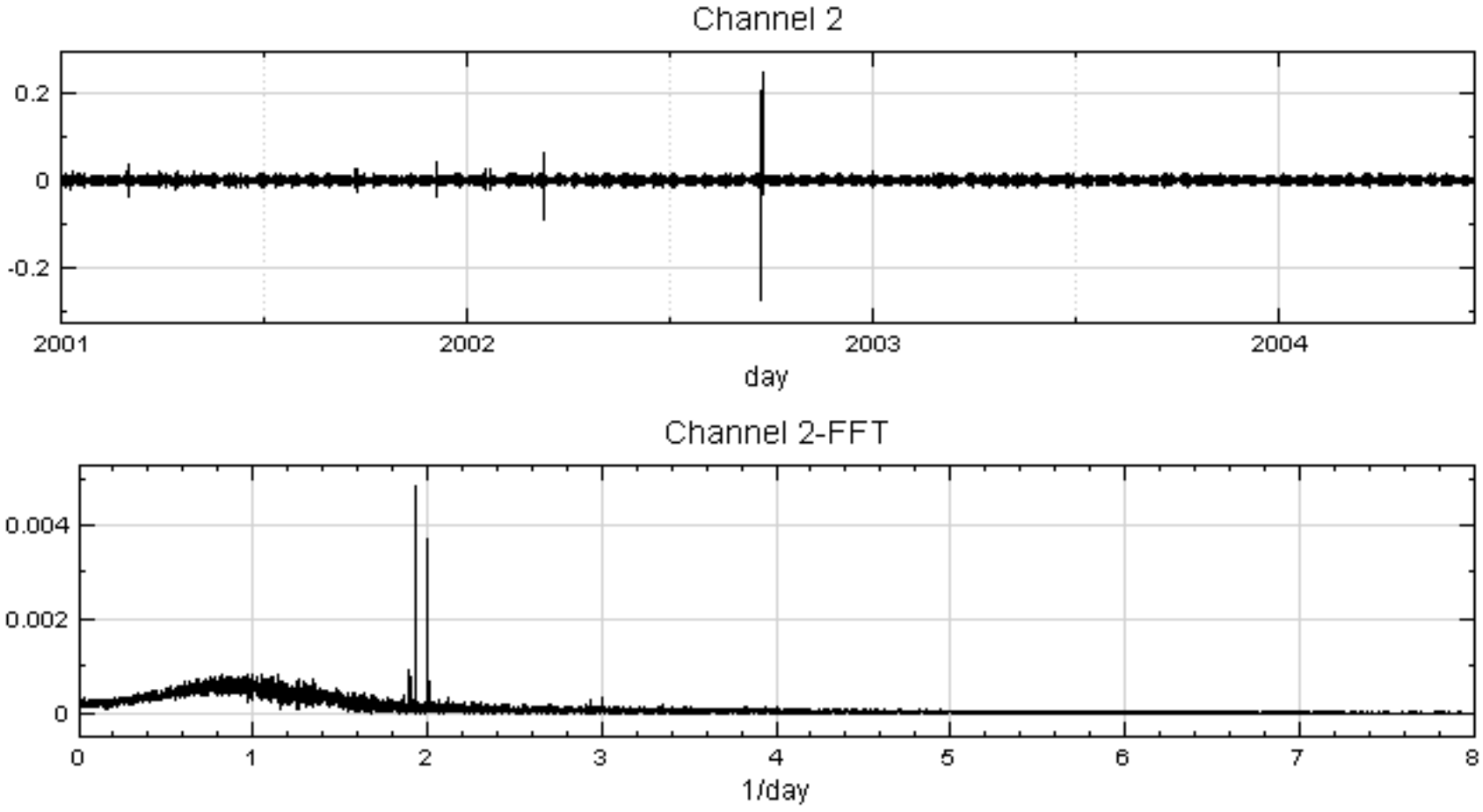
宜蘭大隱


well_02100121- IGaussFilter
1
0
-1
2001
2002
2003
2004
day
well_02100121- IGaussFilter-Morlet
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
1/day
2001
2002
2003
2004
day

宜蘭大隱(EMD)

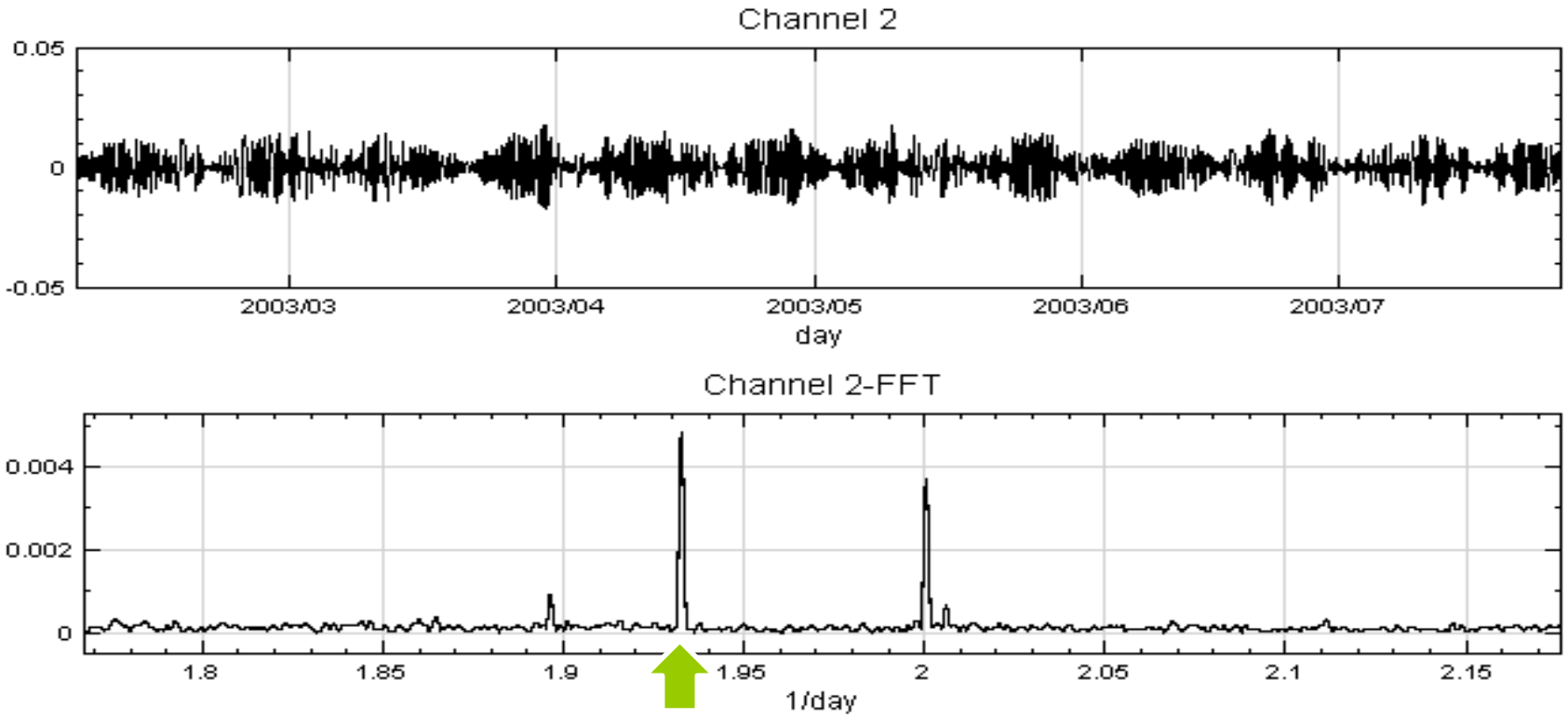


IMF2 (semi-diurnal tide)



IMF2 (semi-diurnal tide)

Beat wave occurs twice per month.



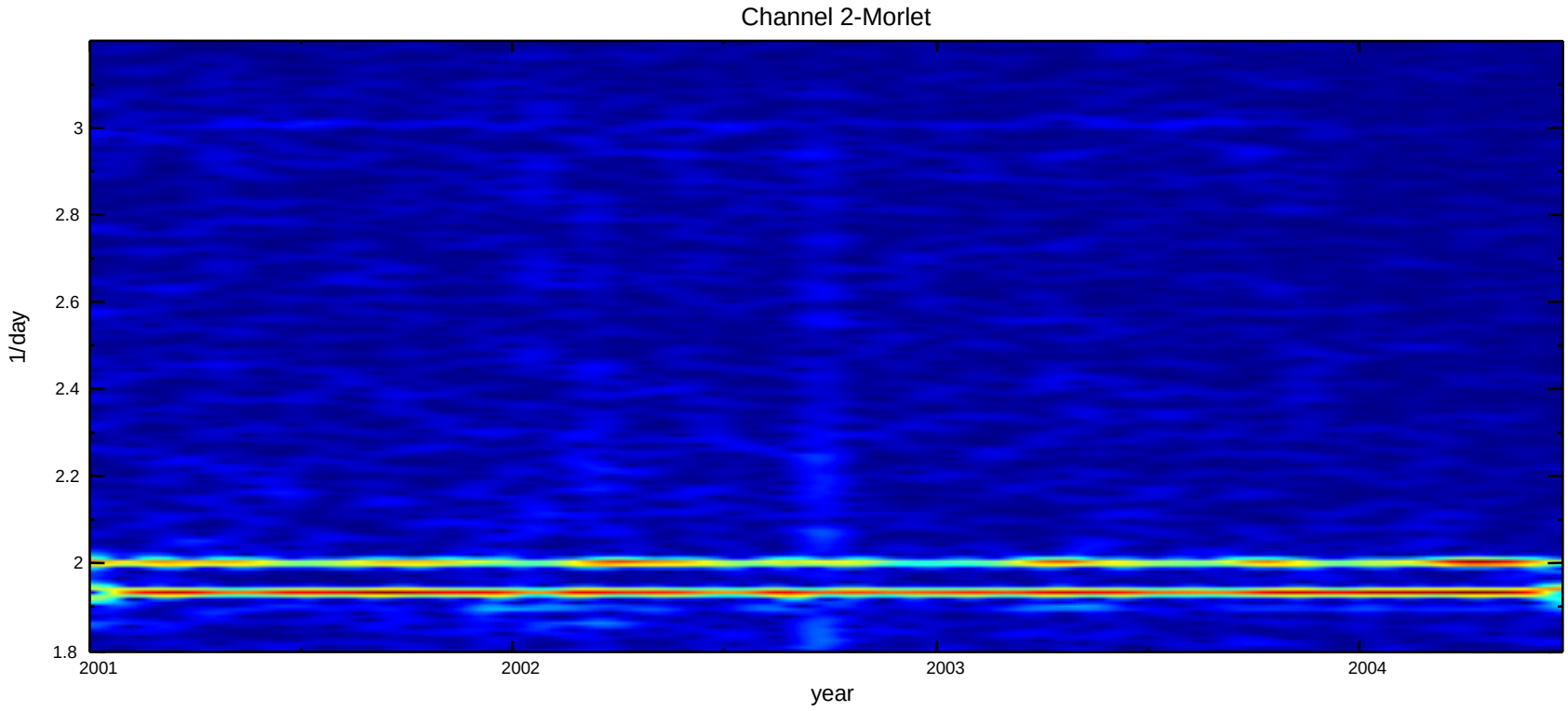
1.9323

Beat wave

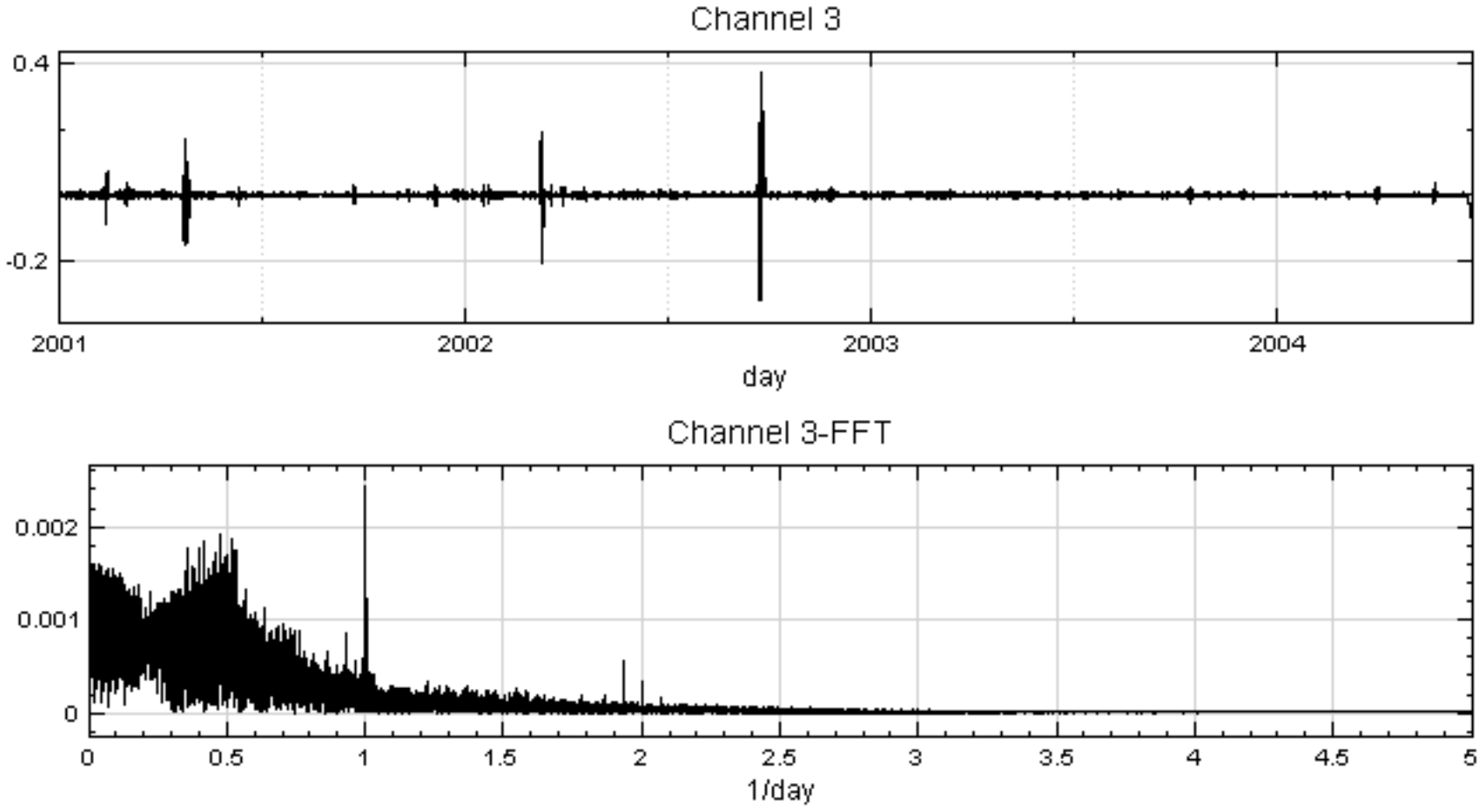
$$\cos(\omega t) + \cos((\omega + \delta\omega)t) \cong 2\cos(\omega t)\cos(\frac{\delta\omega}{2}t)$$

$$T = \frac{2}{f} = \frac{2}{2 - 1.9323} = 29.5 \text{ (days)}$$

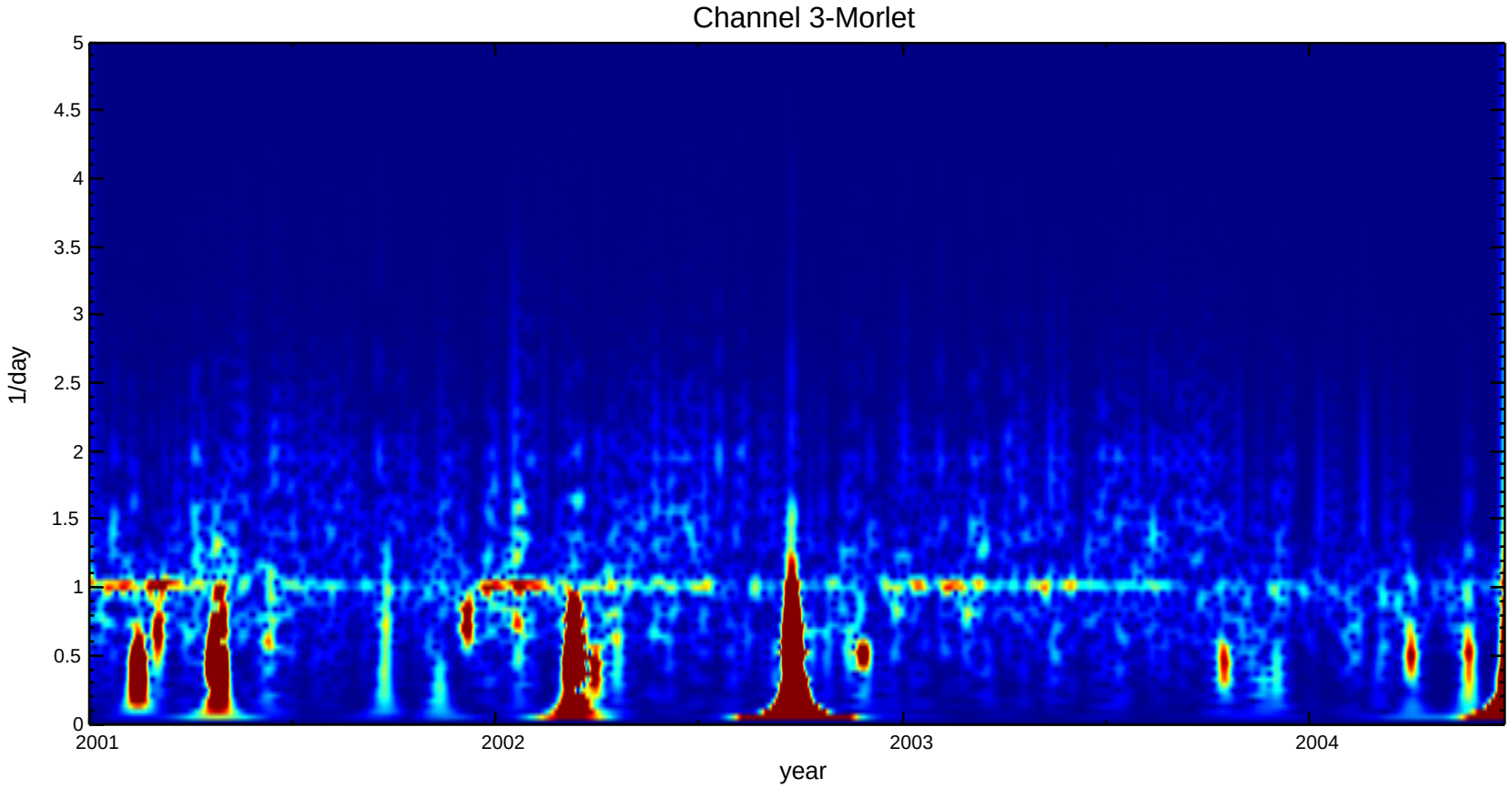
IMF2 (semi-diurnal tide)



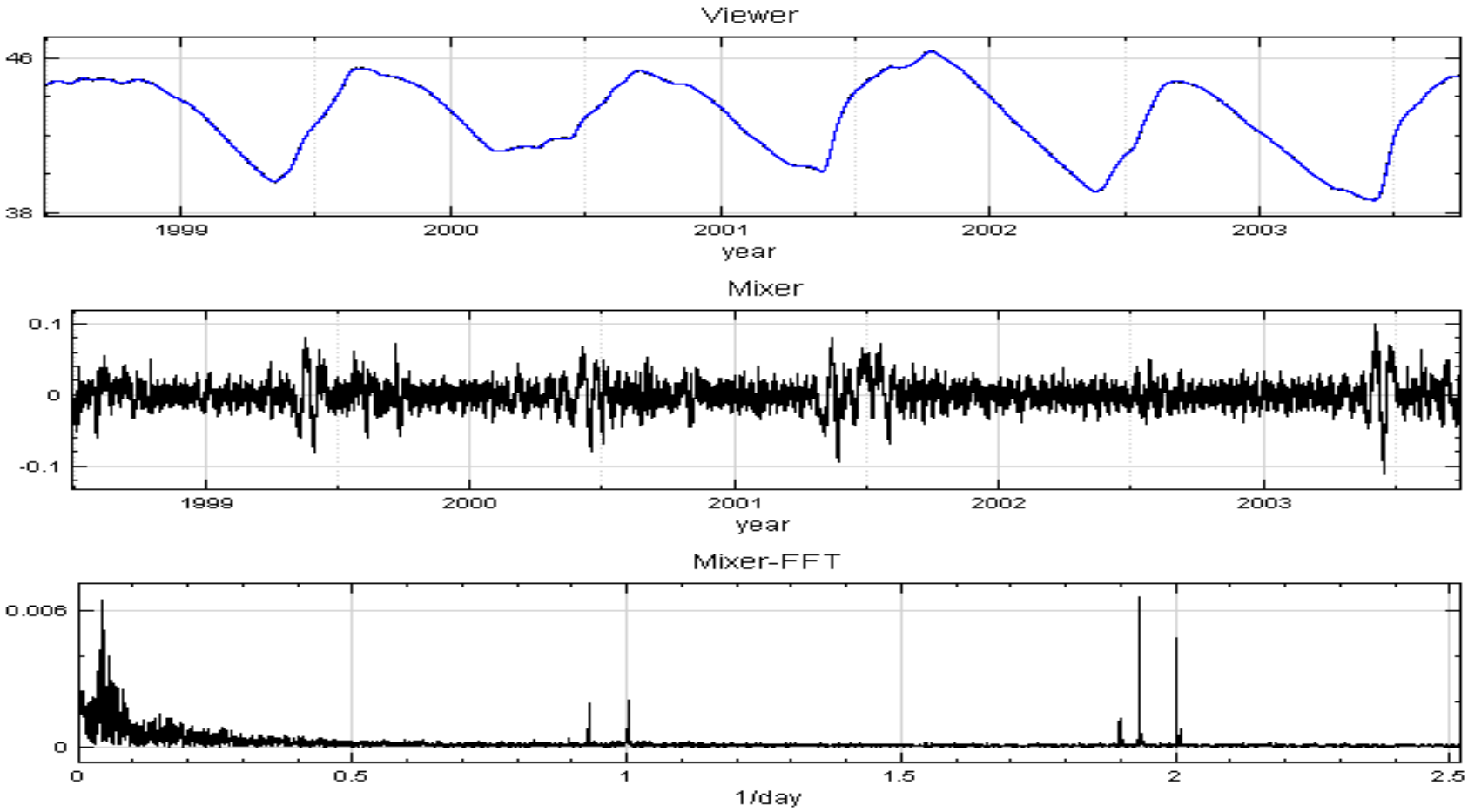
IMF3 (once per day)



IMF3 (cont'd)

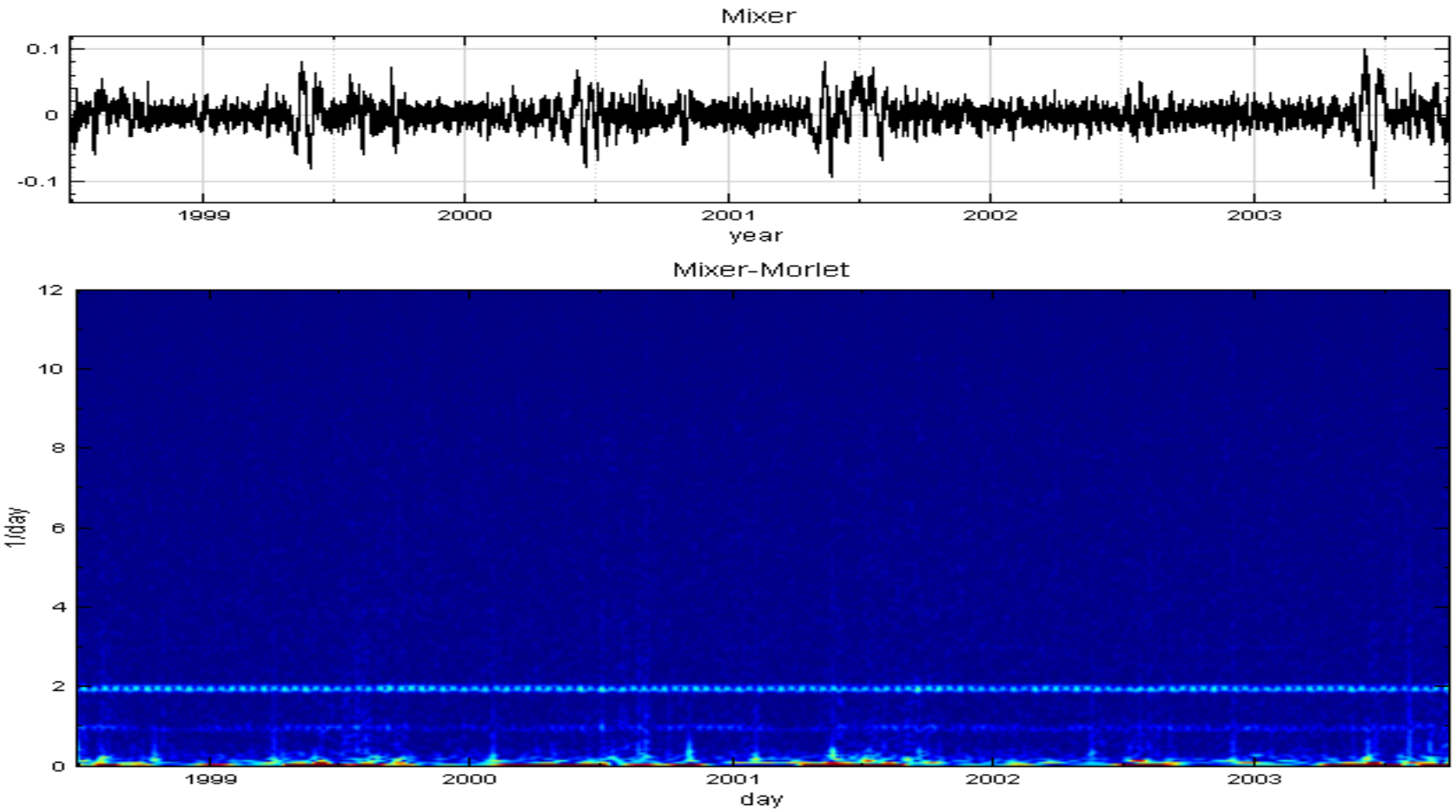

Channel 3-Morlet
1/day
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
2001
2002
2003
2004
year

吉洋人工湖(2)

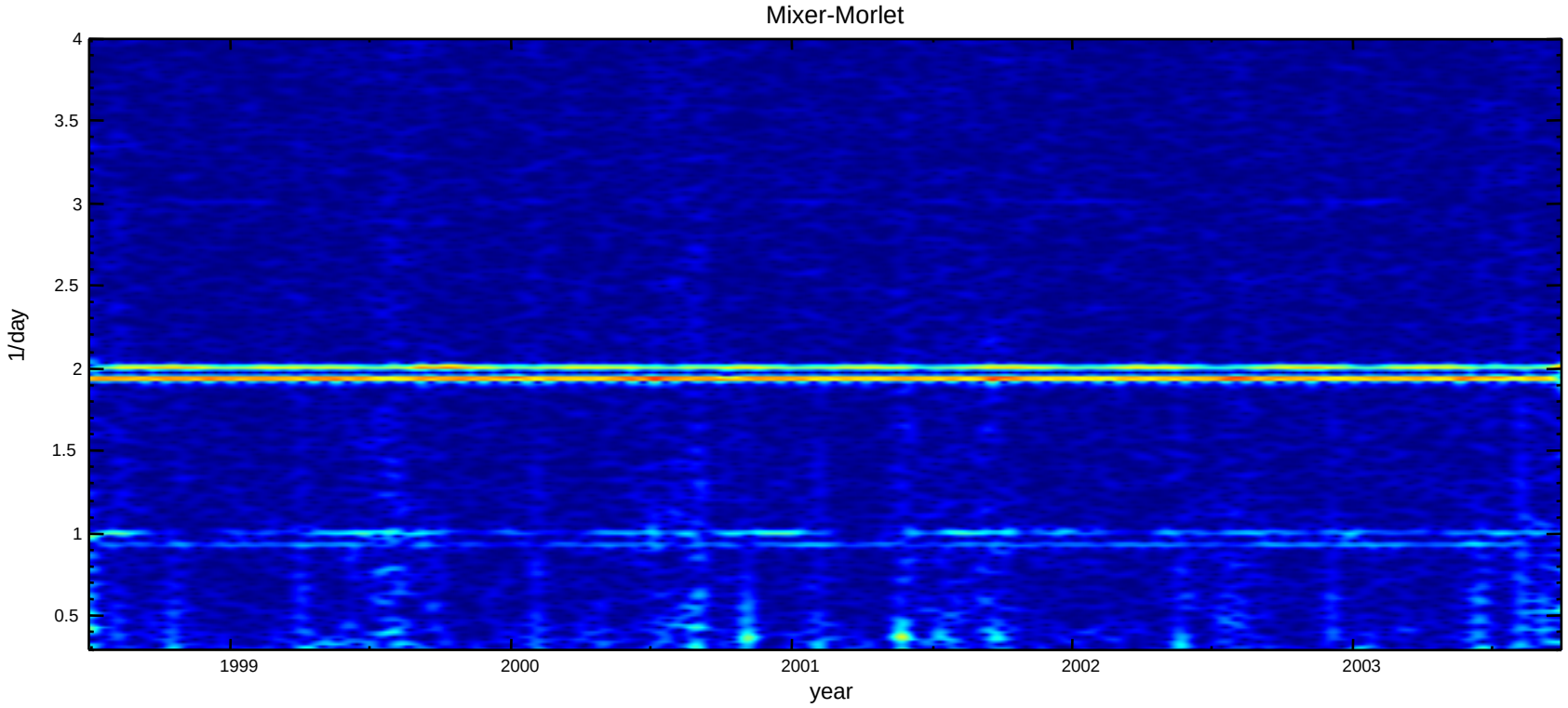


Non-periodical signal is separated via EMD. The periodical part is shown in the middle plot. Its spectrums follows.

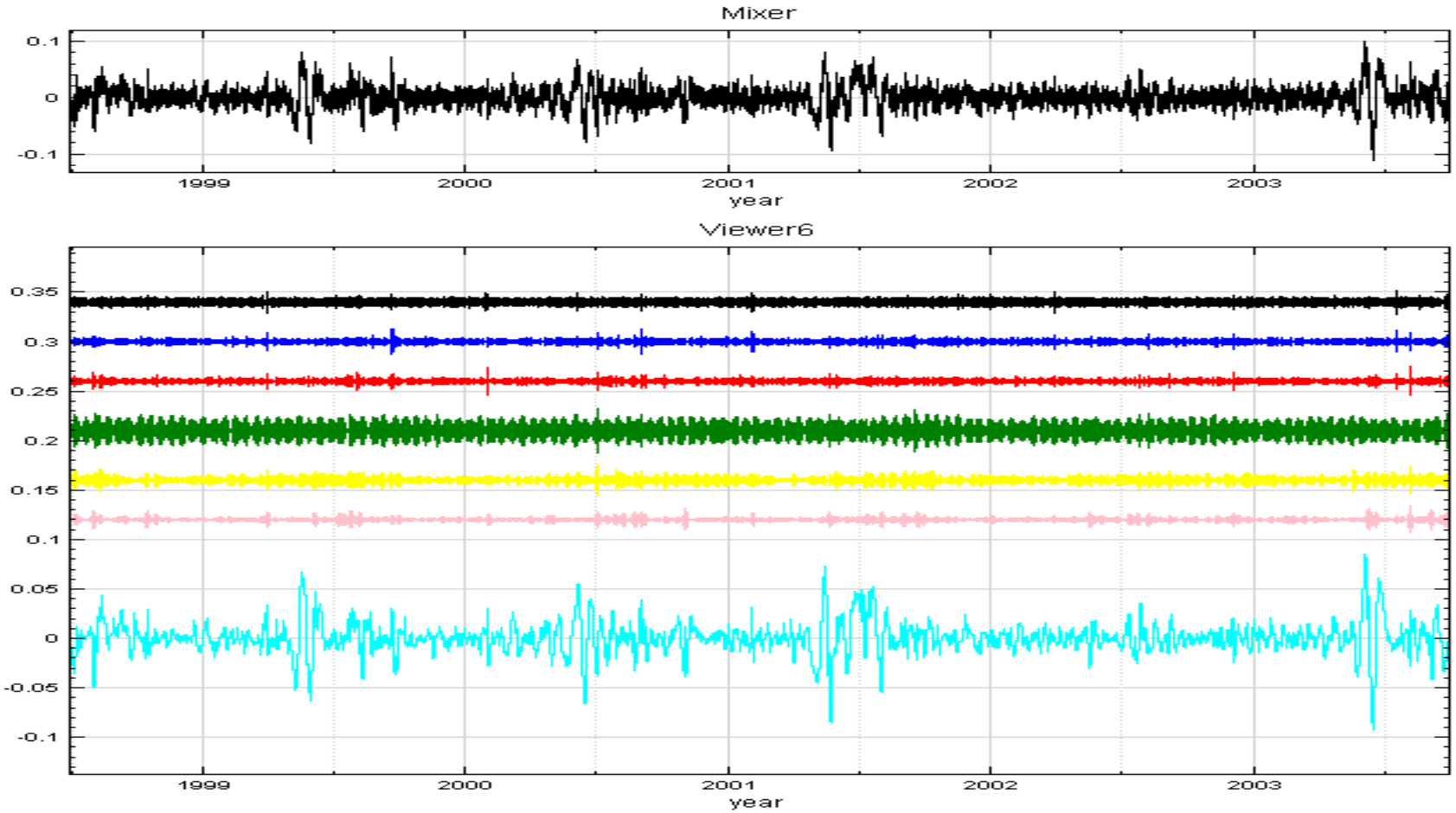
TF Plot of 吉洋人工湖(2)



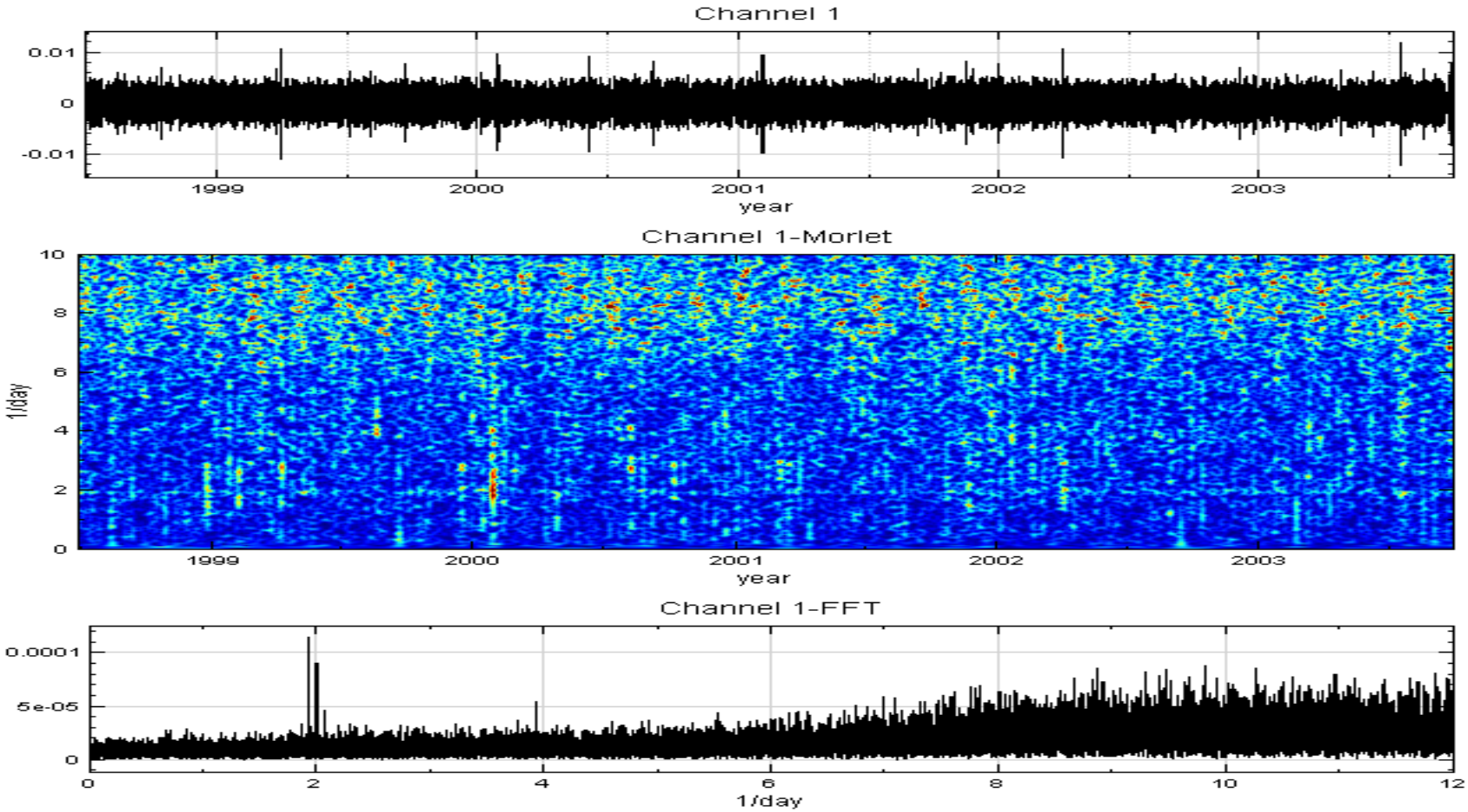
TF Plot


Mixer-Morlet
4
3.5
3
2.5
2
1.5
1
0.5
1/day
1999
2000
2001
2002
2003
year

Empirical Mode Decomposition

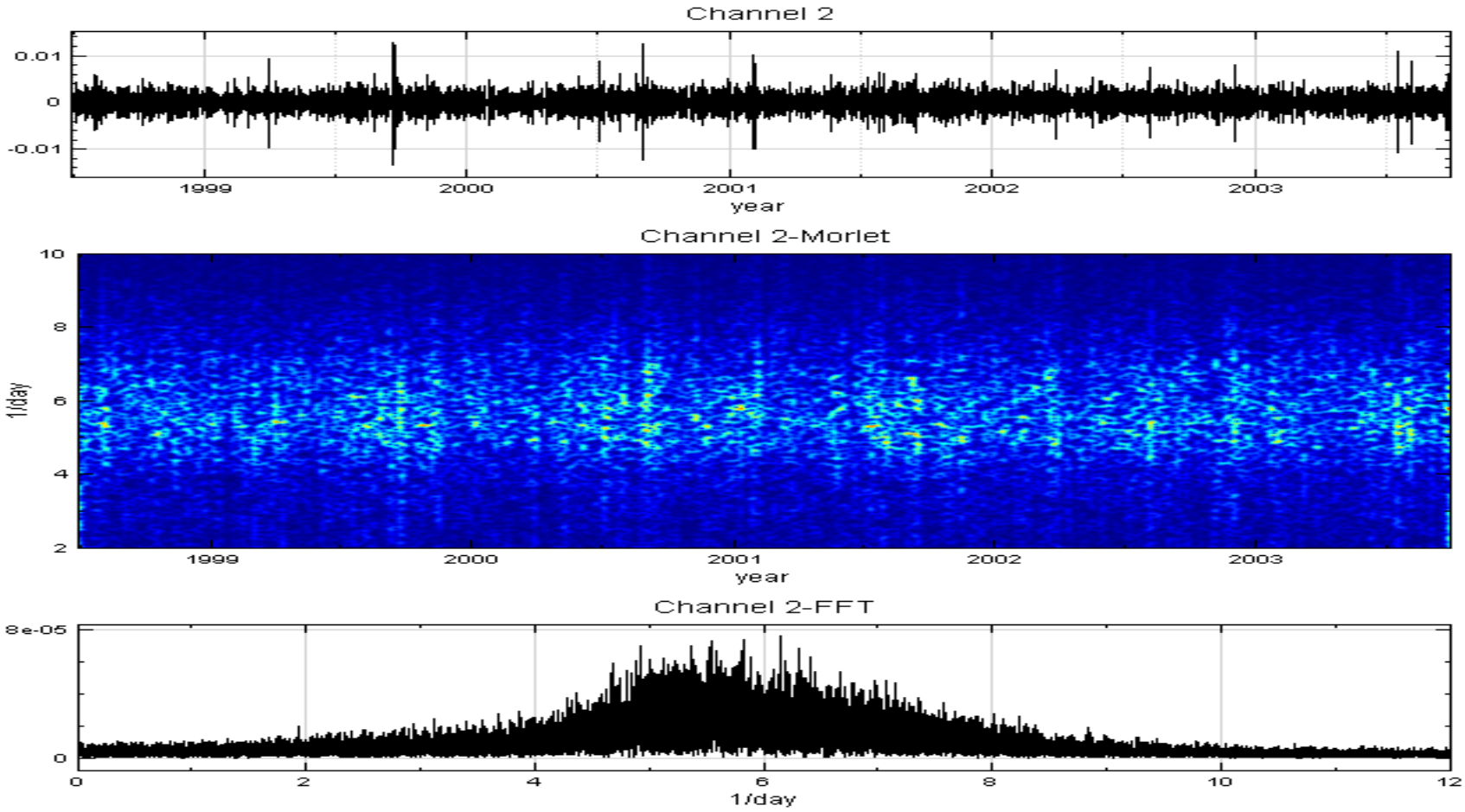


IMF1



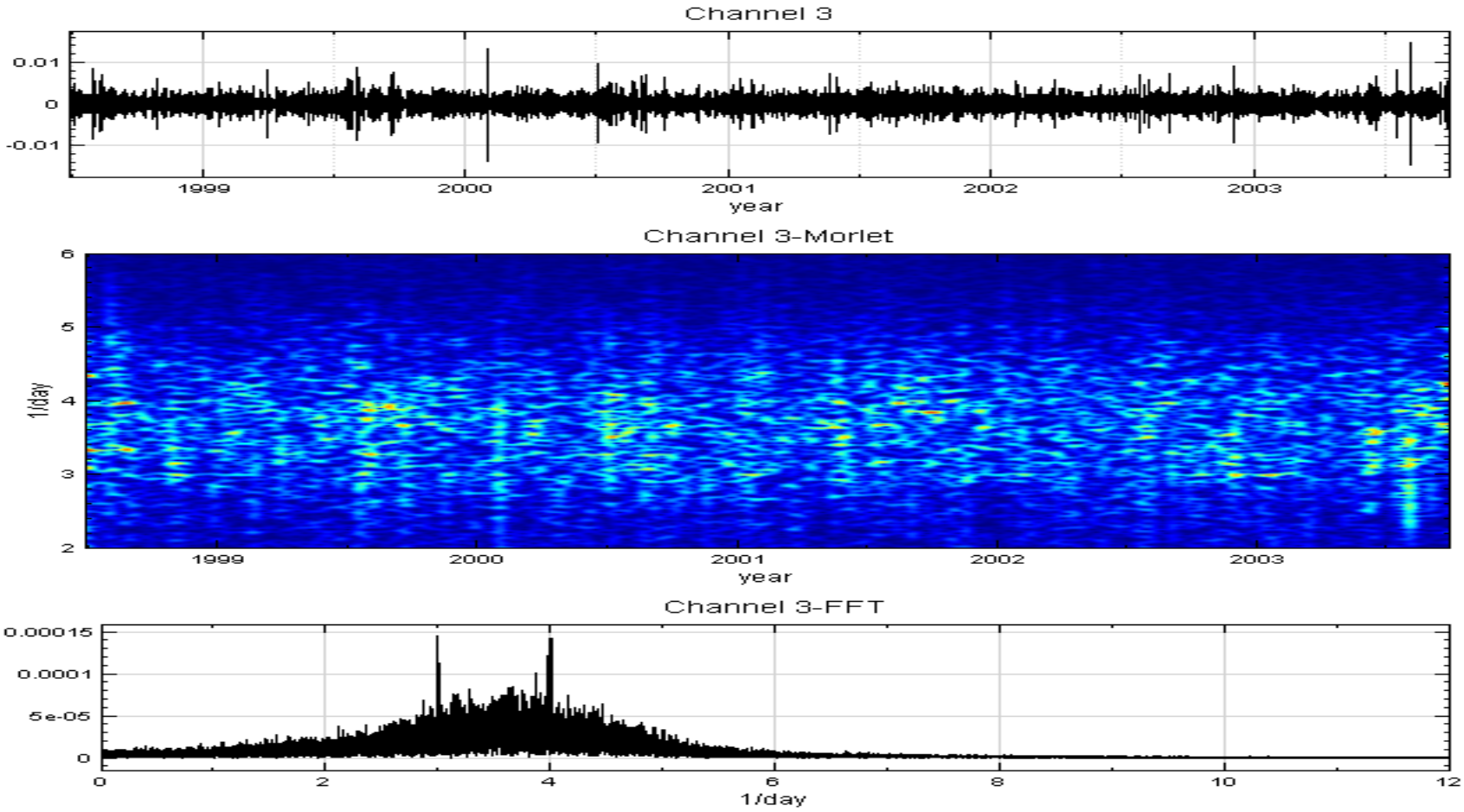
The first IMF is mostly high frequency noise. Though semi-diurnal Frequency appears, its amplitude is small.

IMF2

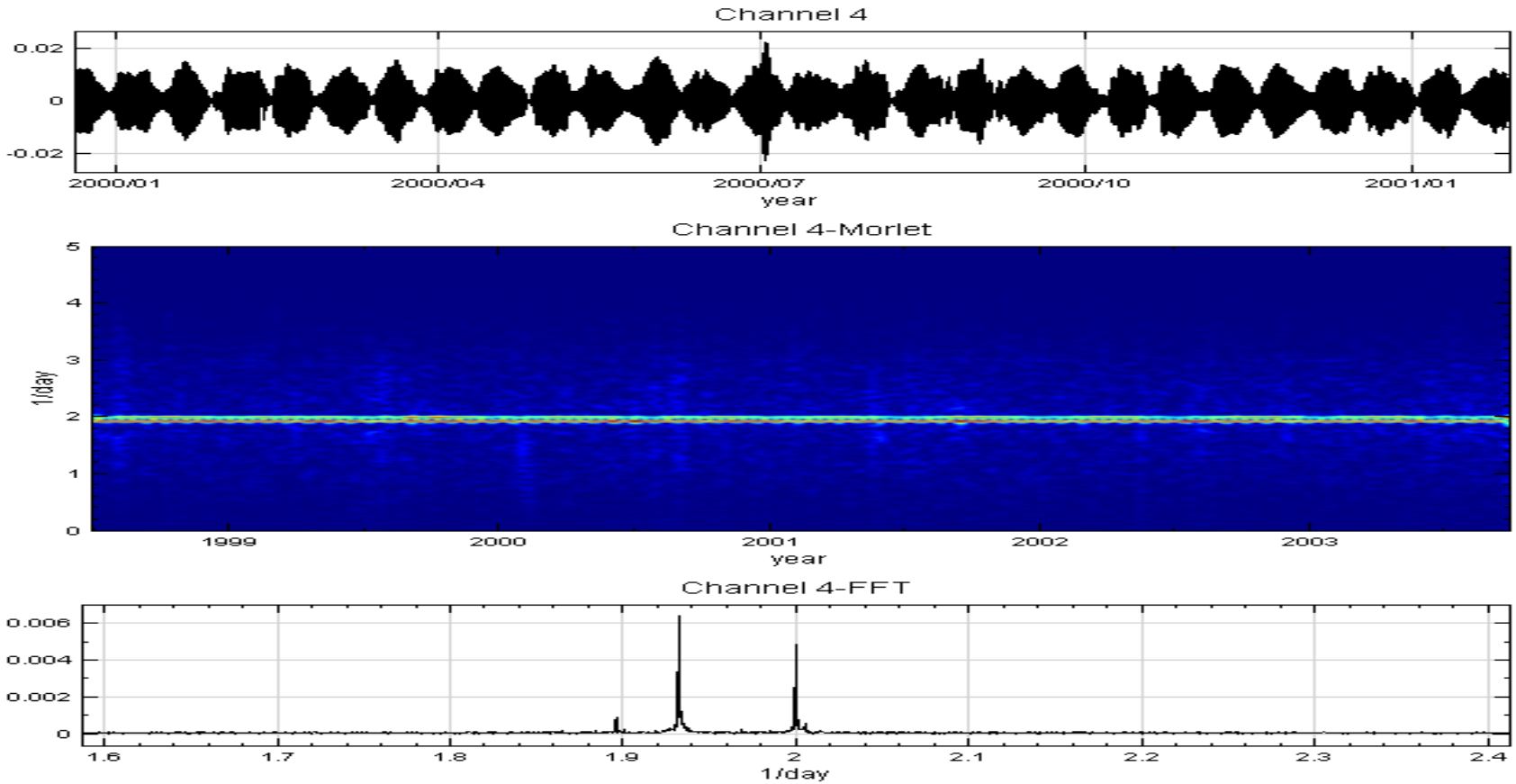


The component is relatively small compared to other IMFs.

IMF3

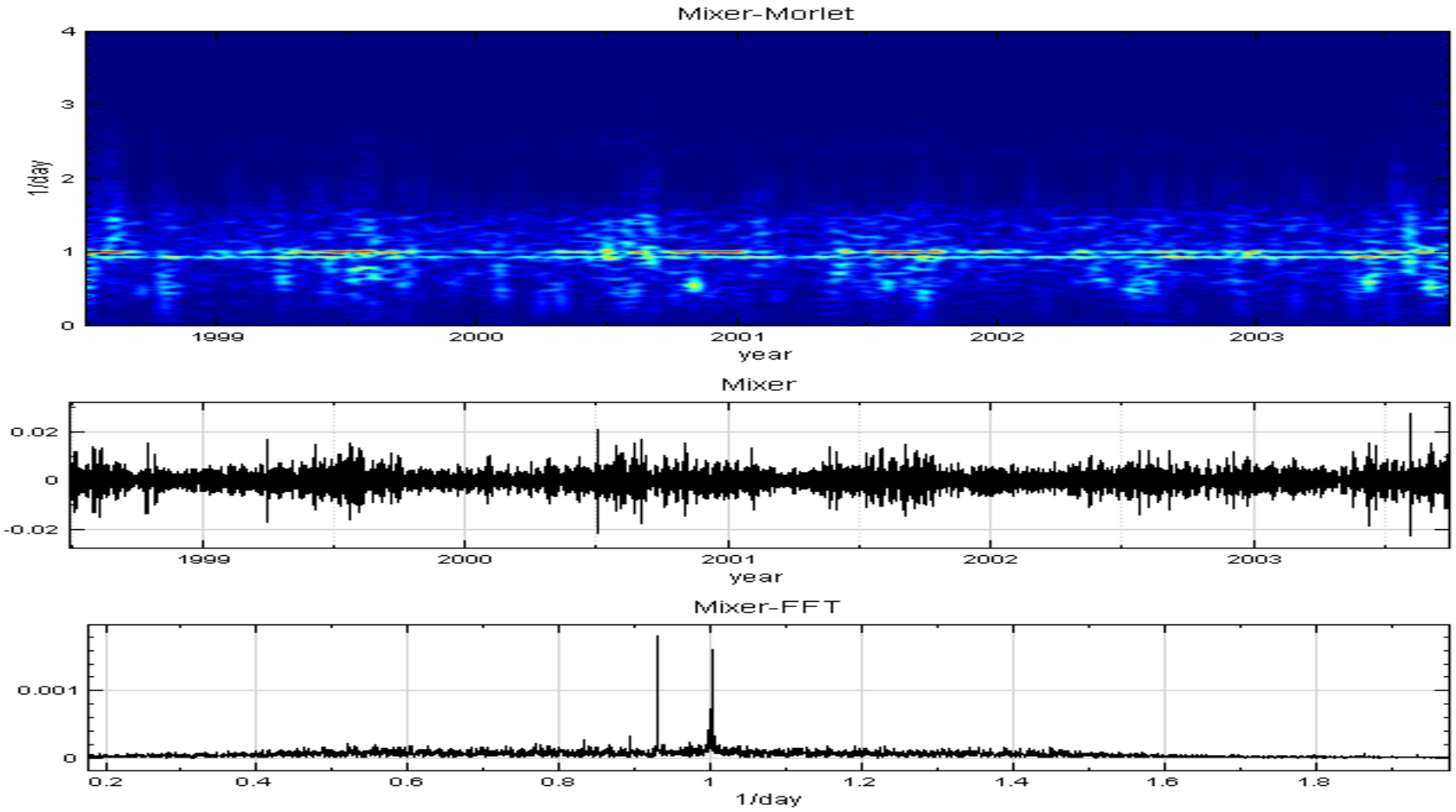

Channel 3
0.01
0
-0.01
1999
2000
2001
2002
2003
year
Channel 3-Morlet
6
5
4
3
2
1/day
1999
2000
2001
2002
2003
year
Channel 3-FFT
0.00015
0.0001
5e-05
0
0
2
4
6
8
10
12
1/day

IMF4: Semi-diurnal tide



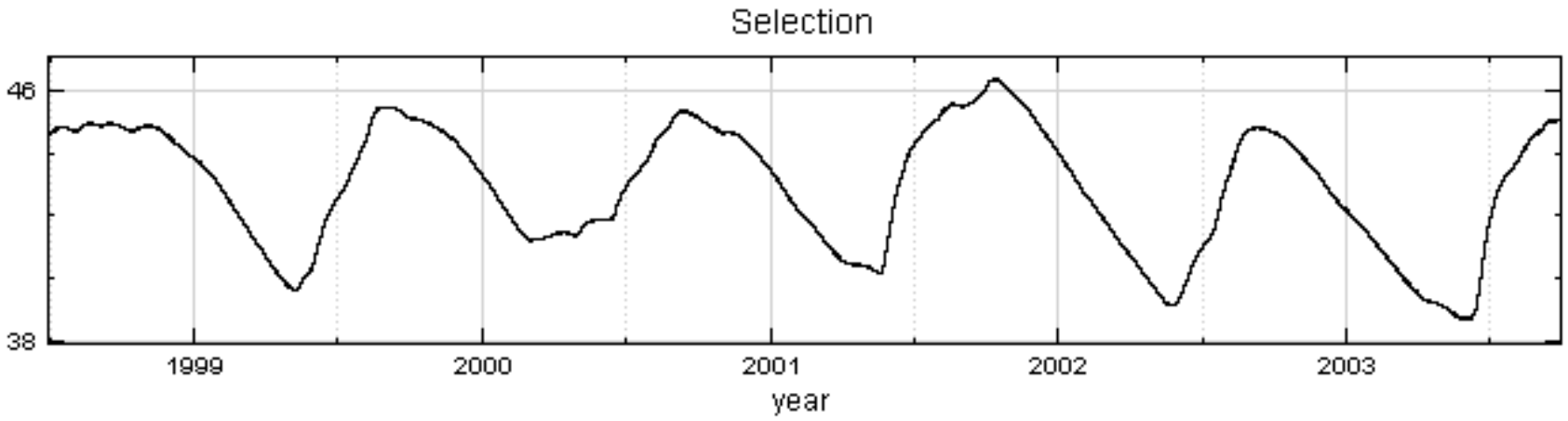
The frequency does not change seasonally. It appears nothing to do with precipitation. The centrifugal and centripetal forces from the Sun cause the semi-diurnal variation. Gravitational force from the Moon results in the monthly beat wave phenomena.

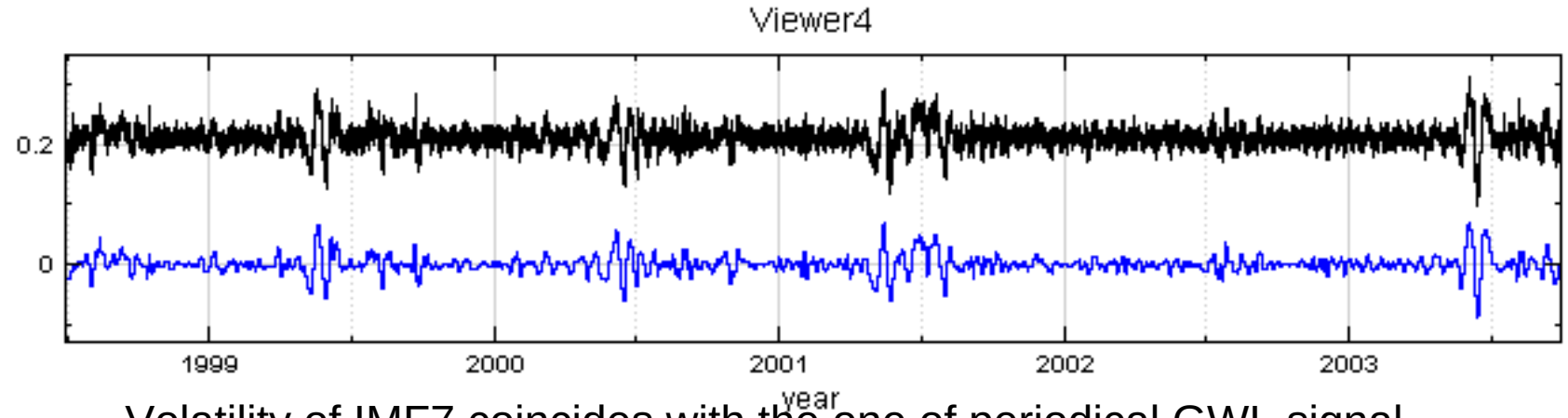
IMF5+IMF6: diurnal period



Note that in TF plot diurnal intensity varies with precipitation.
It might suggest diurnal frequency is caused by precipitate injection to the reservoir.

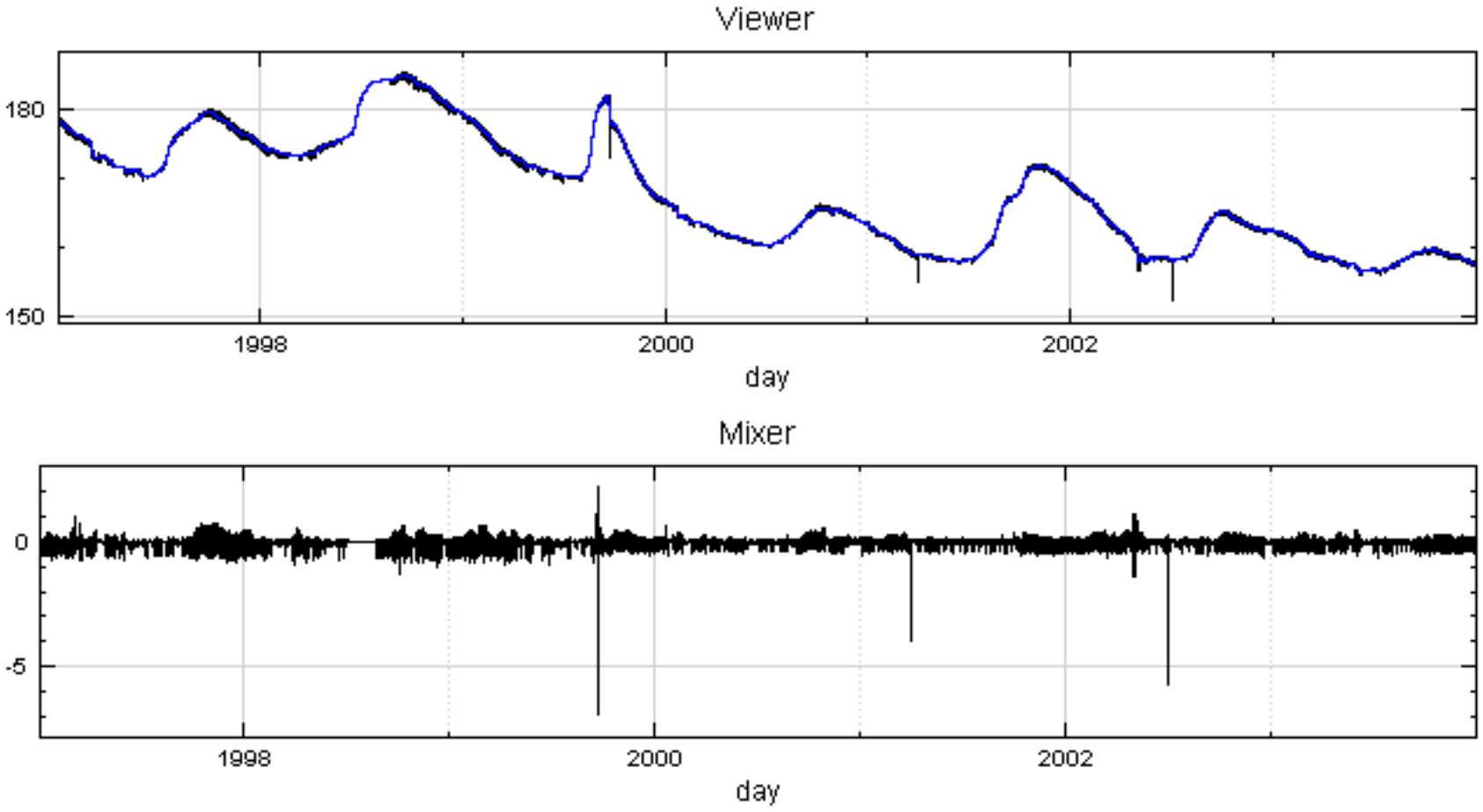
IMF7: precipitation



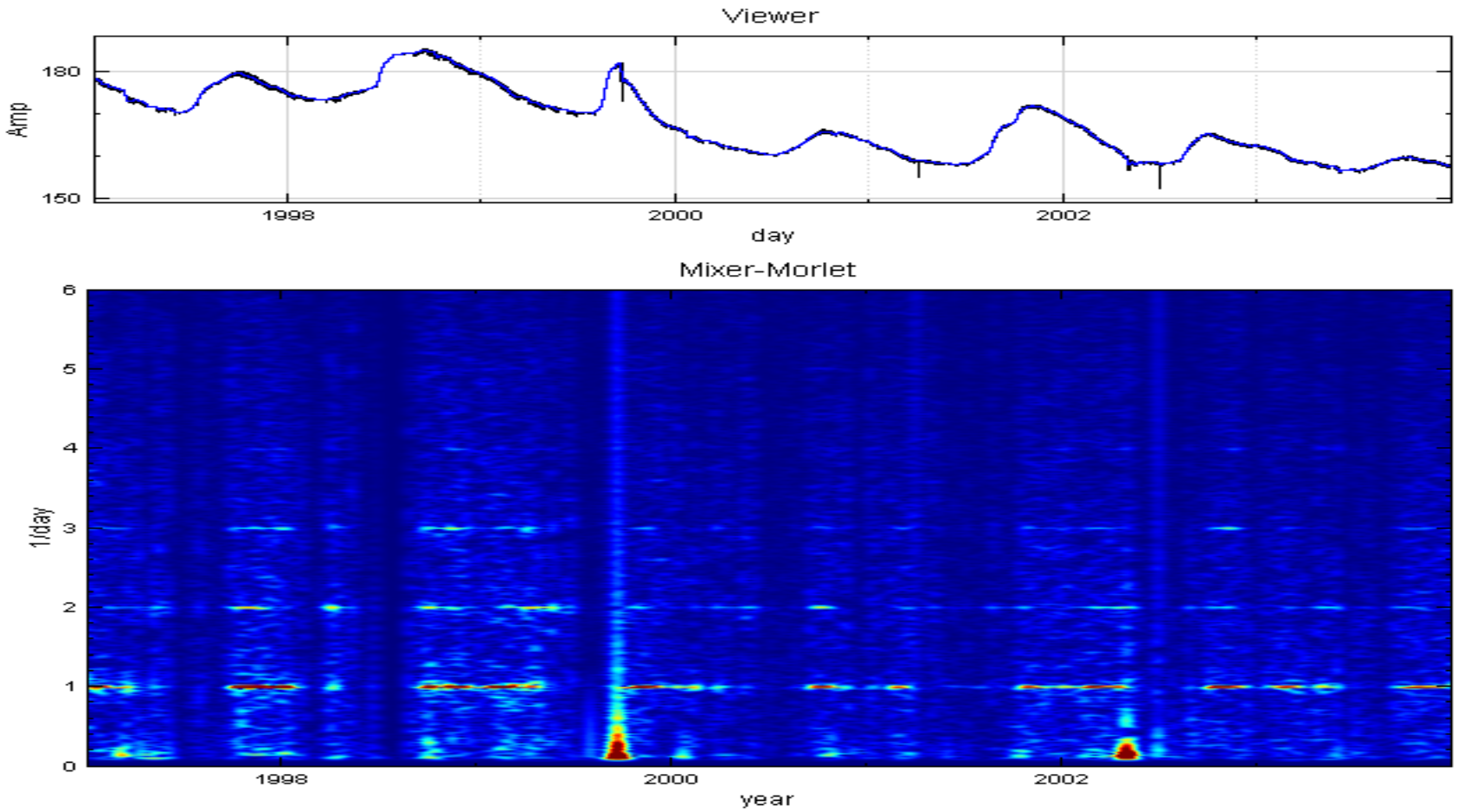


Volatility of IMF7 coincides with the one of periodical GWL signal. Increase of volatility correlates with the increase of GWL. This suggests IMF7 is related to precipitation which in this case is the major contribution to the raise of GWL.

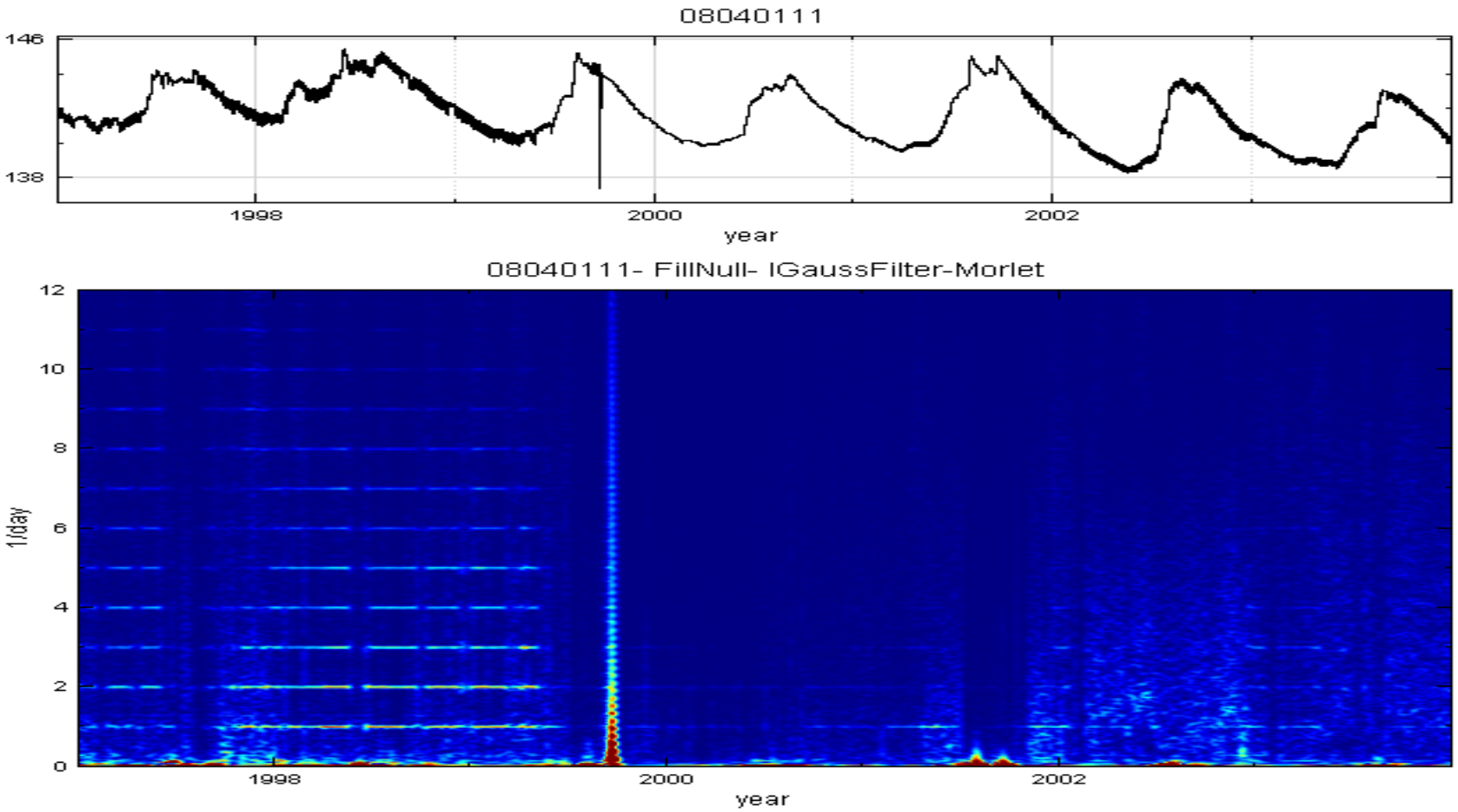
Well around Chi-Chi Earthquake (南投新光)



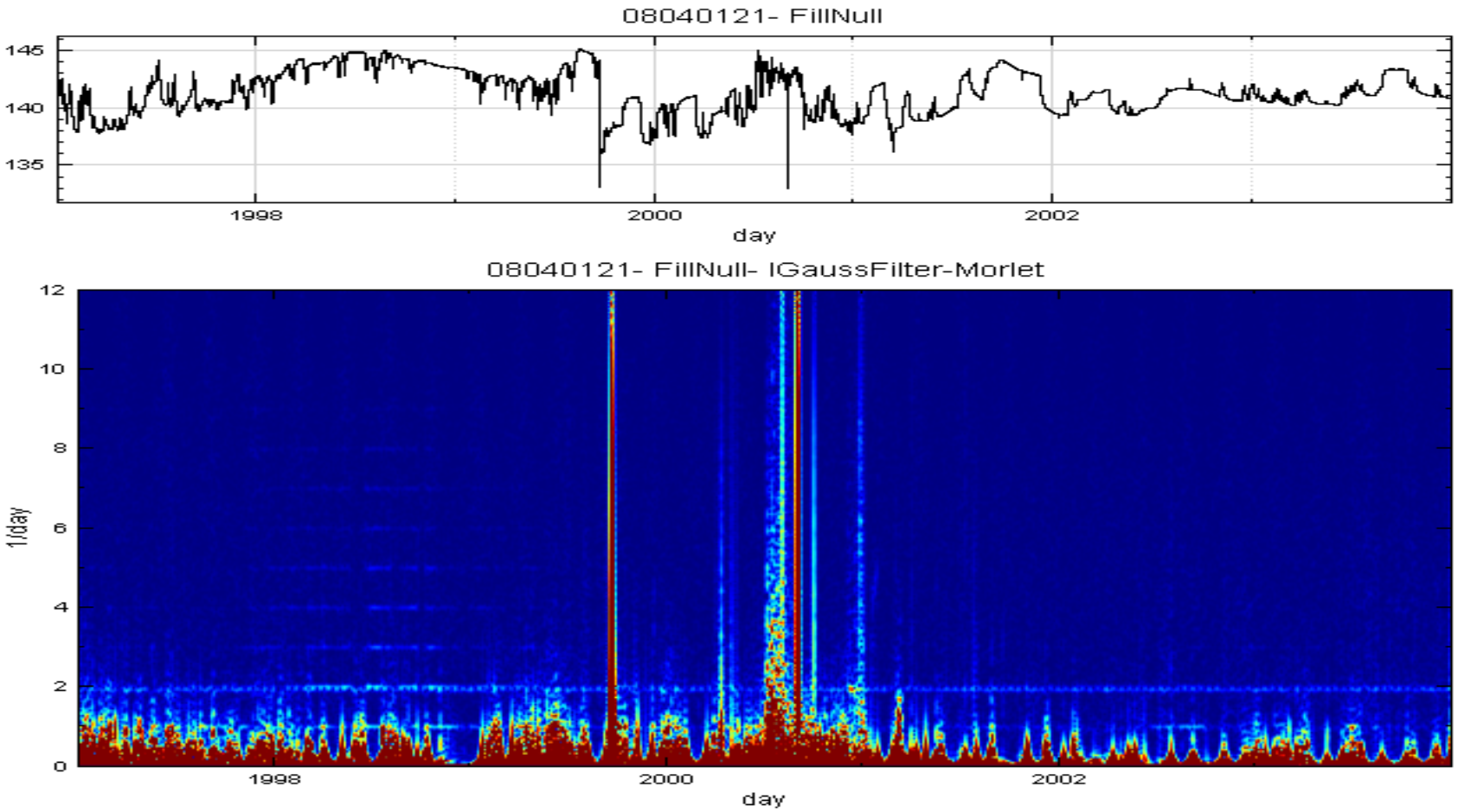
Well around Chi-Chi Earthquake (南投新光)



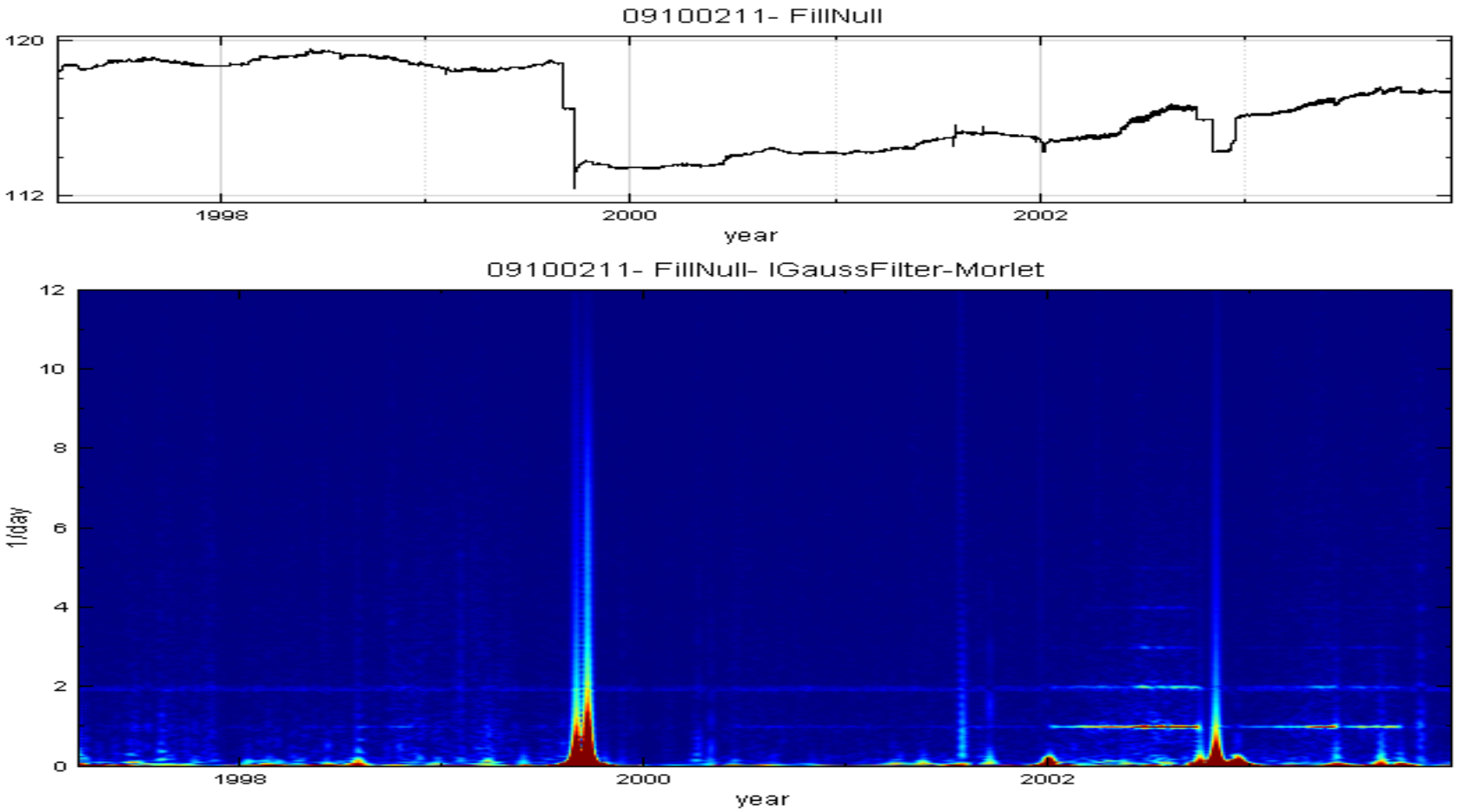
Well around Chi-Chi Earthquake (南投竹山(1))



Well around Chi-Chi Earthquake (南投竹山(1))



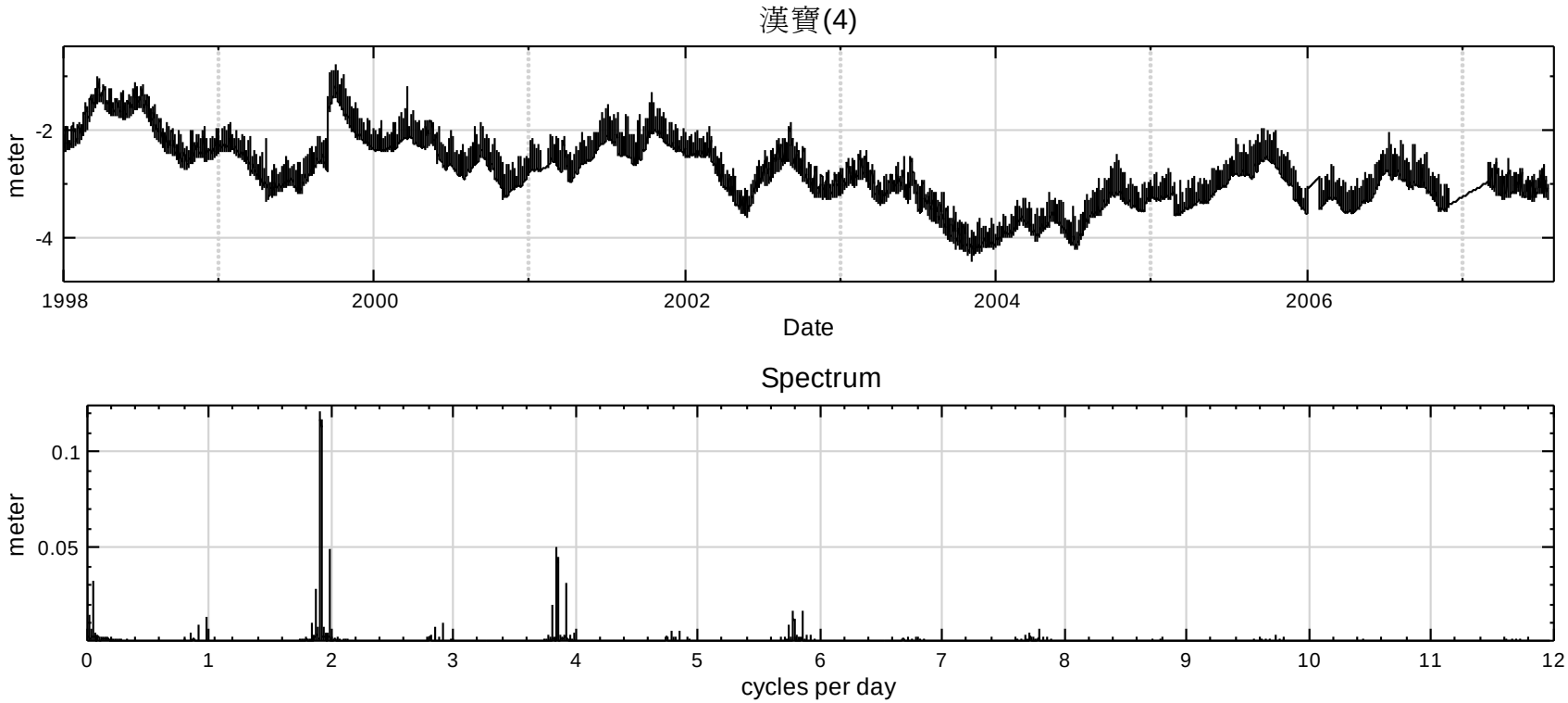
Well away from Chi-Chi Earthquake 雲林觸口(1)



Constitutes of GWL Signal

- Trend
- Anomaly: earthquake, data missing, equipment maintenance, etc.
- Stochastic: rainfall, recharging/discharging, pumping
- Periodical: pumping, earth tide, tectonic vibration

漢寶(4) (depth: -294m)

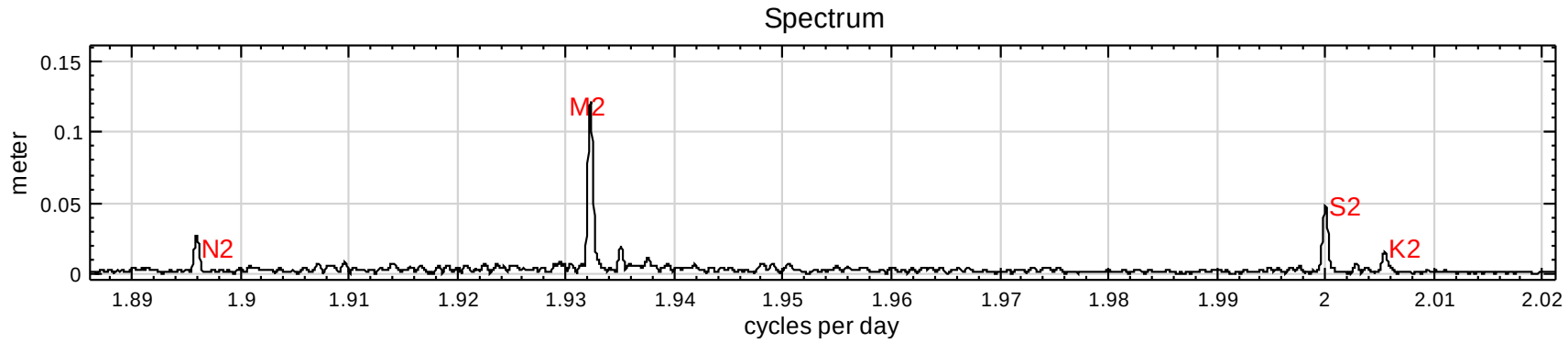


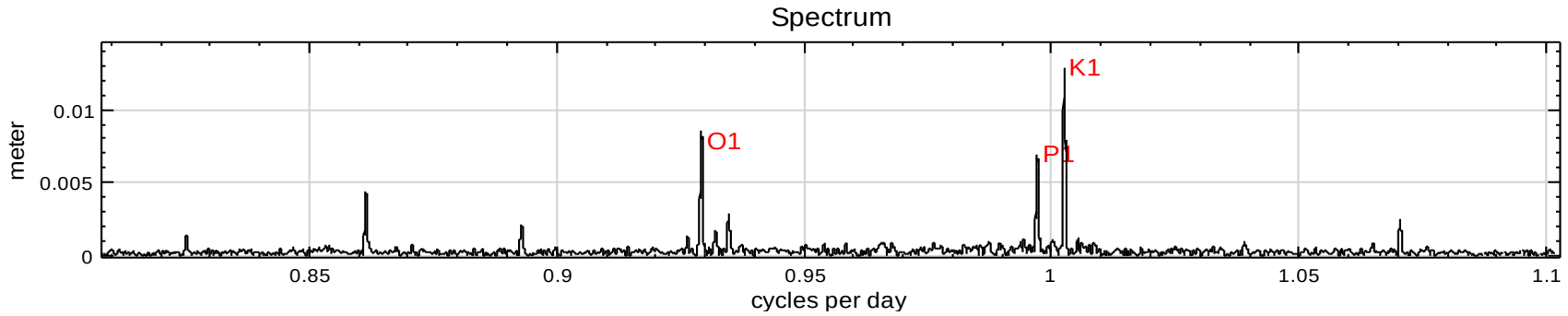
Principal body tide constituents*

Semi-diurnal			
Tidal constituent	**Period**	**Vertical amplitude (mm)**	**Horizontal amplitude(mm)**
M_2	12.421 hr	384.83	53.84
S_2	12.000 hr	179.05	25.05
N_2	12.658 hr	73.69	10.31
K_2	11.967 hr	48.72	6.82
[edit] Diurnal			
Tidal constituent	**Period**	**Vertical amplitude (mm)**	**Horizontal amplitude(mm)**
K_1	23.934 hr	191.78	32.01
O_1	25.819 hr	158.11	22.05
P_1	24.066 hr	70.88	10.36
φ_1	23.804 hr	3.44	0.43
ϕ_1	23.869 hr	2.72	0.21
S_1	24.000 hr	1.65	0.25
[edit] Long term			
Tidal constituent	**Period**	**Vertical amplitude (mm)**	**Horizontal amplitude(mm)**
M_f	13.661 days	40.36	5.59
M_m	27.555 days	21.33	2.96
S_{sa}	0.50000 yr	18.79	2.60
lunar node	18.613 yr	16.91	2.34
S_a	1.0000 yr	2.97	0.41

* from Wiki http://en.wikipedia.org/wiki/Earth_tide

Principal Body Tide Constituents in GWL Spectrum





Remarks

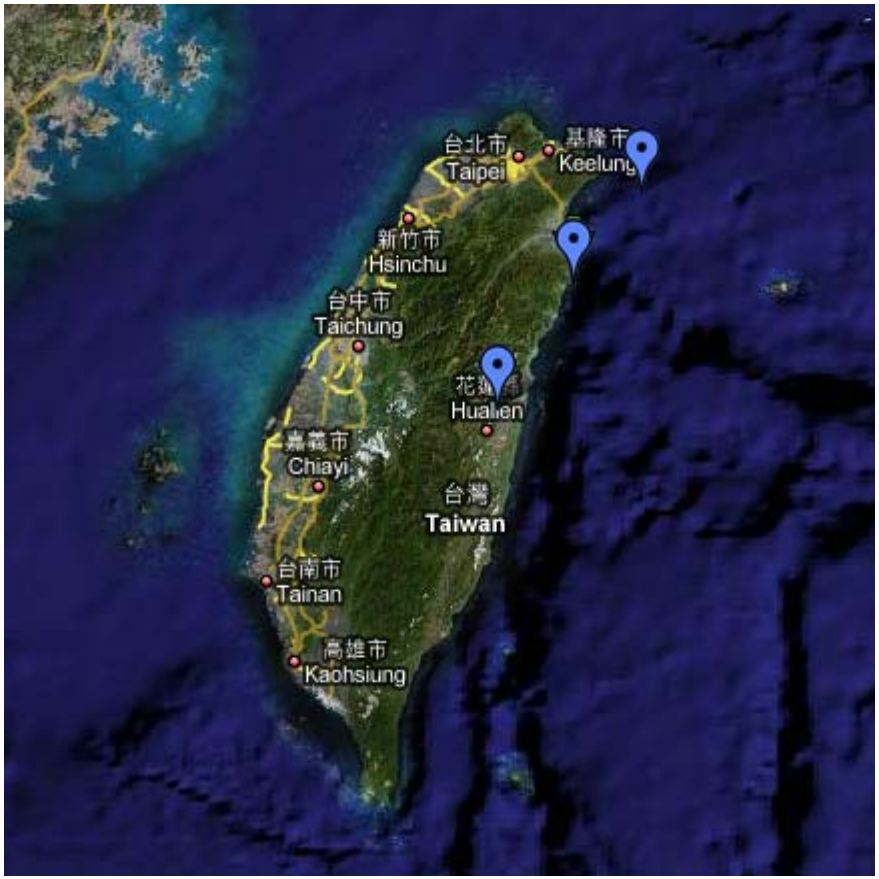
- Periodical GWL signal predicts well the earth tide of M2, S2, N2, K2, O1, K1, and P1. Frequencies meet almost identical to theoretical data.
- The spectrum shows no sign of coincidence to earth tide modes of small amplitude nor of long term period.
- Unidentified frequency suggests existence of other mechanism including diffusive fluid flowing within ground water.

HwaLien 2004/07/05-2004/07/15

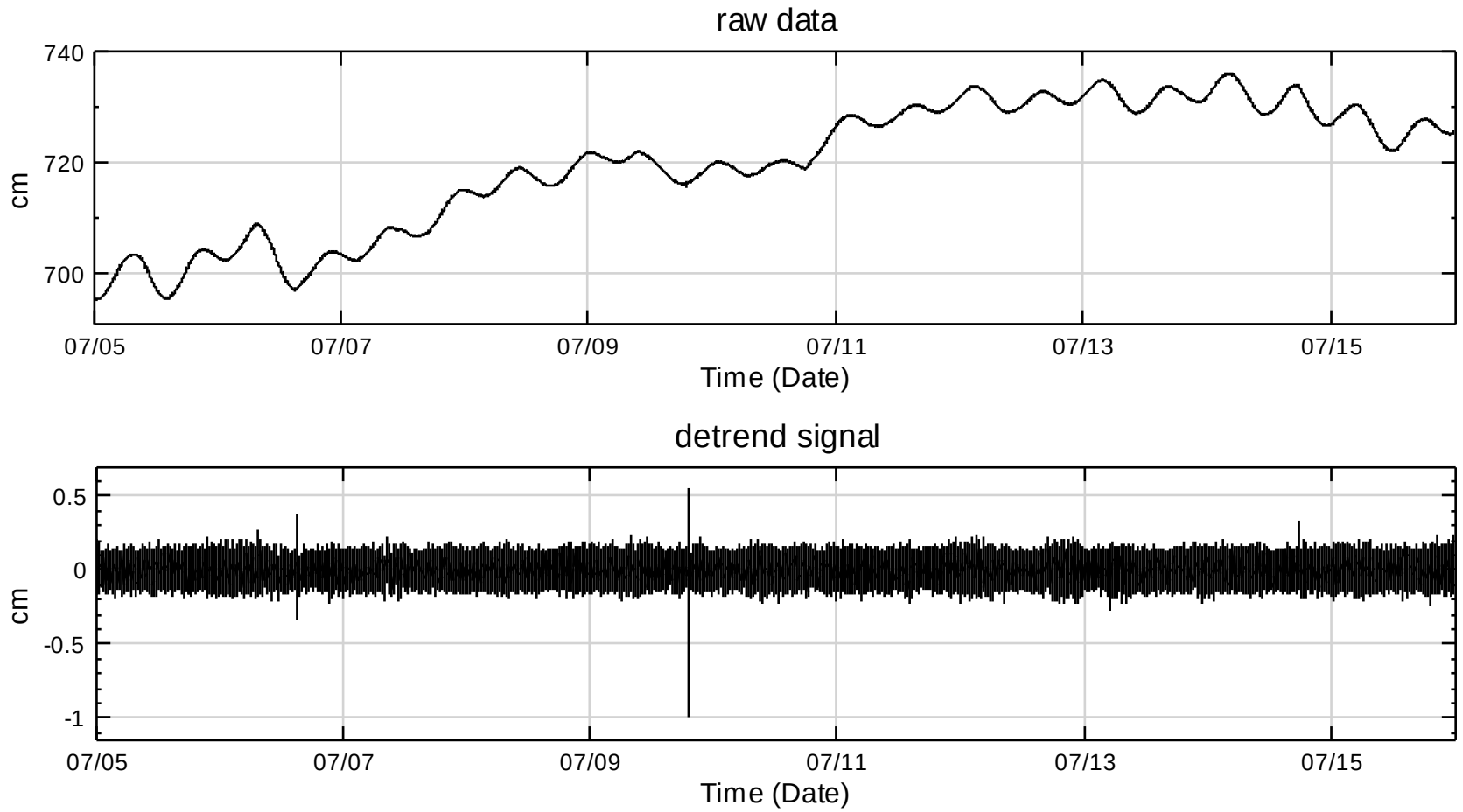
- 中央氣象局地震測報中心　第068號有感地震報告
- 發震　時　間：　93年 7月 6日15時32分 3.3秒
- 震　央　位　置　　北　緯　24.91°
- 　　東　經　122.22°
- 震　源　深　度：　9.8 公里
- 芮　氏　規　模：　5.8
- 相　對　位　置：　宜蘭蘇澳地震站東北方 49.7 公里

- 中央氣象局地震測報中心　第069號有感地震報告
- 發　震　時　間：　93年 7月 9日19時19分29.2秒
- 震　央　位　置：　北　緯　23.86°
- 　　東　經　121.43°
- 震　源　深　度：　19.5 公里
- 芮　氏　規　模：　4.8
- 相　對　位　置：　花蓮西林地震站北　方 5.6 公里

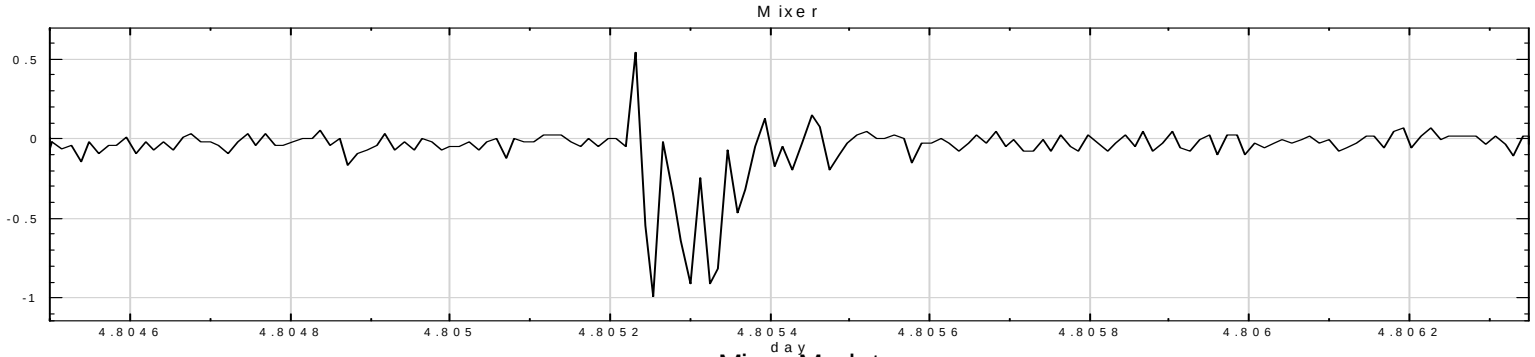
- 中央氣象局地震測報中心　第070號有感地震報告
- 發　震　時　間：　93年 7月11日21時10分47.3秒
- 震　央　位　置：　北　緯　24.47°
- 　　東　經　121.85°
- 震　源　深　度：　14.2 公里
- 芮　氏　規　模：　4.3
- 相　對　位　置：　宜蘭南澳地震站東偏北 12.0 公里

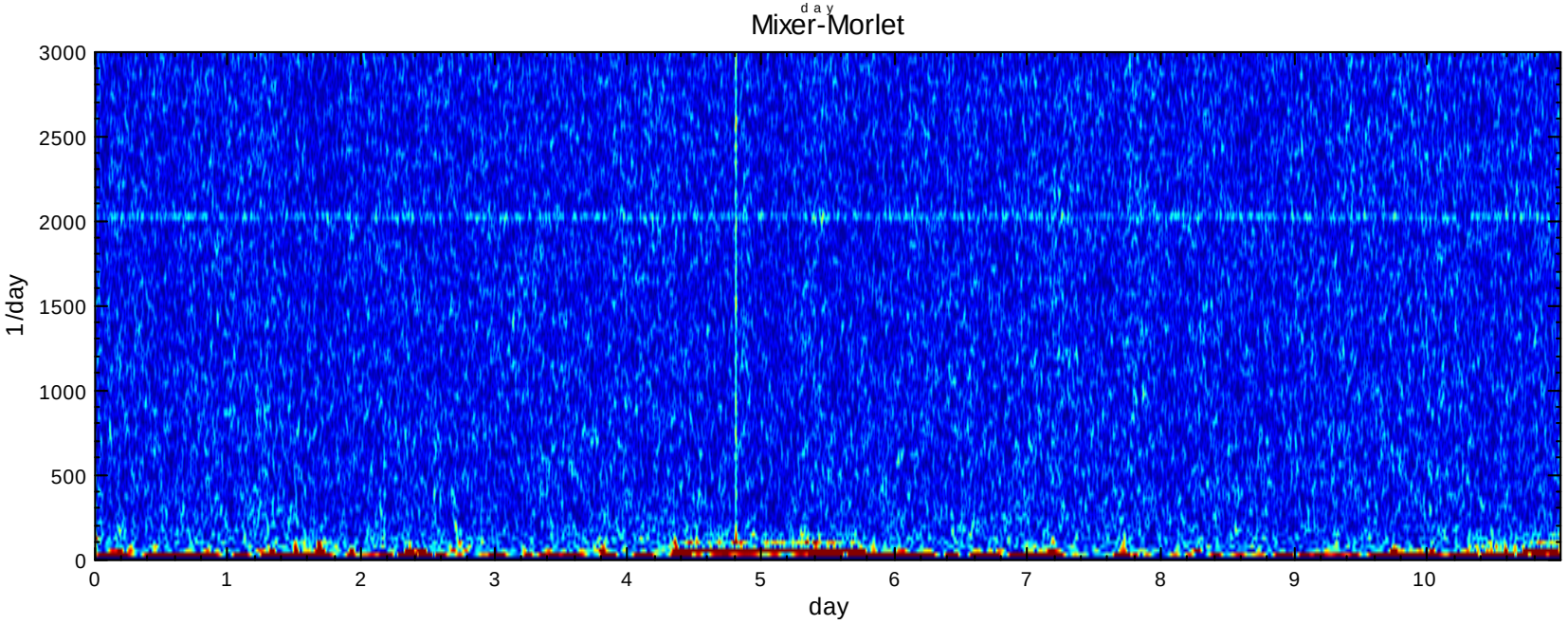


Signal and Trend Removal

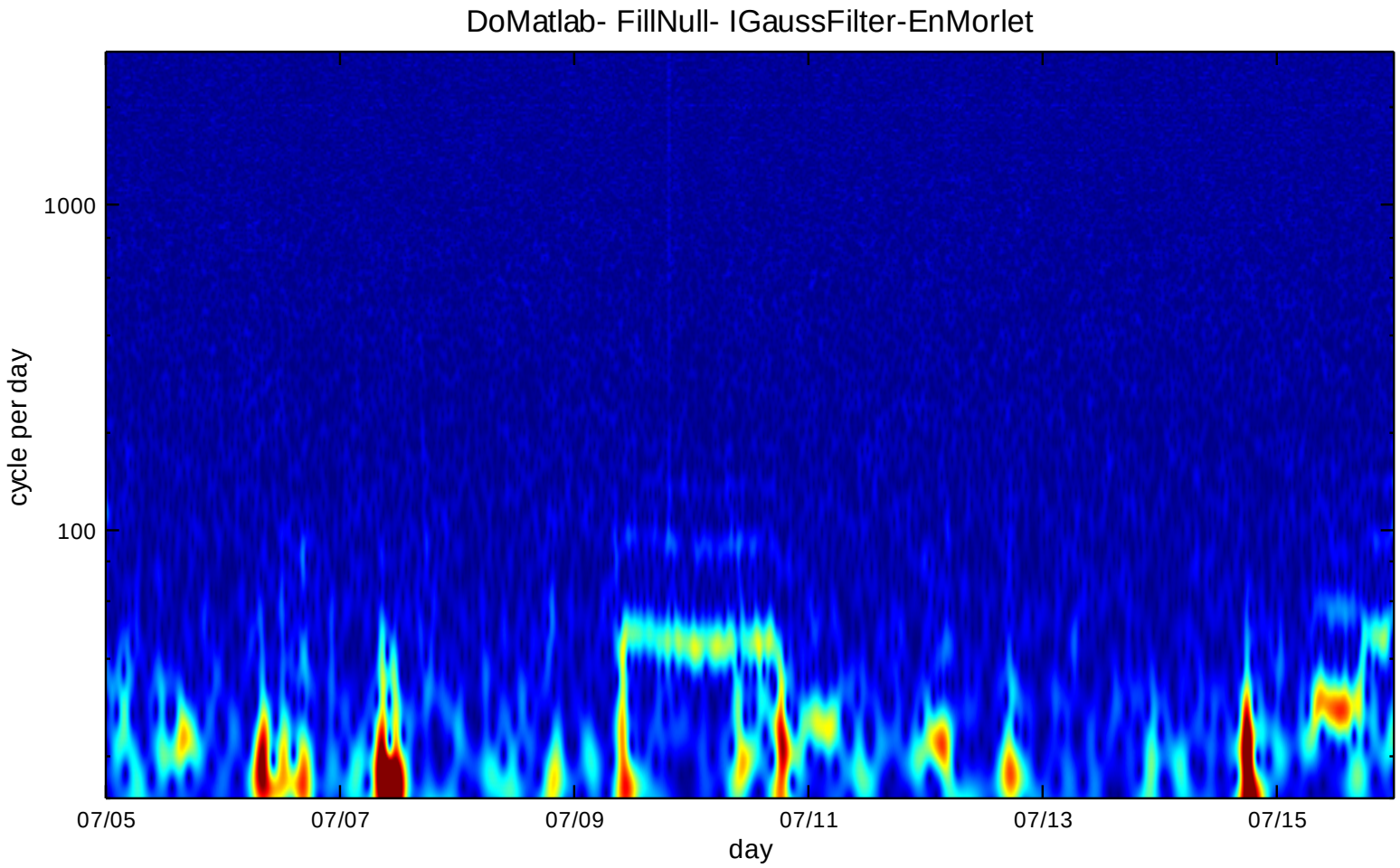


Precursor to Earthquake?

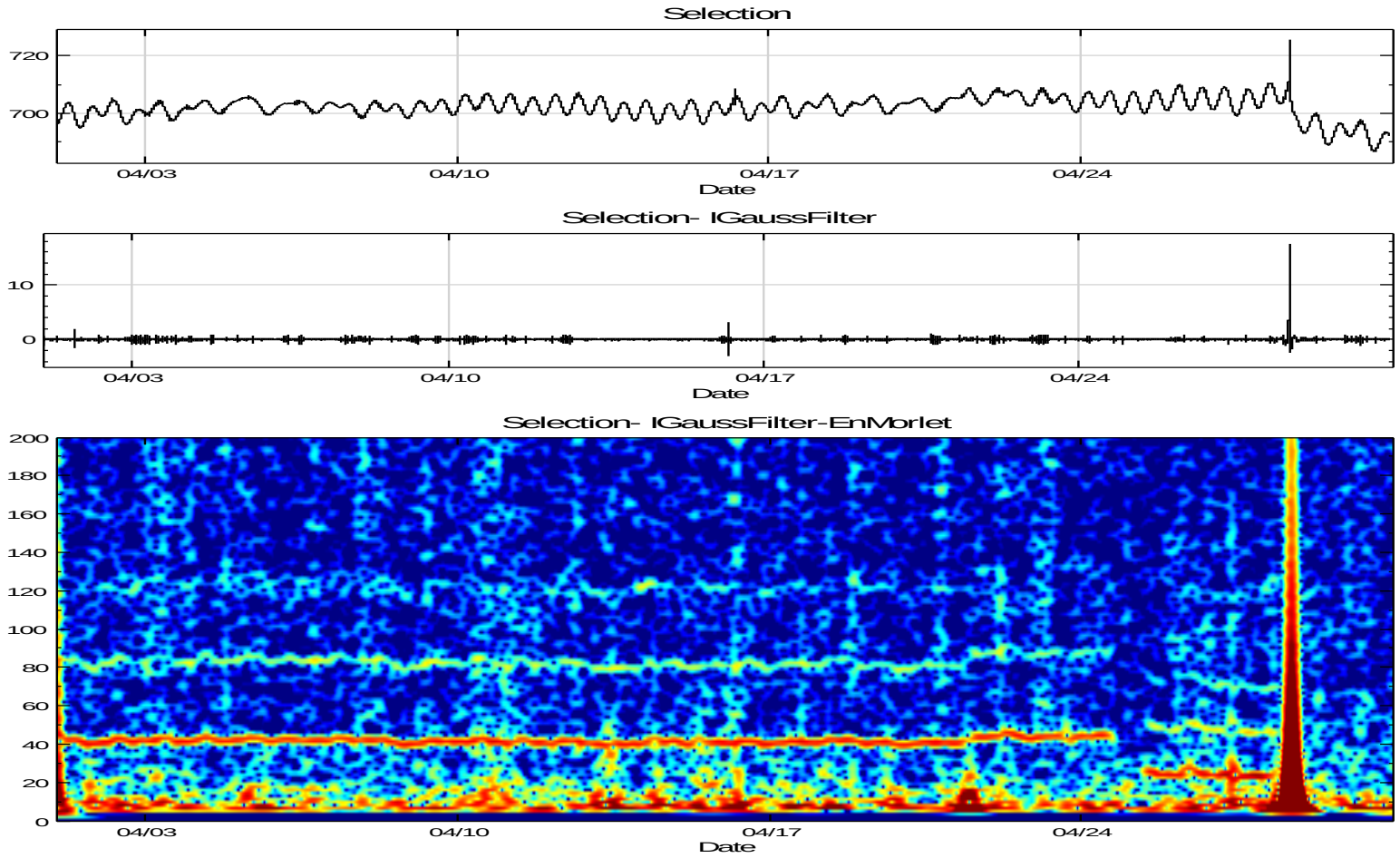




Time-Frequency Plot



April, 2006


Selection
720
700
04/03
04/10
04/17
04/24
Date
Selection- IGaussFilter
10
0
04/03
04/10
04/17
04/24
Date
Selection- IGaussFilter-EnMorlet
200
180
160
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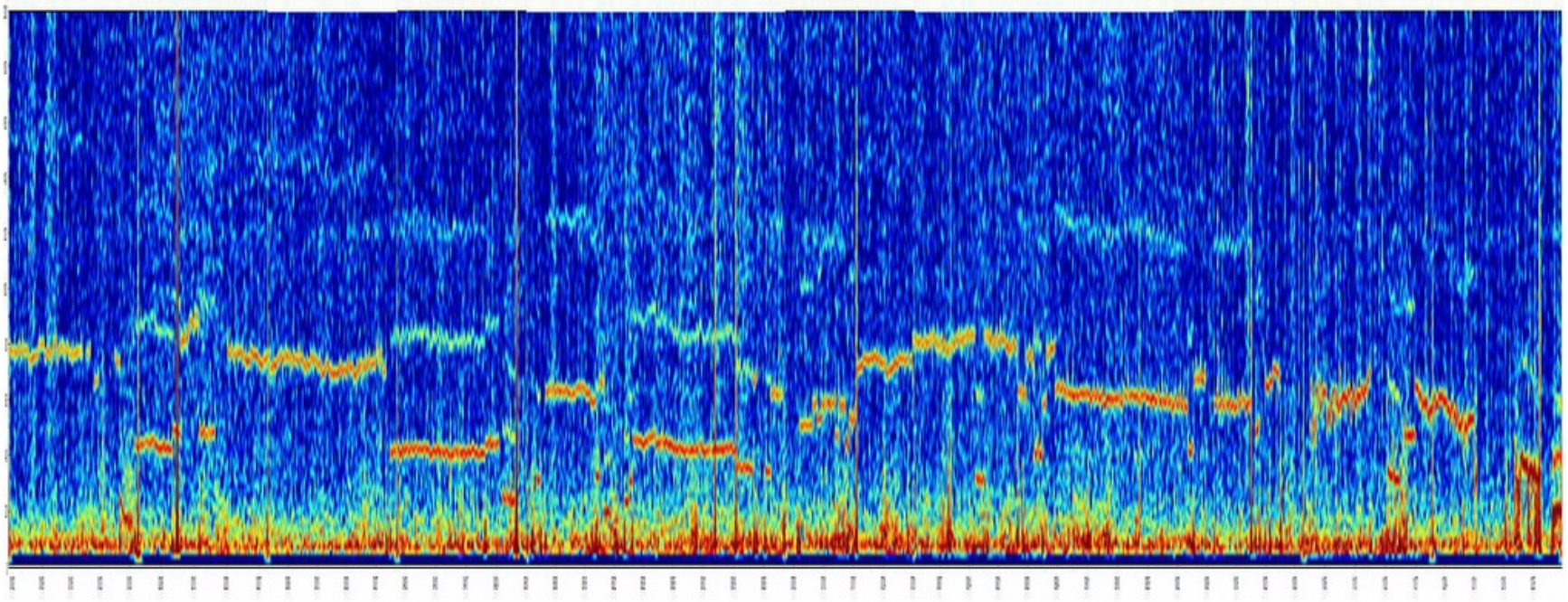
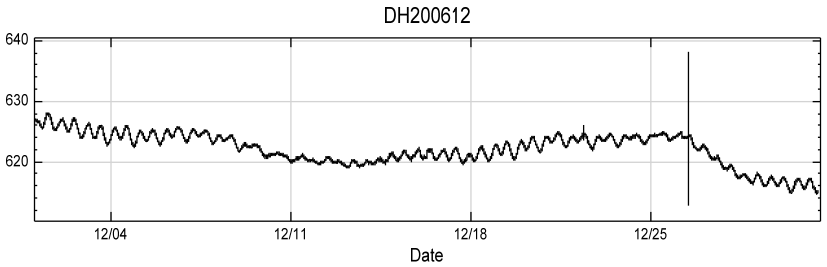
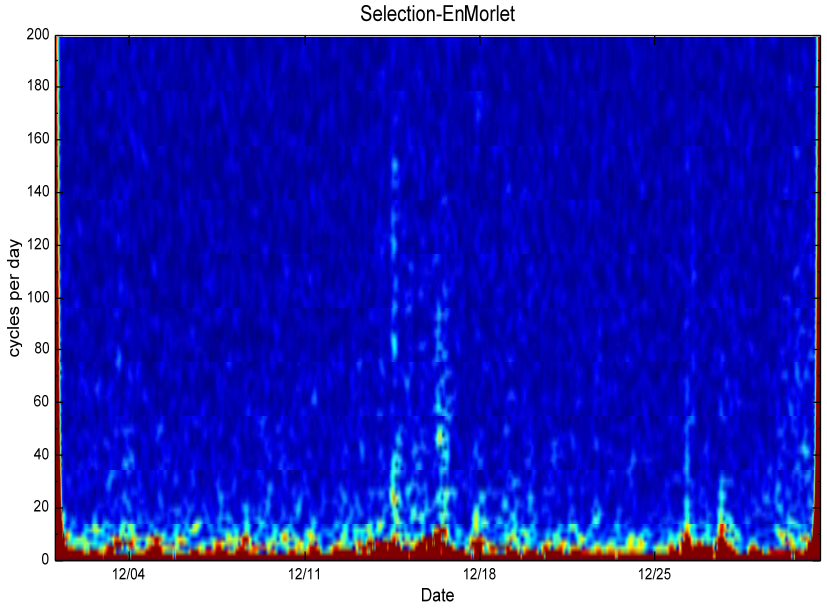
20
0
04/03
04/10
04/17
04/24
Date

HwaLien 2006



Remark





- Well DonHer does not show similar oscillation.

Conjectures to the Oscillation of GWL

- Elastic rebound theory (H. F. Reid, 1906)
- Flexual motion of elastic tectonic plate: Oscillation of plate is subjective to different boundary conditions, primarily due to the asthenosphere or the Earth Tide.
- Seismo-Gravational Oscillation (L. N. Petrova, 1988) : regular oscillation of the Earth with periods 0.2-6 hours.

Some Calculation

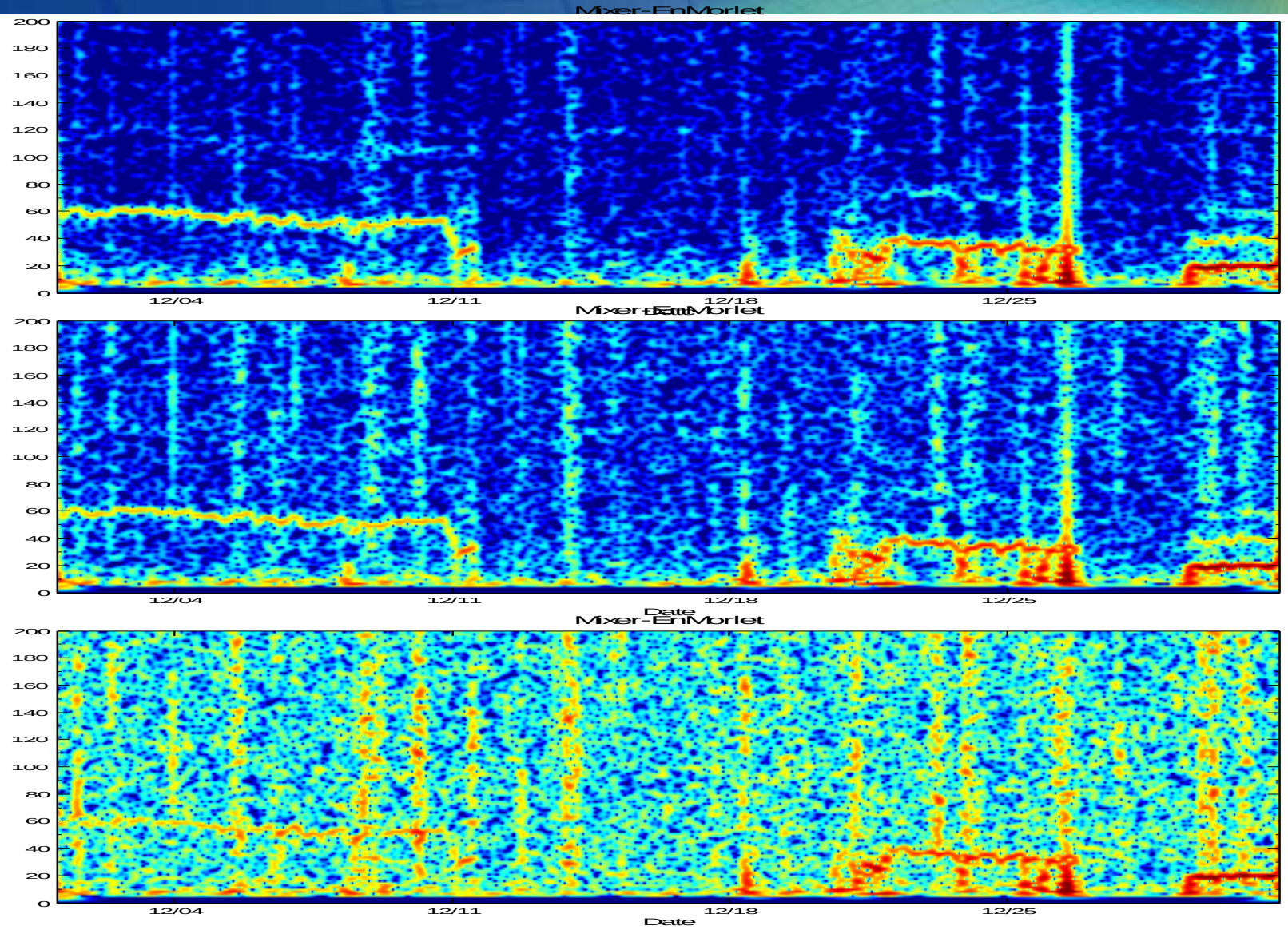
- Classical plate theory
- Neumann boundary condition
- Young’s modulus: 17.28E10 kg/(m*sec^2)
- Density : 3380 kg/m^3
- Thickness : 700 km
- Plate size: 2300 * 2300 km^2
- Poisson’s ratio: 0.28

=> first mode of oscillation : 30 min

Suggested Criteria for Doing Time-Frequency Analysis

- recorded length: over 10000 points in total.
- Bit rate: more than 8 bits.
- Sampling rate/Data Length:
  - Once per day => 24 years
  - Once per hour => 1 year
  - Once per minute => 1 week
  - Once per second => 3 hours
  - Vice versa…

Down sampled (2sec,10sec,100sec)



Summary

- Time-frequency analysis provides insightful information related to recharge, precipitation, earth tide, and event anomaly.
- In some cases, EMD (Empirical Mode Decomposition) can be used to separate earth tide. The strength of earth tide might serve as an indicator to the size of ground water reservoir.
- The abrupt rise of GWL without recharge nor daily pumping harmonics suggests abnormal water injection to reservoir. It is worthy of further investigation to see if it is a precursor to earthquake.
- Oscillation of GWL in HwaLien shows correlation to tectonic plate vibration which might be an indicator to internal stress of the plate.
- All the analysis is done using Visual Signal of AnCAD.

Acknowledgement

- 氣象局： 蔡俊雄課長，趙曉玲，宋馥淇
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- 台大水工：譚義績主任，李天浩教授
- 中研院：汪中和教授，陳界宏博士
- 成大航太：鄭育能教授
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