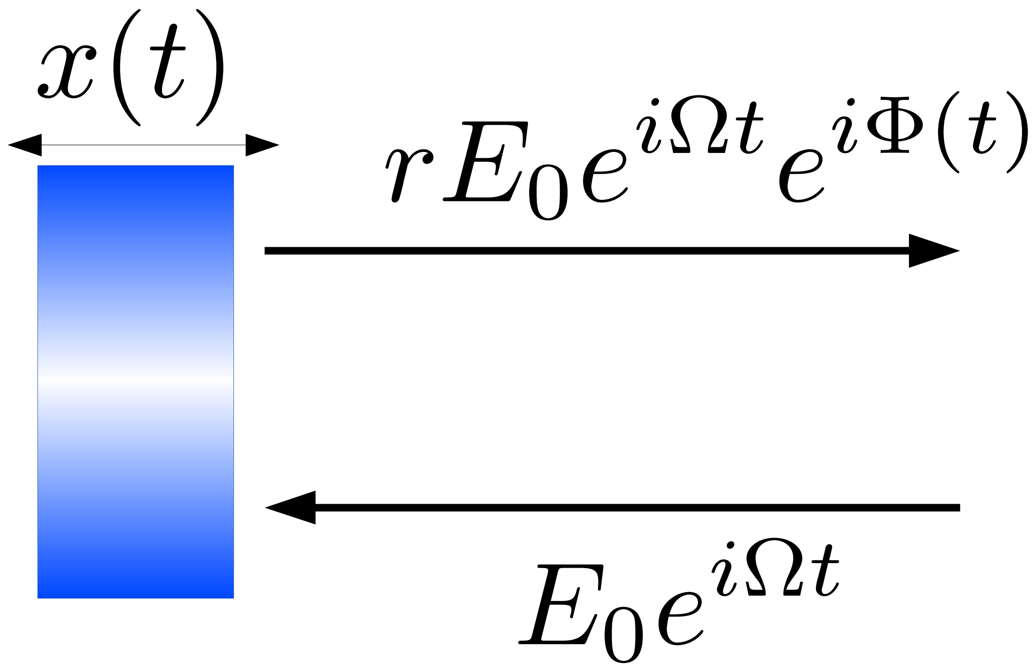
Scattered Light Workshop at GEO600

2013/7/17 Yoichi Aso

2013/6/10 – 6/15　　参加者 KAGRA:2, LIGO: 3, Virgo: 8, GEO: 多数

散乱光雑音の基礎

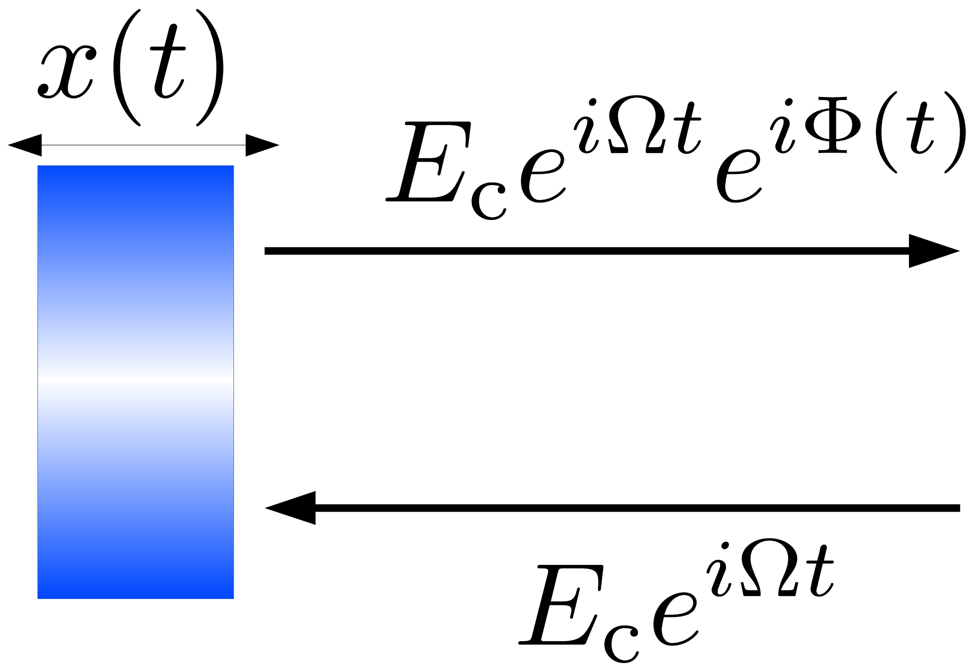
反射光の受ける位相変化



$$\Phi(t) = 2kx(t)$$

重力波信号の場合

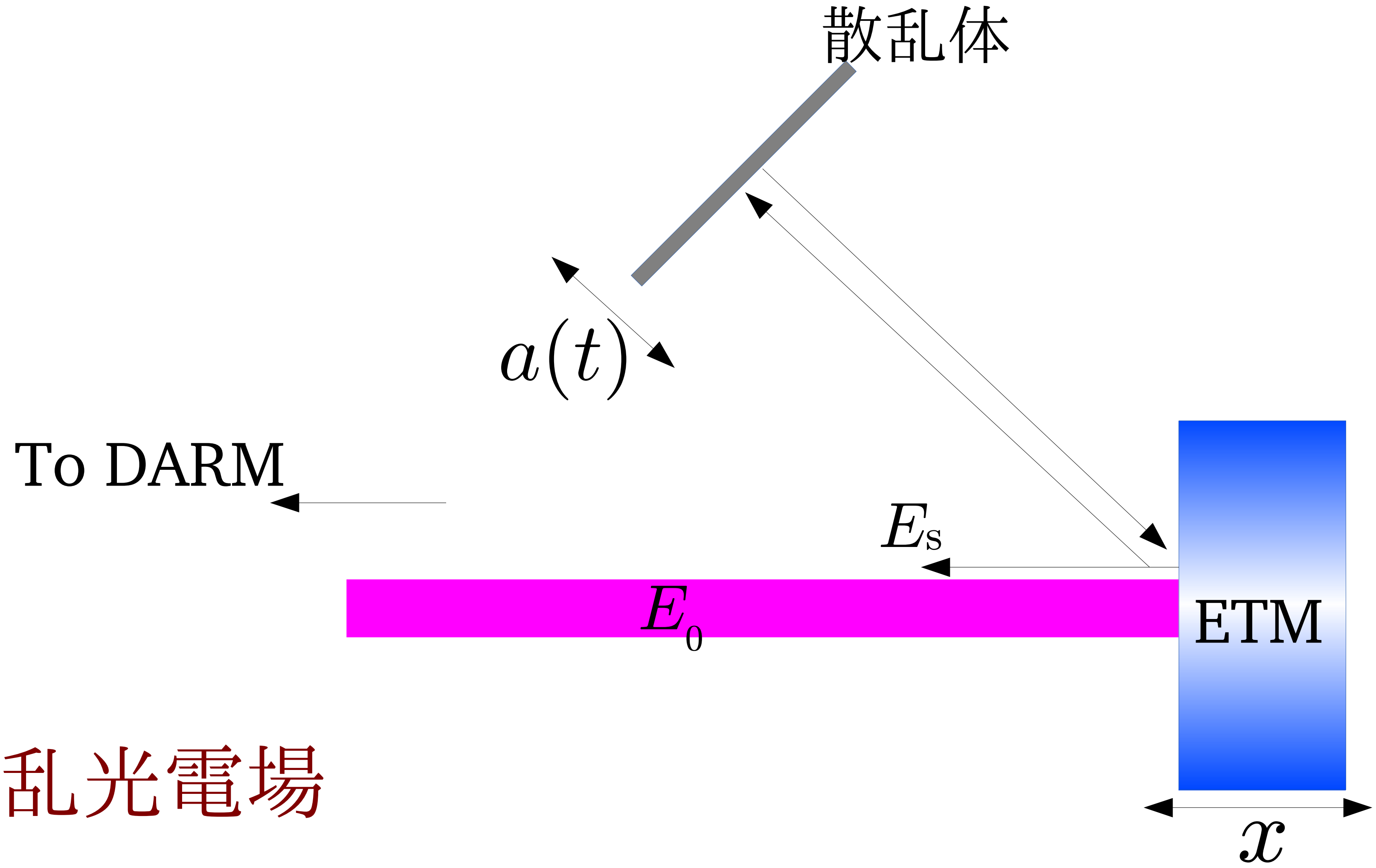
$$x(t) = L \cdot h(t)$$



$$\Phi(t) = 2kx(t)$$

$$E_\mathrm{c} e^{i\Omega t} e^{i\Phi(t)} = E_\mathrm{c} e^{i\Omega t} \cdot \{1 + i2kLh(t)\}$$

散乱光の場合



散乱光電場

$$E_{\mathrm{s}} e^{i\Omega t} e^{i\Phi(t)} = E_{\mathrm{s}} e^{i\Omega t} \{\cos[\Phi(t)] + i \sin[\Phi(t)]\}$$

$$\Phi(t) = 2ka(t)$$

重力波

$$E_{\rm c} e^{i\Omega t} \cdot \{1 + i2kLh(t)\}$$

散乱光

$$E_{\rm s} e^{i\Omega t}\{\cos[\Phi(t)] + i\sin[\Phi(t)]\}$$

重力波振幅等価散乱光雑音

$$h_{\rm sc}(t) = \frac{E_{\rm s}}{E_{\rm s}} \frac{\sin[\Phi(t)]}{2kL}$$

2つの問題

1. 時系列である　→　パワースペクトルが計算したい

2. 腕共振器以外で発生した散乱光の影響は?

重力波振幅等価散乱光雑音

$$h_{\mathrm{sc}}(t) = \frac{E_{\mathrm{s}}}{E_{\mathrm{c}}} \frac{\sin[\Phi(t)]}{2kL}$$

二つの問題

- 周波数領域で考えたい
- 腕共振器以外から入射した散乱光の影響は?

$$h_{\mathrm{sc}}(t) = \frac{E_{\mathrm{s}}}{E_{\mathrm{c}}} \frac{\sin[\Phi(t)]}{2kL}$$

散乱光の位相振幅が小さい場合

$$\Phi(t) << 1$$

単一周波数変動を考える

$$E_{\mathrm{s}} e^{i\Omega t} e^{i\Phi(t)} \qquad \Phi(t) = \hat{\Phi}(\omega)\sin(\omega t)$$

$$e^{i\hat{\Phi}(\omega)\sin(\omega t)} \simeq J_0(\hat{\Phi}) + iJ_1(\hat{\Phi})e^{i\omega t} + iJ_1(\hat{\Phi})e^{-i\omega t}$$

$$= J_0(\hat{\Phi}) + \underline{i2J_1(\hat{\Phi})\cos(\omega t)}$$

$$i\hat{\Phi}\cos(\omega t)$$

$$h_{\mathrm{sc}}(t) = \frac{E_{\mathrm{s}}}{E_{\mathrm{c}}} \frac{\sin[\Phi(t)]}{2kL}$$

$$\Downarrow$$

$$h_{\mathrm{sc}}(t) = \frac{E_{\mathrm{s}}}{E_{\mathrm{c}}} \frac{\hat{\Phi}(\omega)\cos(\omega t)}{2kL}$$

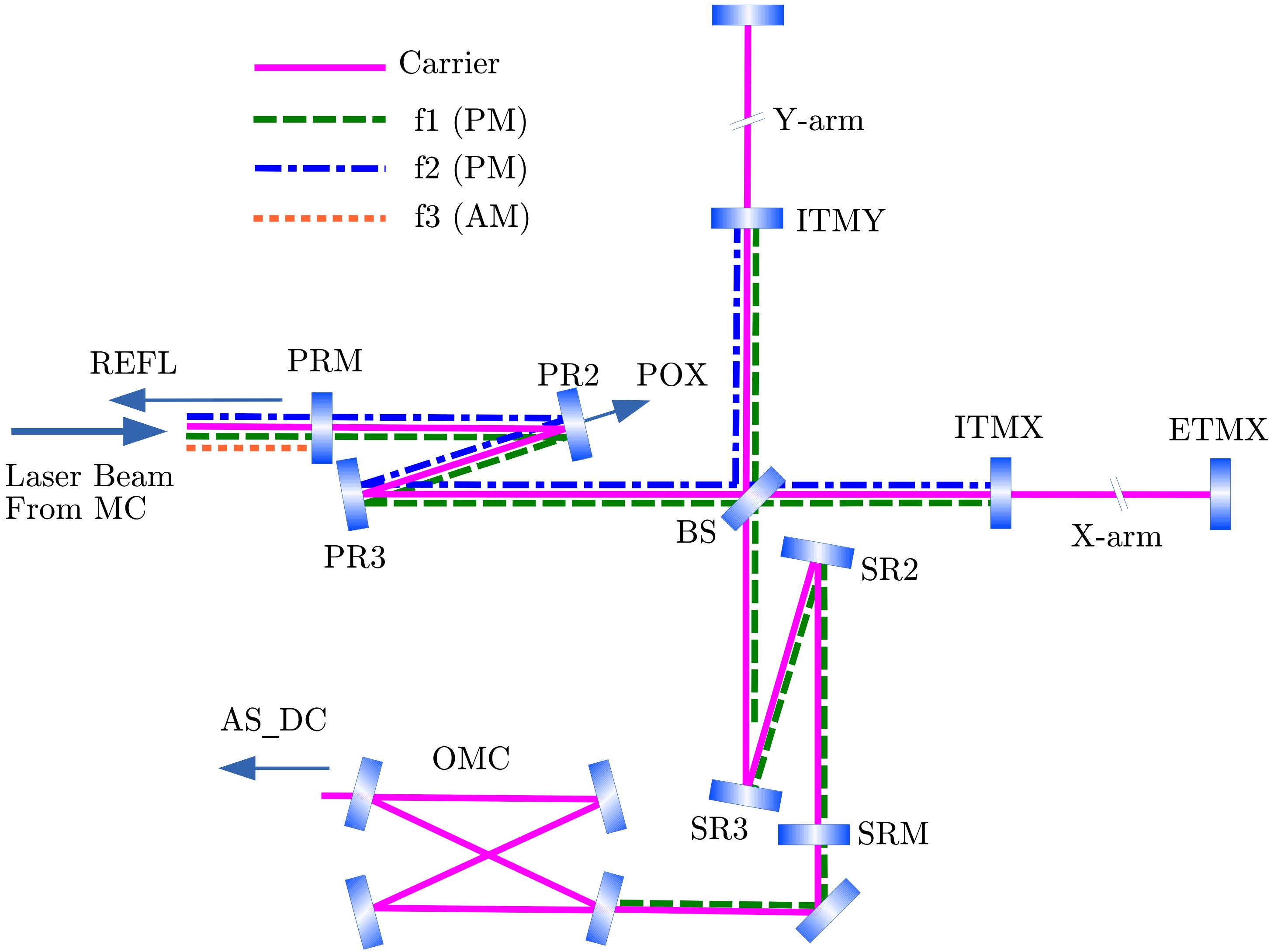
$$\Downarrow$$

$$\hat{h}_{\mathrm{sc}}(\omega) = \left| \frac{E_{\mathrm{s}}}{2kLE_{\mathrm{c}}} \right| \hat{\Phi}(\omega)$$

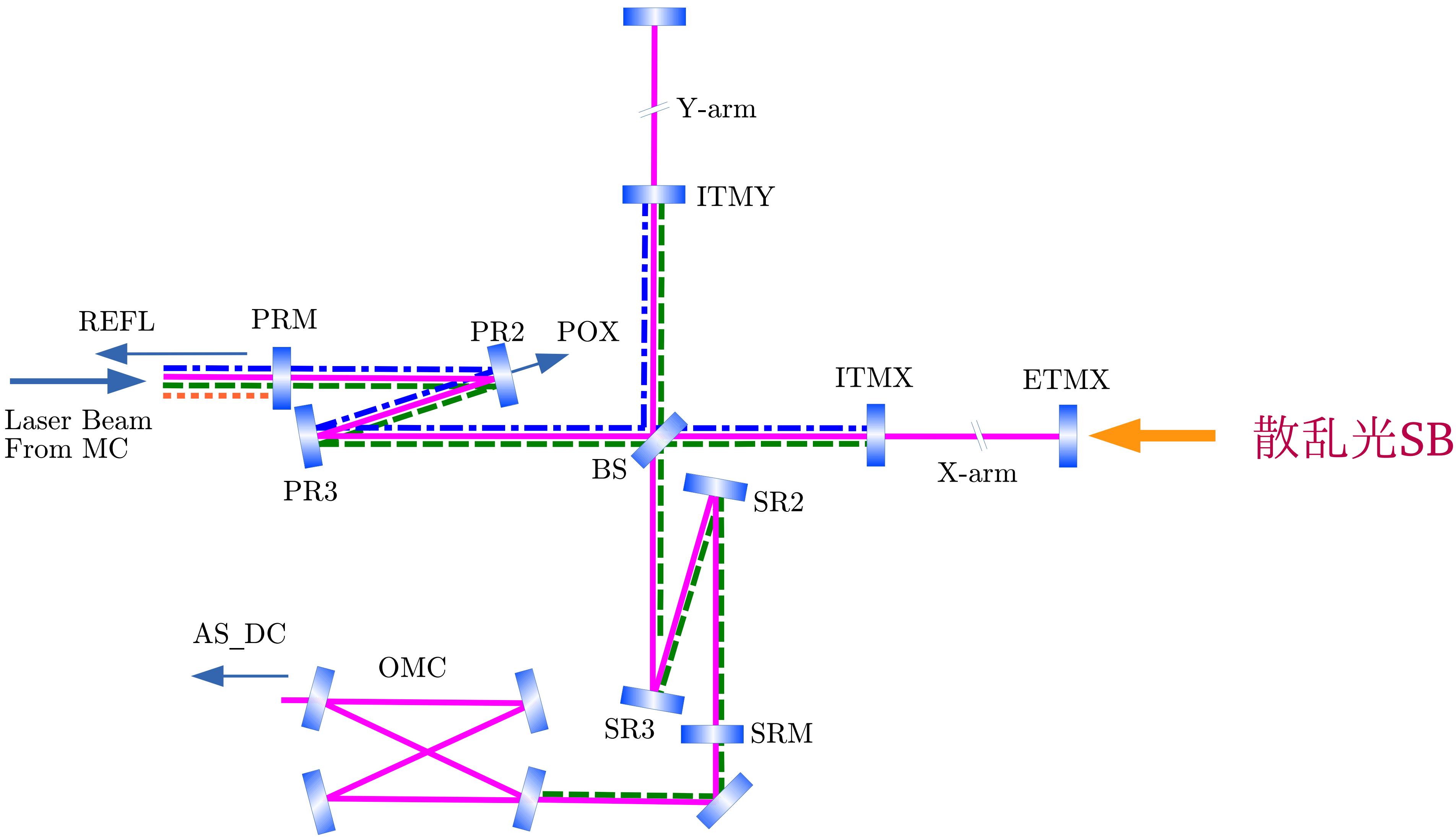
$$e^{i\hat{\Phi}(\omega)\sin(\omega t)} \simeq J_0(\hat{\Phi}) + iJ_1(\hat{\Phi})e^{i\omega t} + iJ_1(\hat{\Phi})e^{-i\omega t}$$

$\pm\omega$のサイドバンド

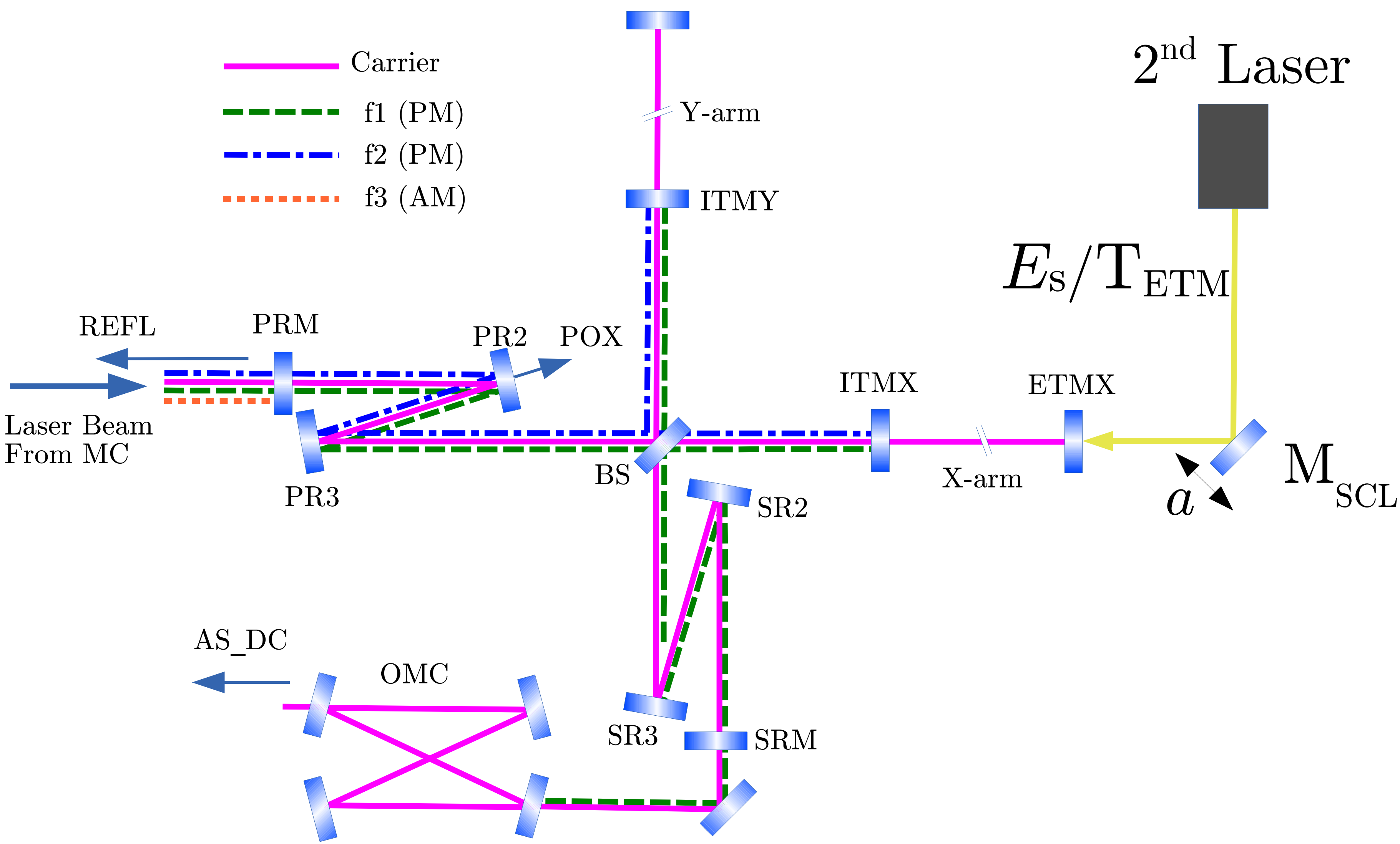
KAGRA Optickle Model

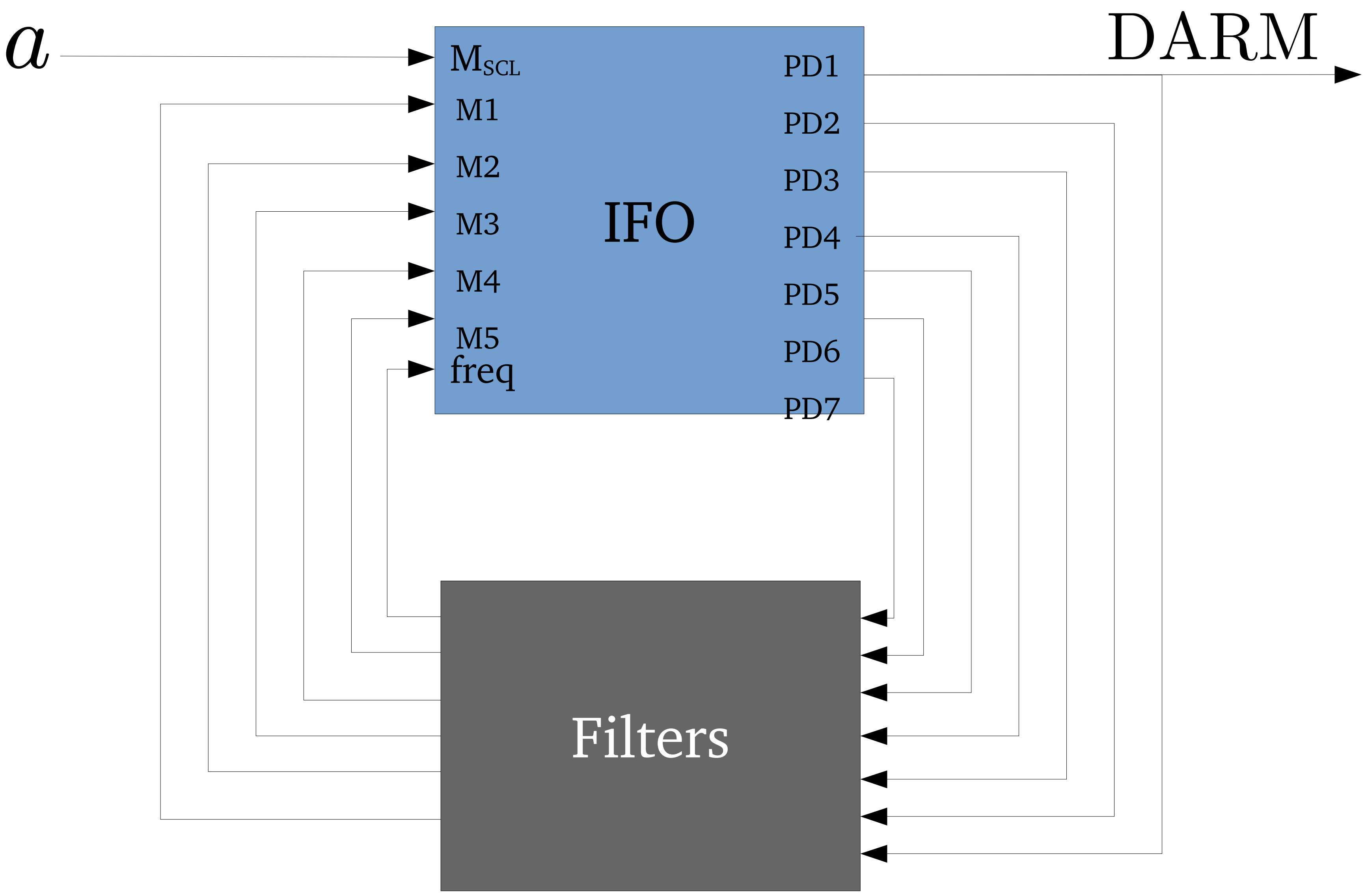


KAGRA Optickle Model



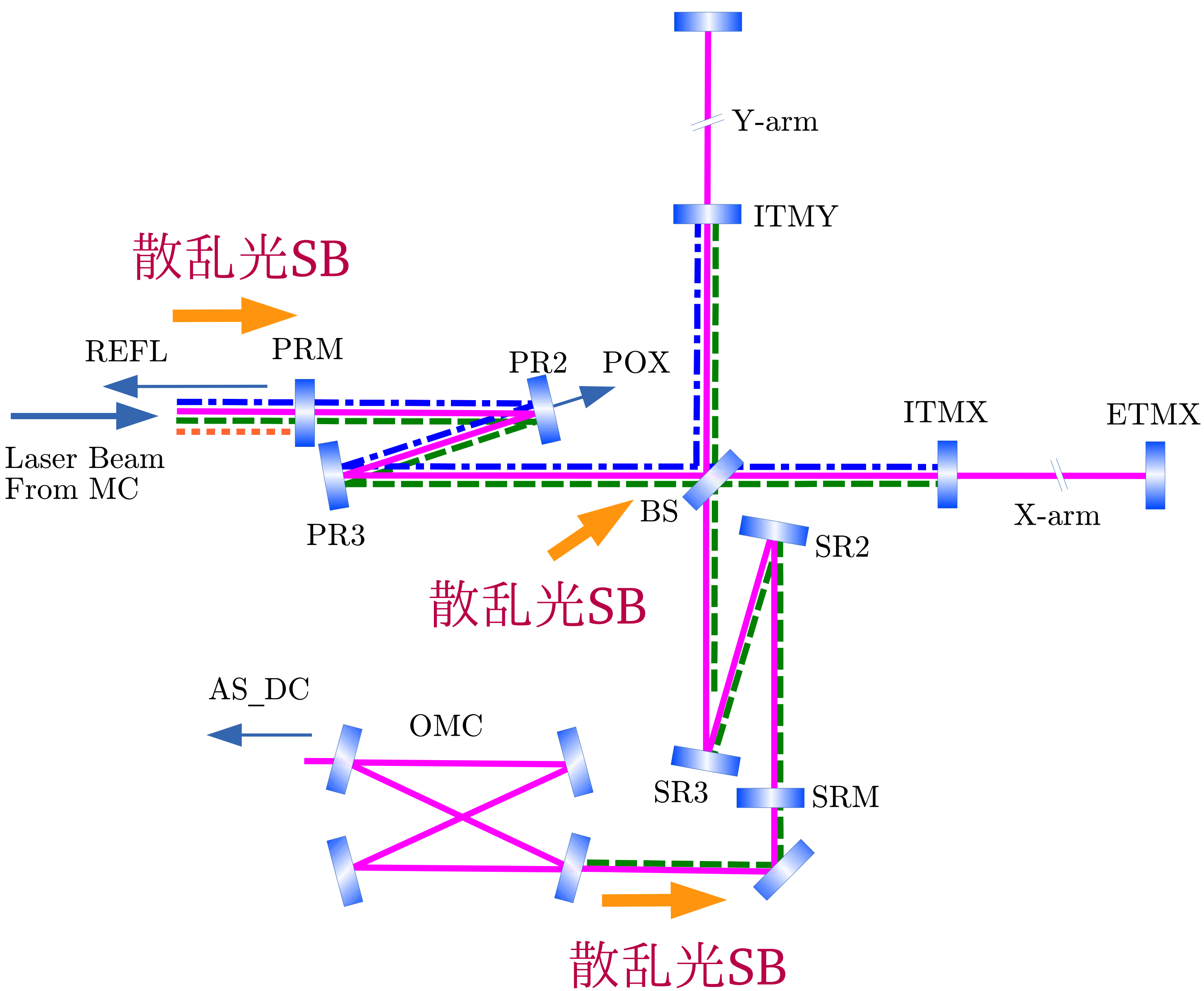
KAGRA Optickle Model



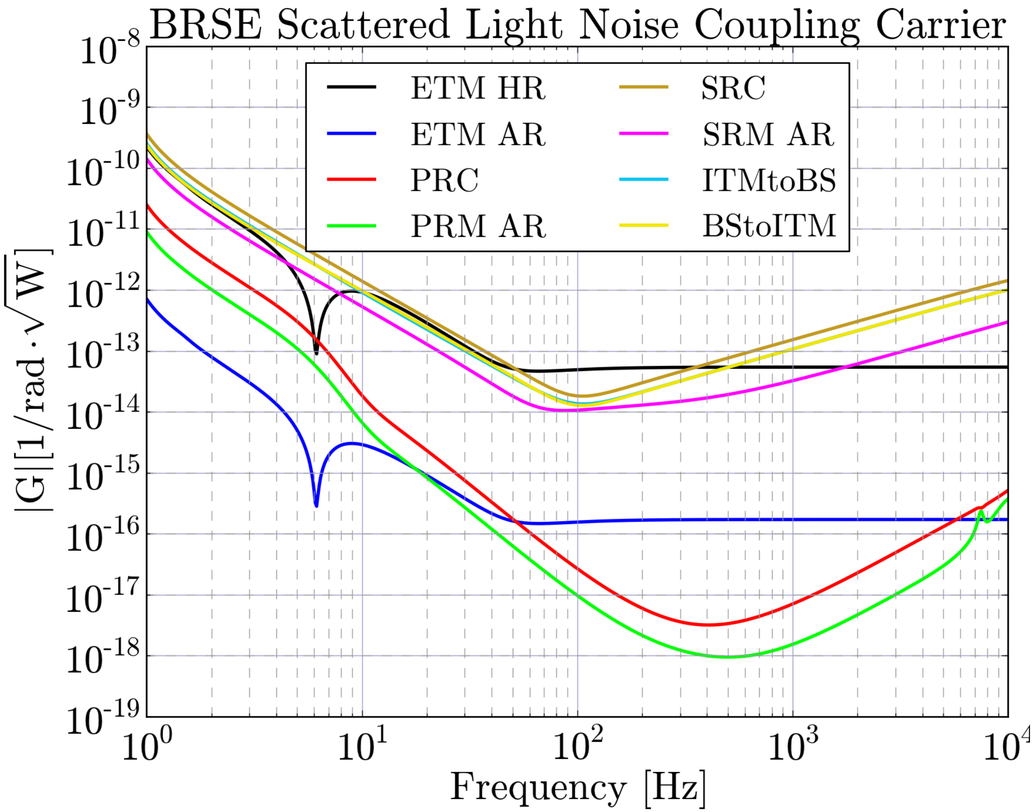


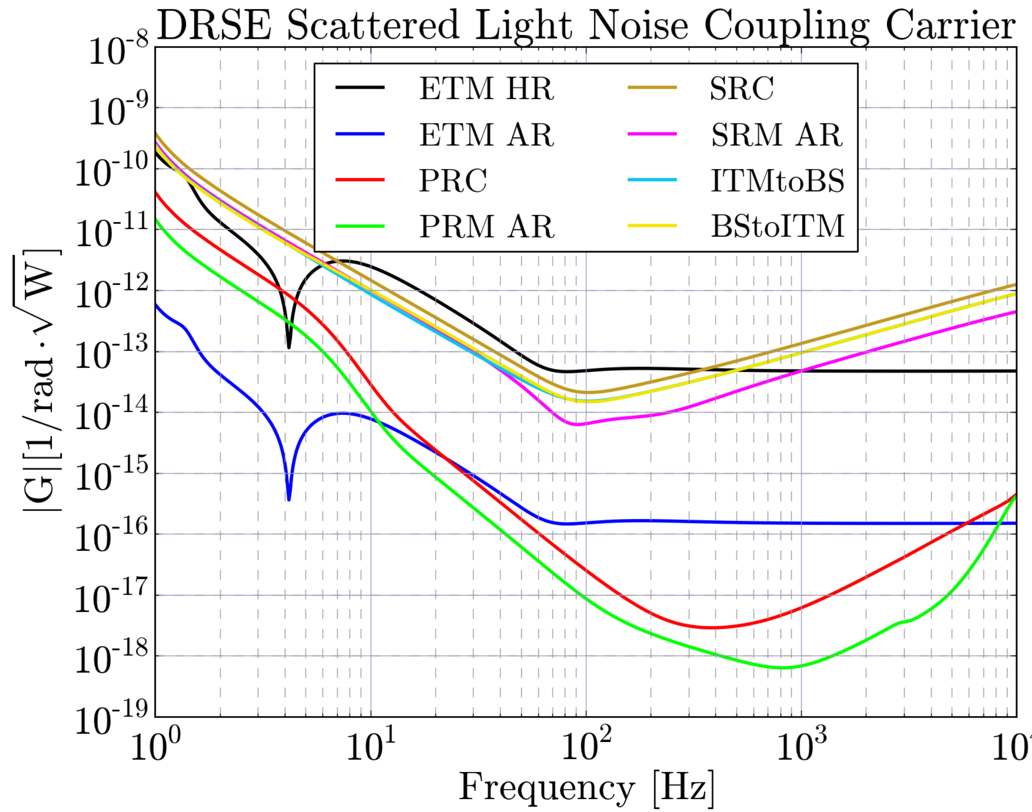
a
DARM
IFO
M_SCL
M1
M2
M3
M4
M5
freq
PD1
PD2
PD3
PD4
PD5
PD6
PD7
Filters

KAGRA Optickle Model



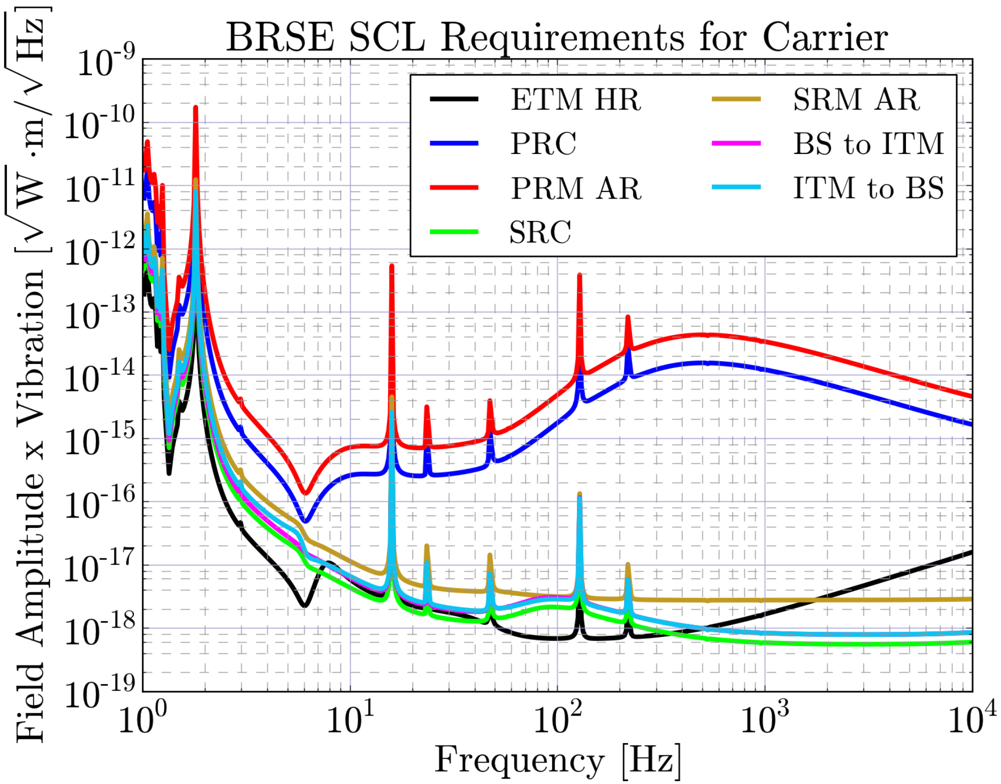
散乱光雑音の伝達関数

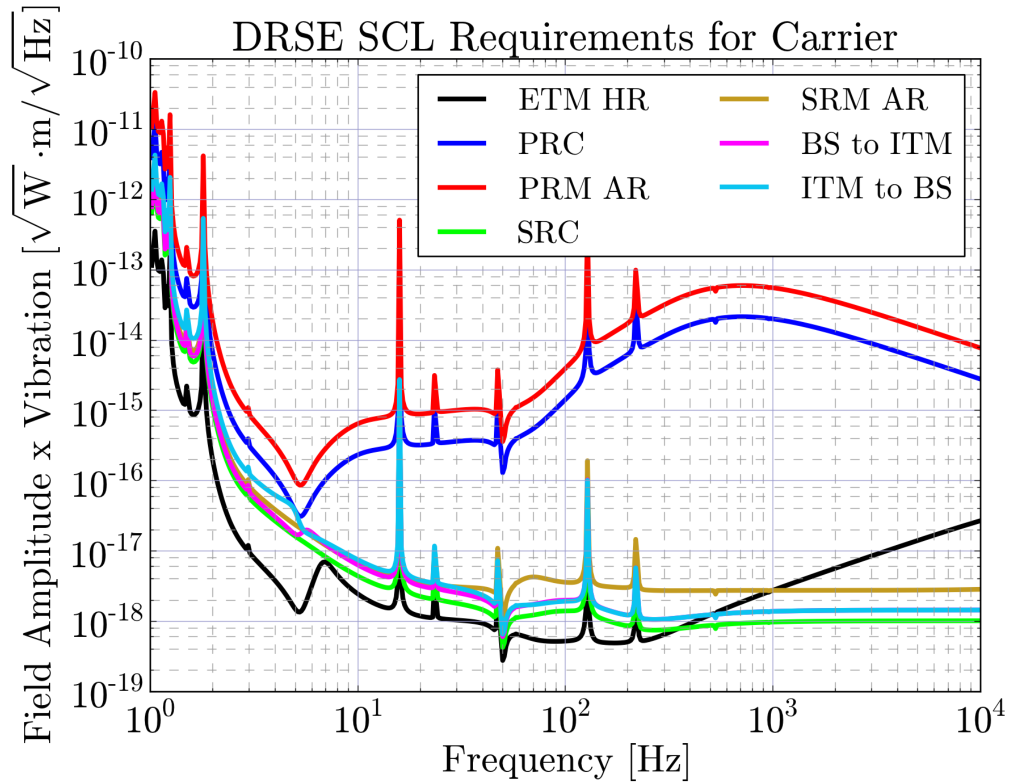


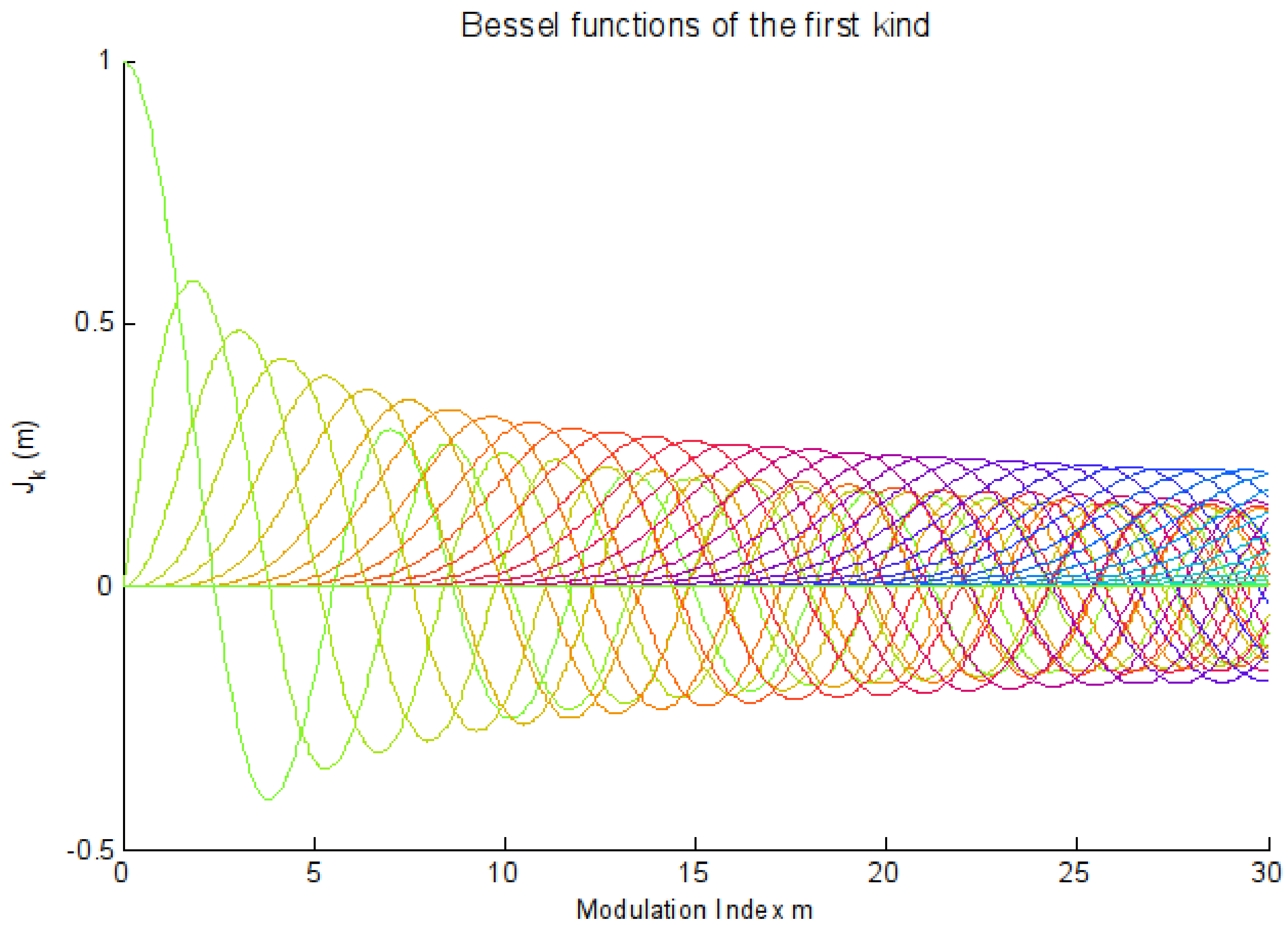


$$\hat{h}_{\mathrm{sc}}(\omega) = |G(\omega)|\, E_{\mathrm{s}} \hat{\Phi}(\omega)$$

$$E_s \cdot a \quad [\sqrt{\mathrm{W}} \cdot \mathrm{m}/\sqrt{\mathrm{Hz}}]$$







Bessel functions of the first kind
1
0.5
0
-0.5
0
5
10
15
20
25
30
J_k (m)
Modulation Index m

散乱光の位相振幅が大きい場合

$$\Phi(t) >> 1$$

散乱光

$$E_{\mathrm{s}} e^{i\Omega t}\{\cos[\Phi(t)] + i \boxed{\sin[\Phi(t)]}\}$$

$$a(t)$$

パワースペクトル $P_a(\omega)$

$$\hat{h}_{\mathrm{sc}}(\omega) = |G(\omega)| \boxed{E_{\mathrm{s}} \hat{\Phi}(\omega)}$$

散乱光サイドバンド振幅

散乱光の位相振幅が大きい場合

$$\Phi(t) >> 1$$

散乱光

$$E_{\mathrm{s}} e^{i\Omega t}\{\cos[\Phi(t)] + i \boxed{\sin[\Phi(t)]}\}$$

$$a(t)$$

パワースペクトル $P_a(\omega)$

$$\hat{h}_{\mathrm{sc}}(\omega) = |G(\omega)| \boxed{\sqrt{P_a(\omega)}}$$

散乱光サイドバンド振幅

$\Phi(t)$ が平均ゼロの定常ガウス雑音の時、任意の $w(t)$に対して

$$\left\langle \exp\left\{ i\int_{-\infty}^{\infty} w(t)\Phi(t)dt \right\rangle\right.$$

$$= \exp\left\{ -\frac{1}{2}\int dt_1 \int dt_2 C_\Phi(t_1 - t_2) w(t_1) w(t_2) \right\}$$

Wiener-Khintchine

$$C_\Phi(\tau) = \langle \Phi(t)\Phi(t+\tau)\rangle = \int_{-\infty}^{\infty} P_\Phi(\omega) e^{i\omega\tau} d\omega$$

$$\left\langle \exp\left\{ i\int_{-\infty}^{\infty} w(t)\Phi(t)dt \right\rangle\right.$$

$$= \exp\left\{ -\frac{1}{2}\int dt_1 \int dt_2 C_\Phi(t_1-t_2)w(t_1)w(t_2) \right\}$$

代入

$$w(t) = \delta(t-t_1) \pm \delta(t-t_2)$$

$$\left\langle e^{i\Phi(t_1)} e^{\pm i\Phi(t_2)} \right\rangle = \exp\left\{ \mp C_\Phi(t_1-t_2) - C_\Phi(0) \right\}$$

$$\left\langle e^{i\Phi(t_1)} e^{\pm i\Phi(t_2)} \right\rangle = \exp\left\{\mp C_\Phi(t_1 - t_2) - C_\Phi(0)\right\}$$

$$C_a(\tau) = < \sin\Phi(t)\sin\Phi(t+\tau) >$$

$$= \left\langle \frac{e^{i\Phi(t)} - e^{-i\Phi(t)}}{2} \cdot \frac{e^{i\Phi(t+\tau)} - e^{-i\Phi(t+\tau)}}{2} \right\rangle$$

$$\Phi(t) \longrightarrow \Phi_0 + \Phi(t)$$

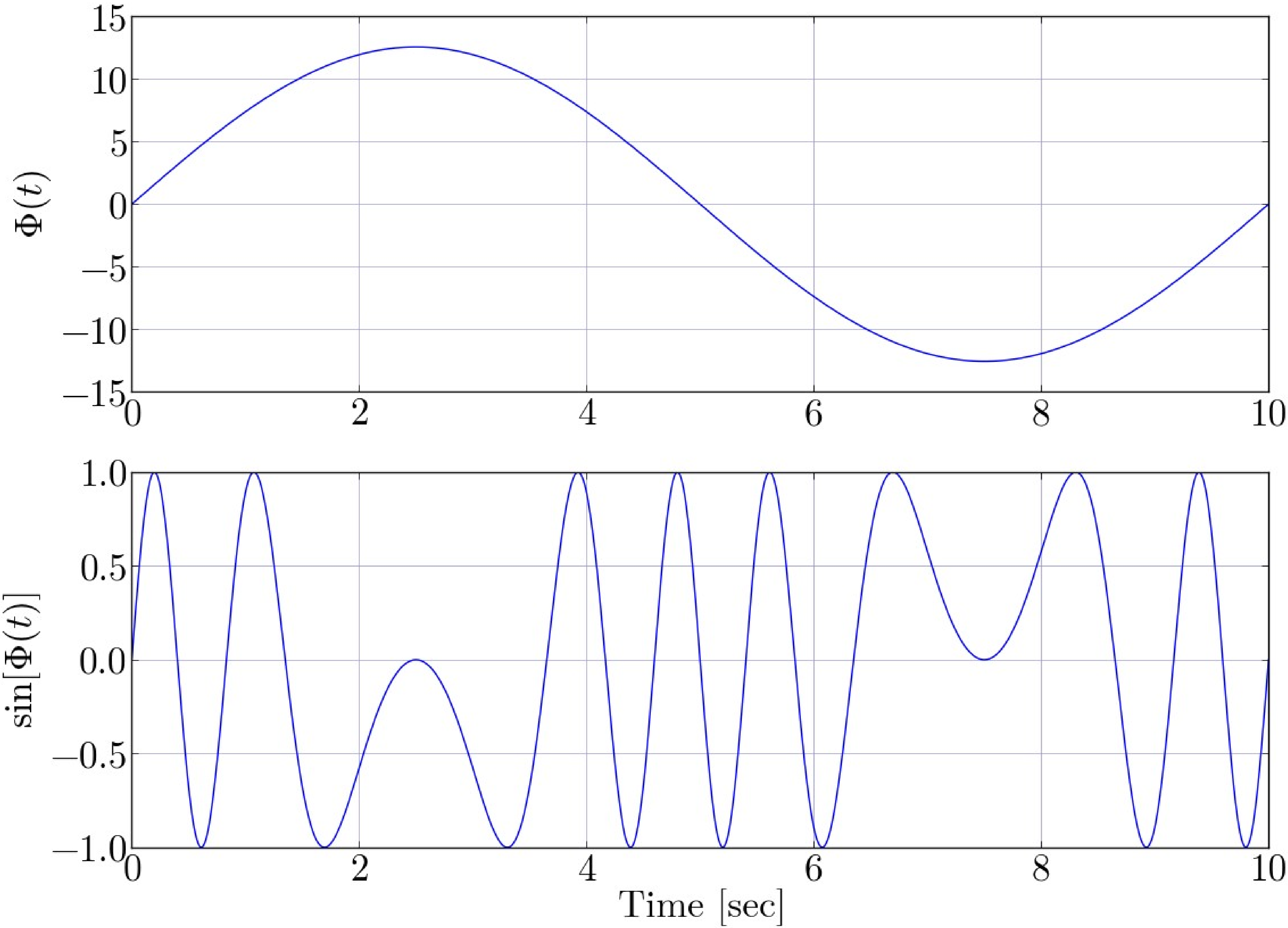
平均ゼロ

$$C_a(\tau) = \frac{1}{2}\exp\{C_\Phi(\tau) - C_\Phi(0)\}$$

$$C_\Phi(\tau) = \int_{-\infty}^{\infty} \underbrace{P_\Phi(\omega)}_{\text{既知}} e^{i\omega\tau} d\omega$$

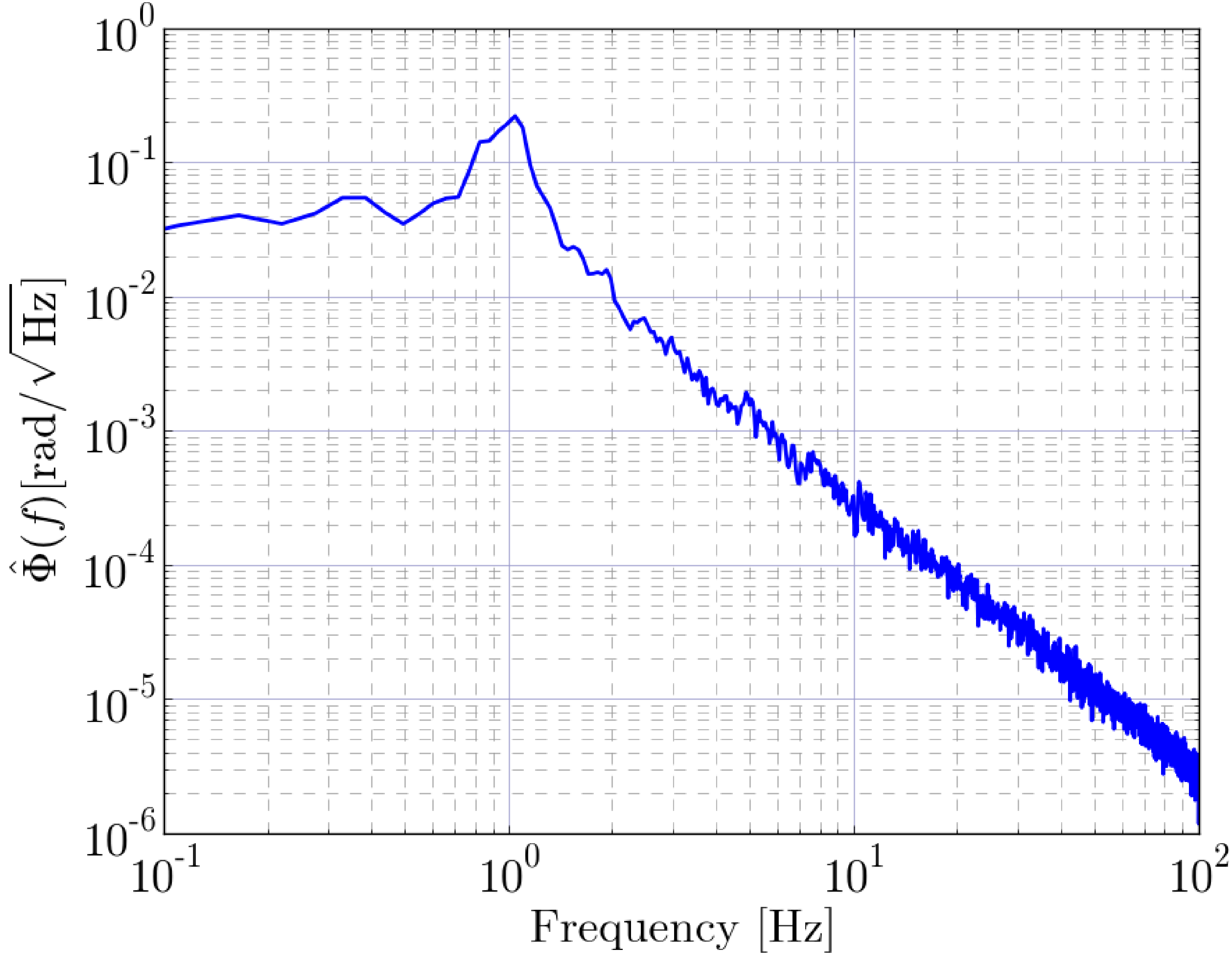
$$C_a(\tau) = \frac{1}{2} \exp\{C_\Phi(\tau) - C_\Phi(0)\}$$

$$\underbrace{P_a(\omega)}_{\text{求めたい}} = \frac{1}{2\pi} \int_{-\infty}^{\infty} C_a(\tau) e^{-i\omega\tau} d\tau$$

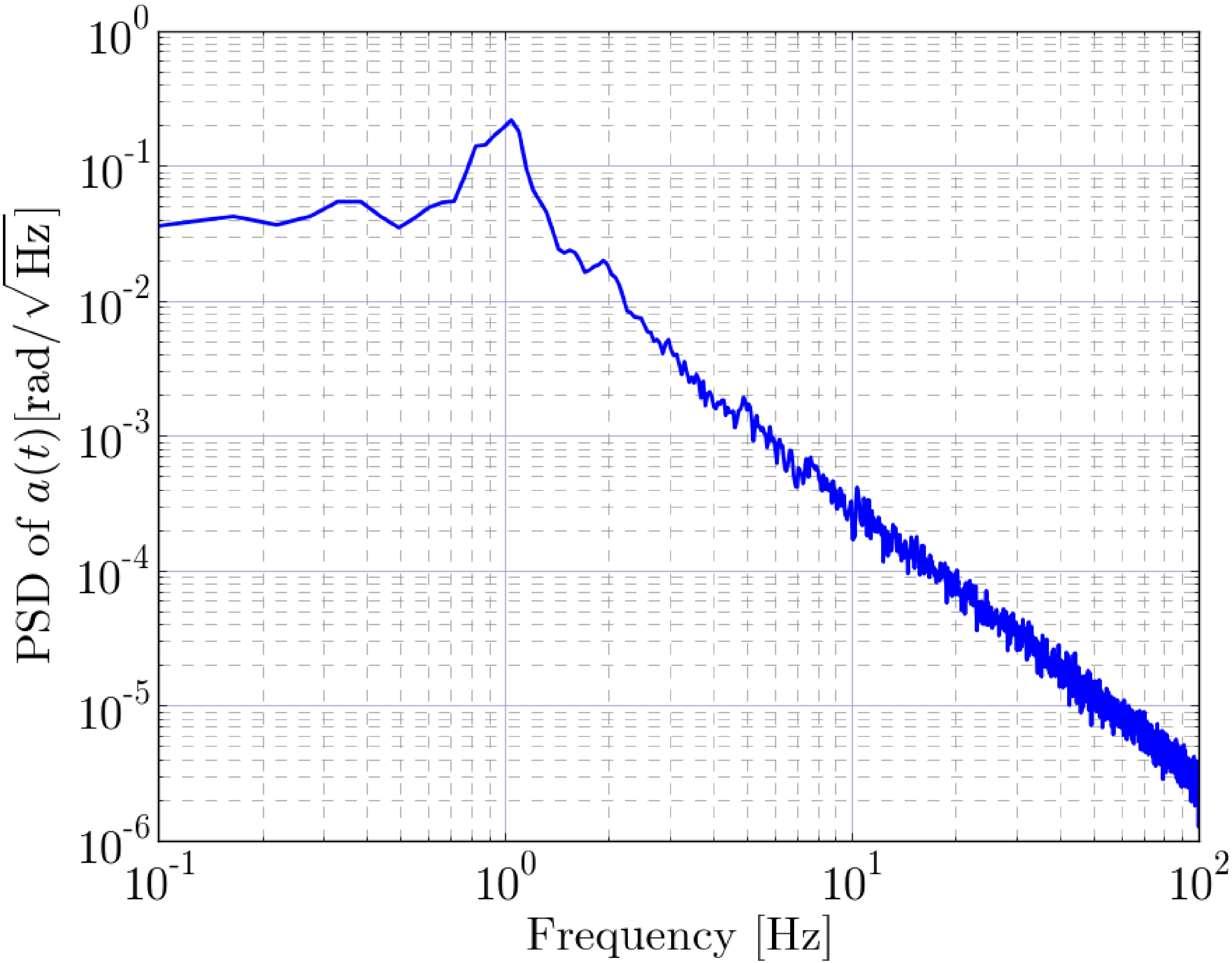


$\Phi(t)$
15
10
5
0
−5
−10
−15
0
2
4
6
8
10
$\sin[\Phi(t)]$
1.0
0.5
0.0
−0.5
−1.0
Time [sec]

位相変動のパワースペクトル

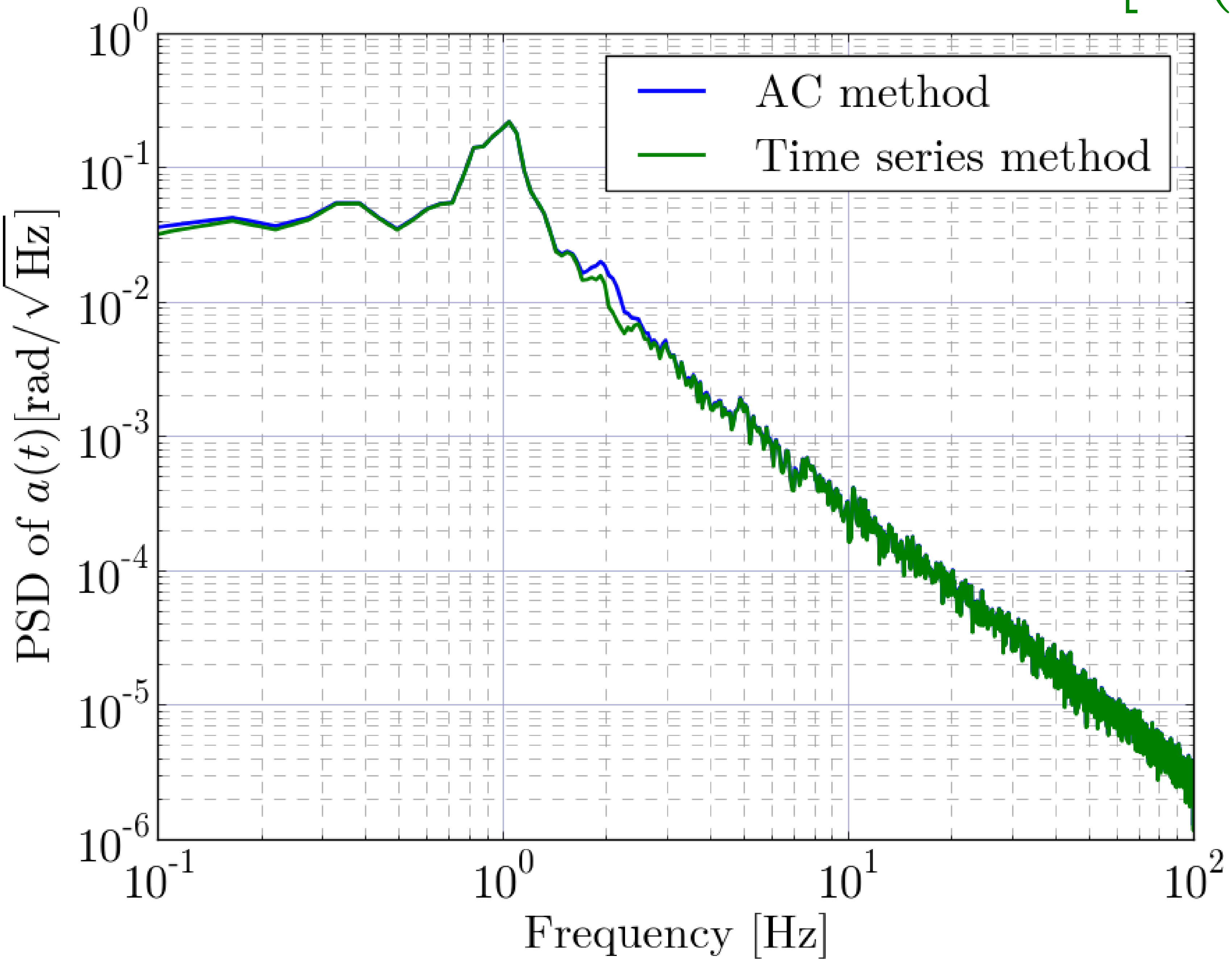


自己相関関数法で$P_a(\omega)$を求める



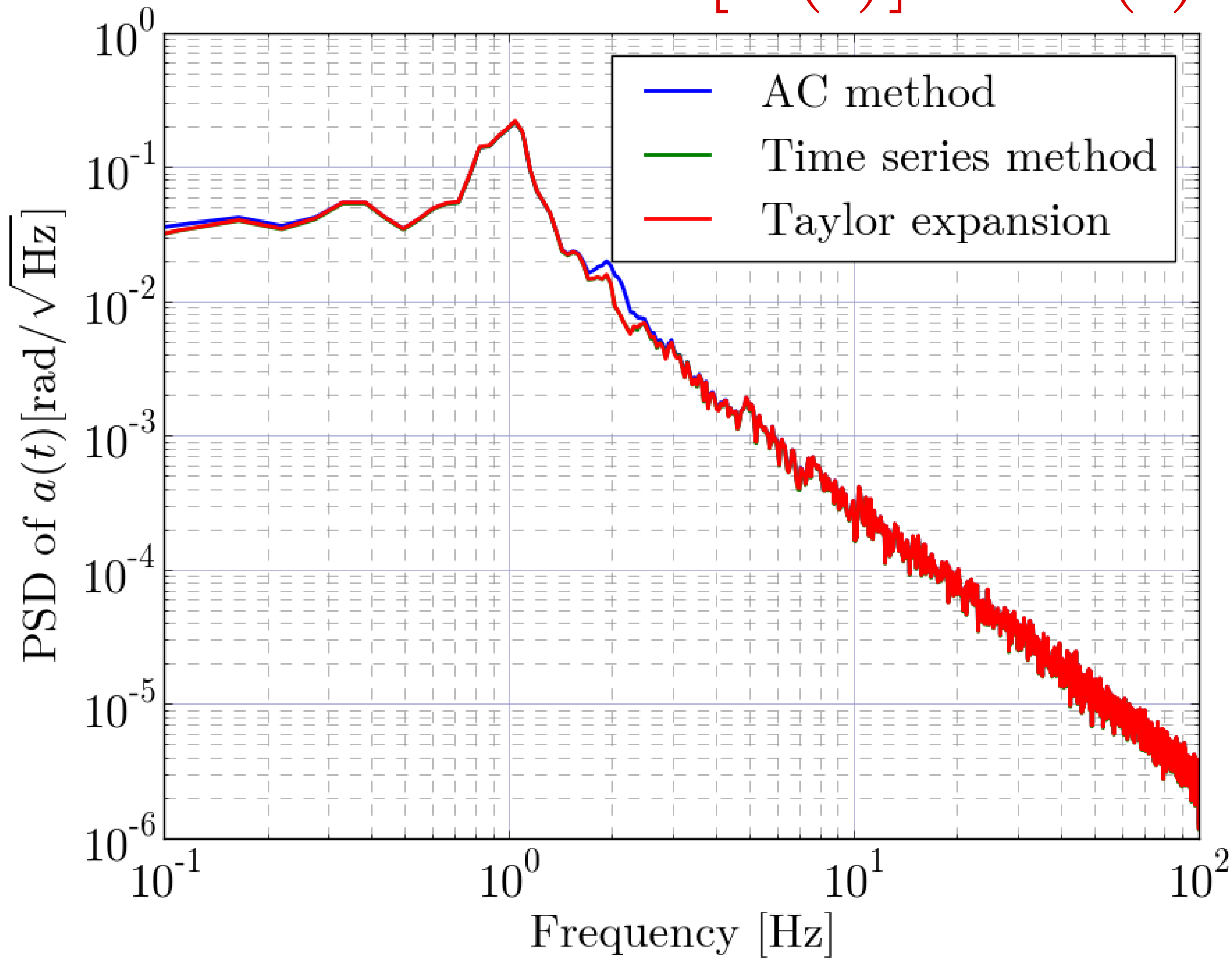
直接法

$\sin[\Phi(t)]$

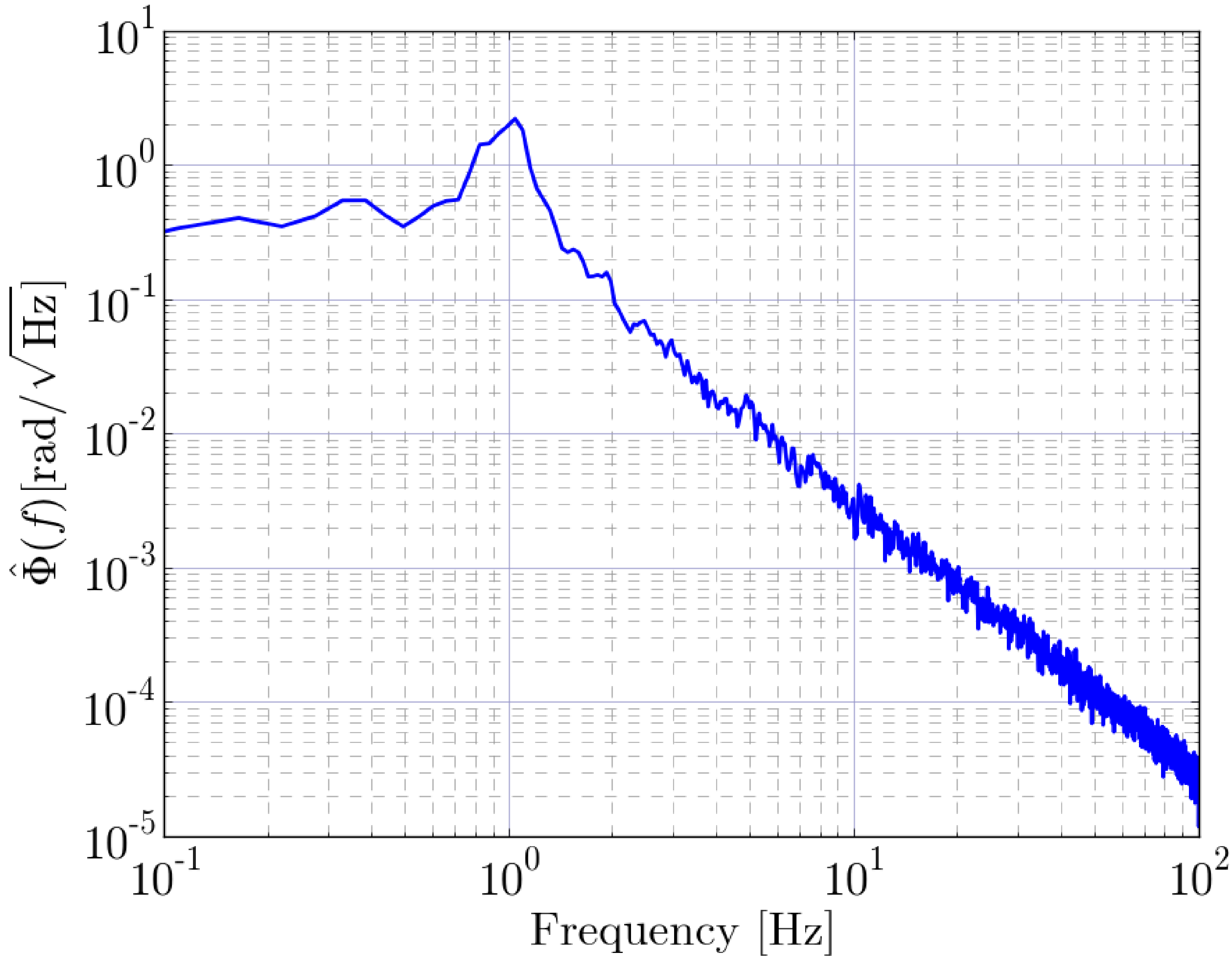


AC method
Time series method
PSD of $a(t)$ [rad/$\sqrt{\mathrm{Hz}}$]
Frequency [Hz]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-1}
10^{0}
10^{1}
10^{2}

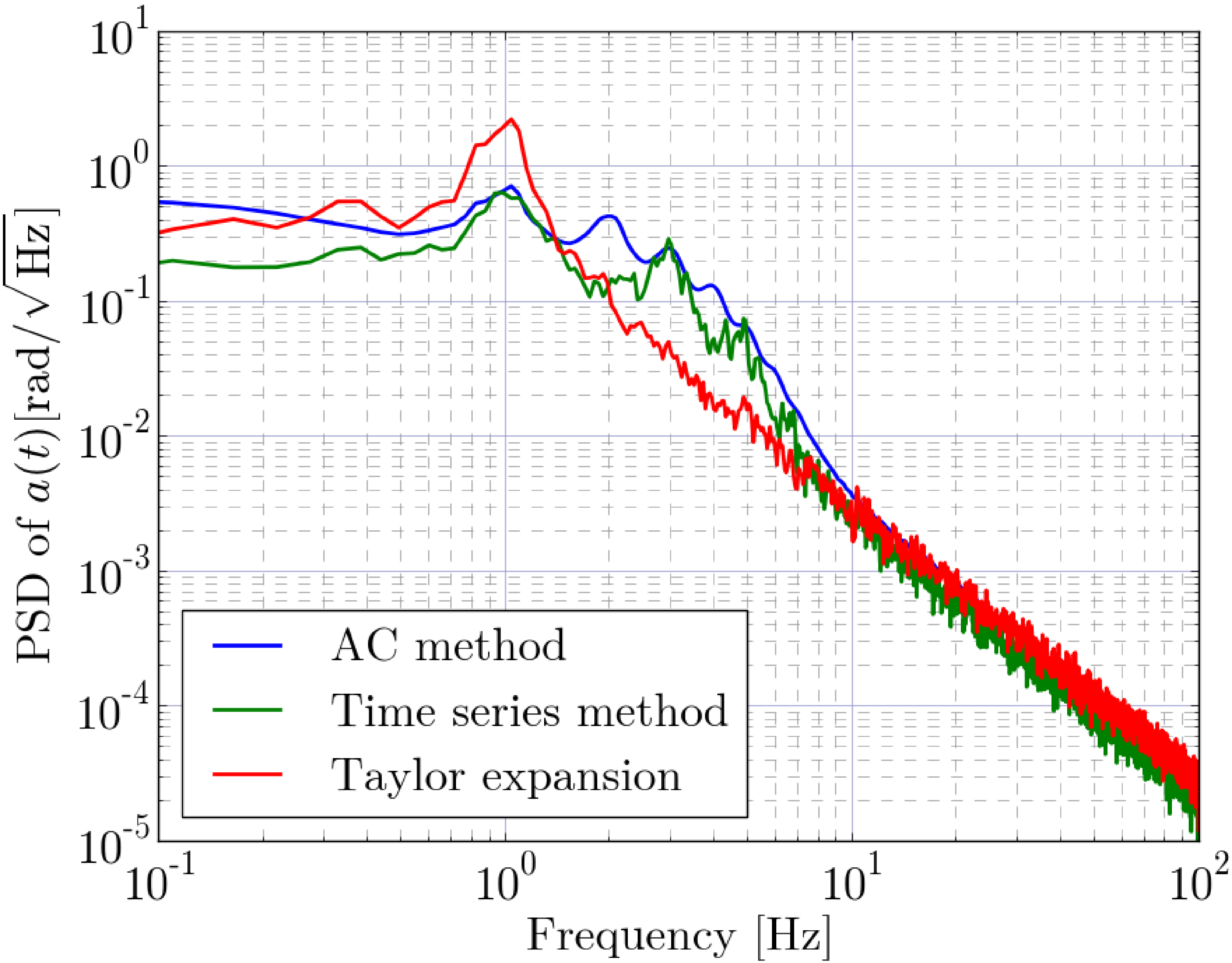
テイラー展開 $\sin[\Phi(t)] \rightarrow \Phi(t)$



少し大きな位相変動

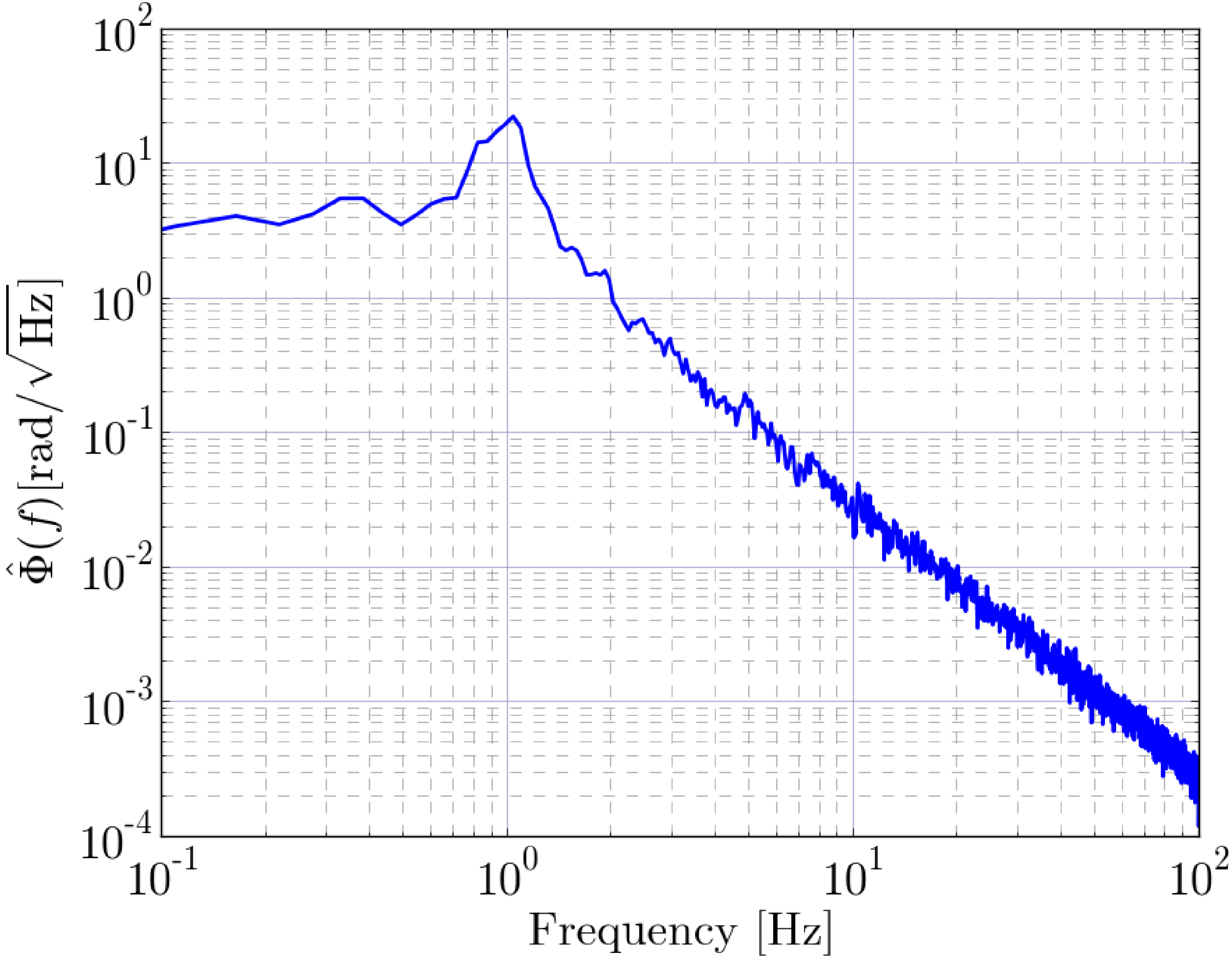


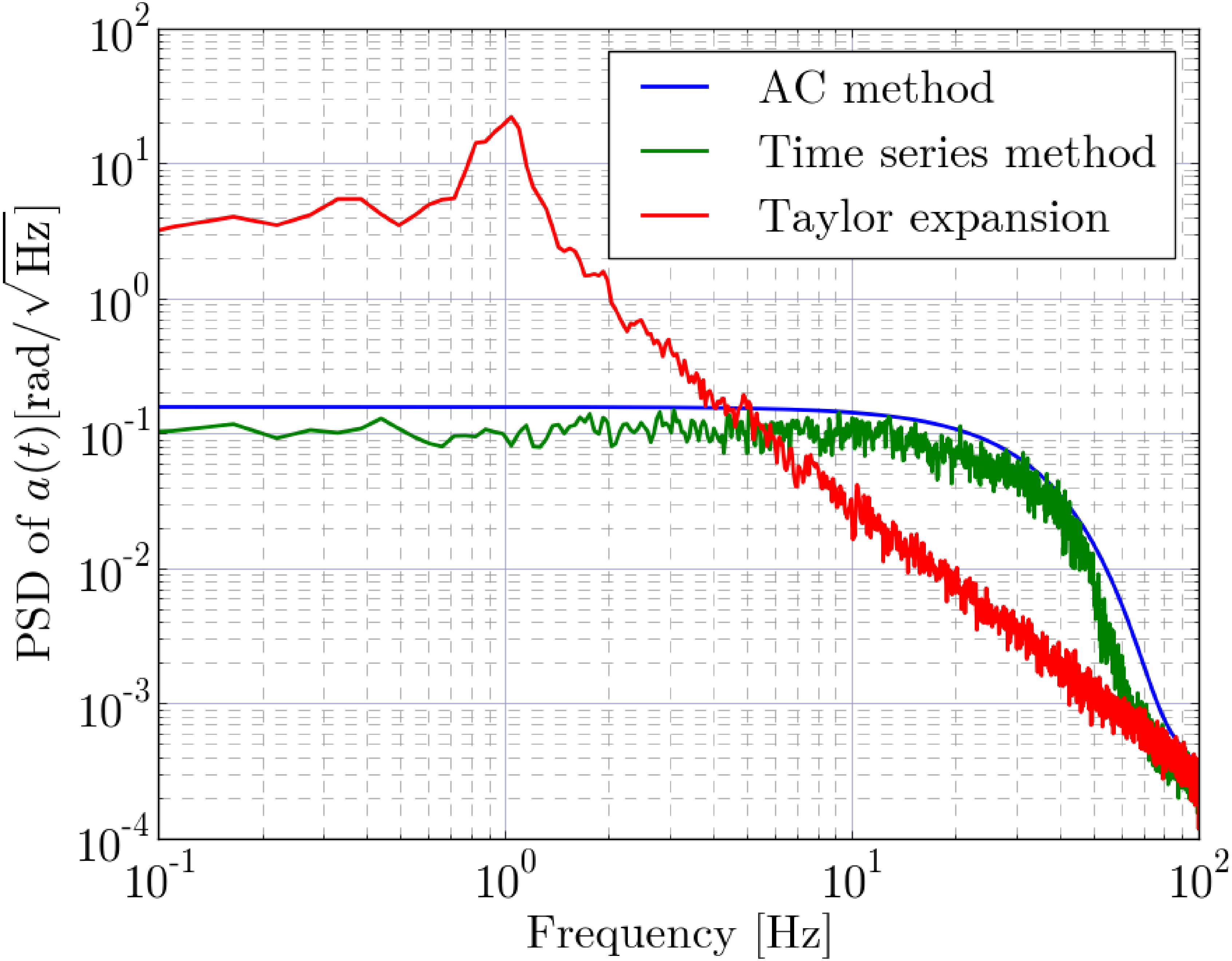
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-1}
10^0
10^1
10^2
Frequency [Hz]
$\hat{\Phi}(f)[\mathrm{rad}/\sqrt{\mathrm{Hz}}]$



PSD of $a(t)$[rad/$\sqrt{\text{Hz}}$]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-1}
10^{0}
10^{1}
10^{2}
Frequency [Hz]
AC method
Time series method
Taylor expansion

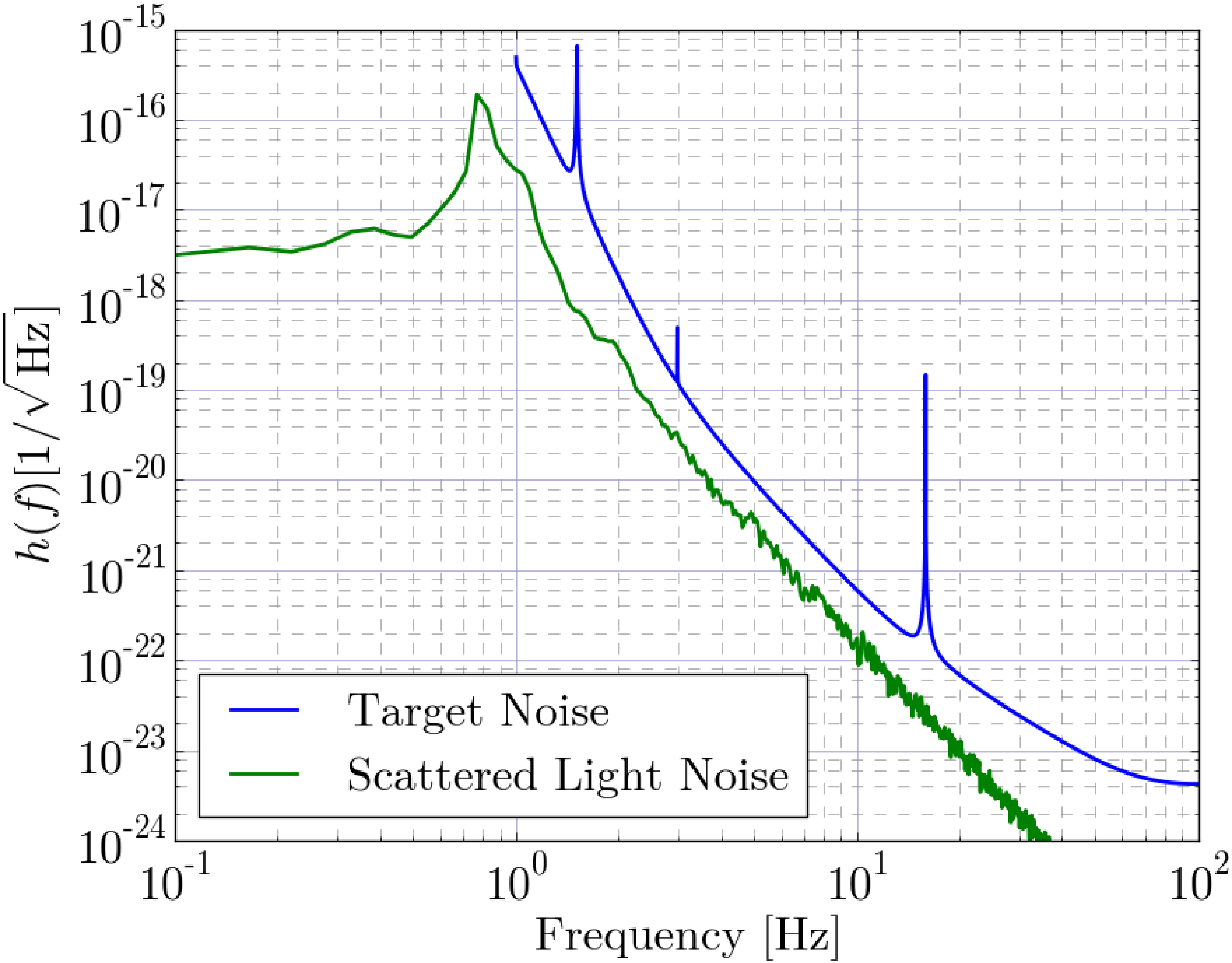
さらに大きな位相変動


10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\hat{\Phi}(f)[\mathrm{rad}/\sqrt{\mathrm{Hz}}]$
10^{-1}
10^{0}
10^{1}
10^{2}
Frequency [Hz]

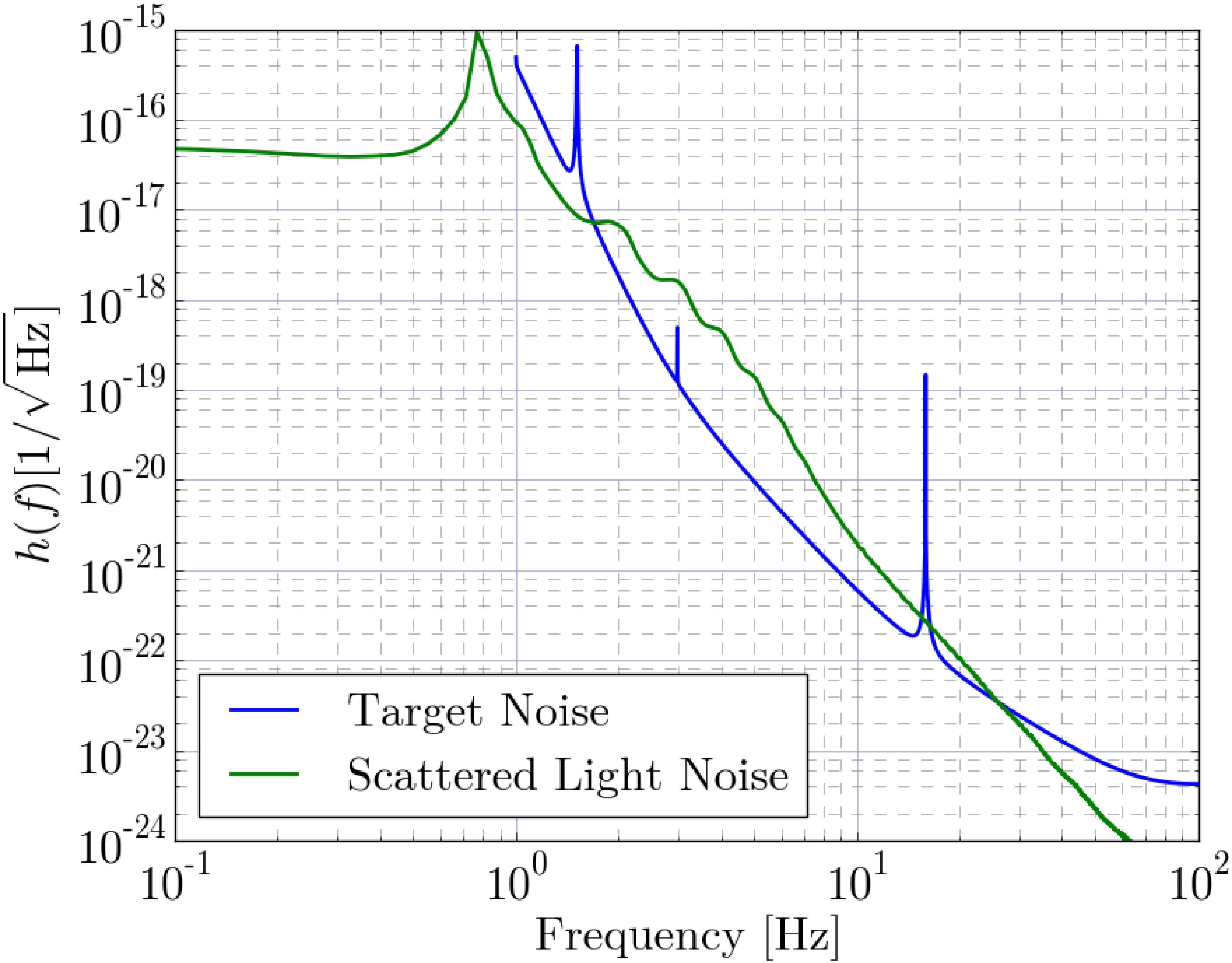


AC method
Time series method
Taylor expansion
PSD of $a(t)$[rad/$\sqrt{\mathrm{Hz}}$]
Frequency [Hz]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-1}
10^{0}
10^{1}
10^{2}

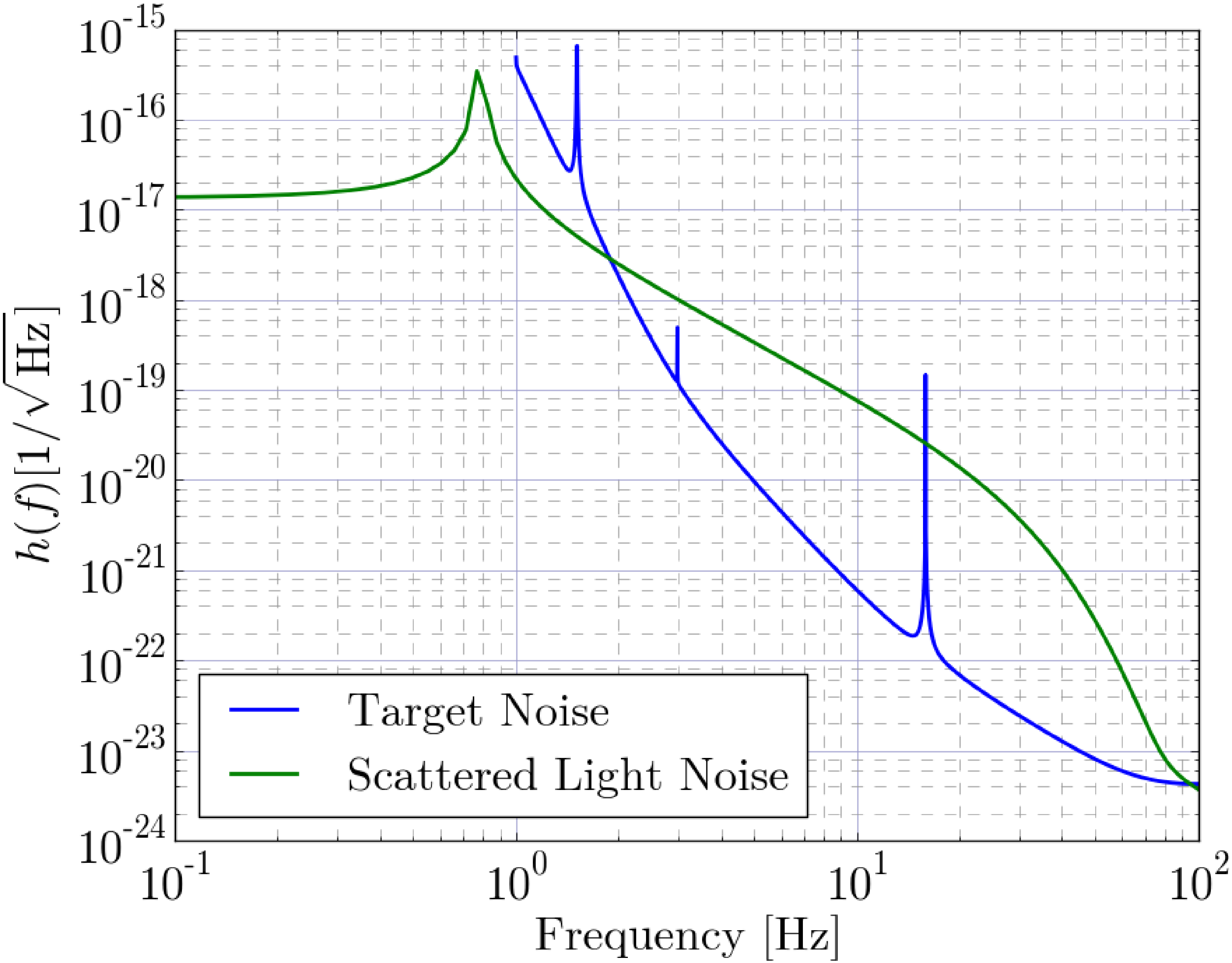
1pW散乱光, SRM ARから入射, 小さい位相揺らぎ(0.2rad)



1pW散乱光, SRM ARから入射, 大きめの位相揺らぎ(2rad)

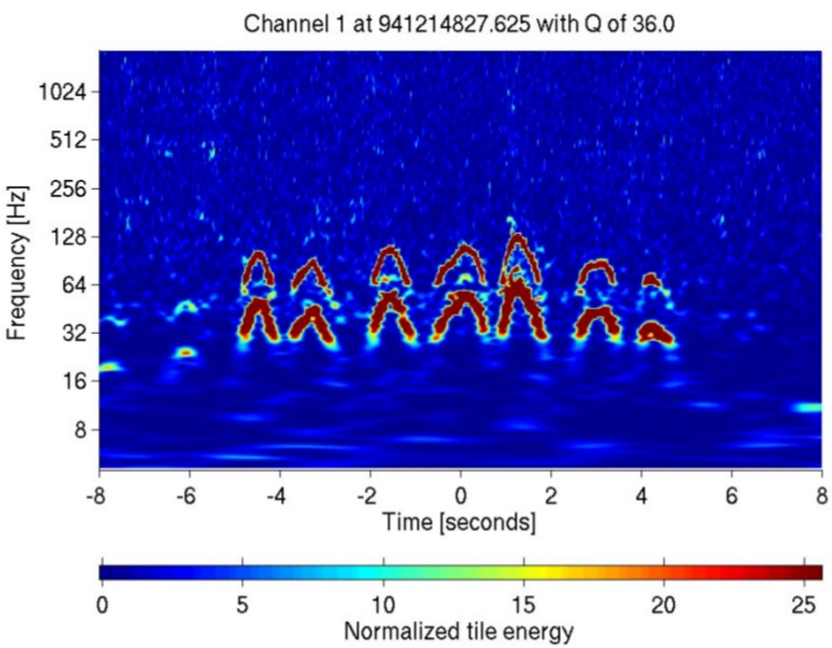


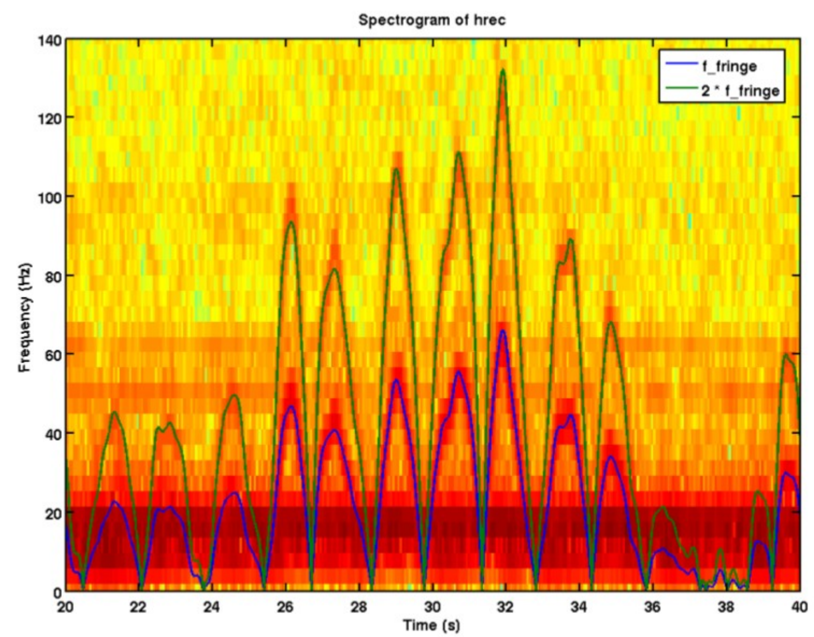
1pW散乱光, SRM ARから入射, 大きい位相揺らぎ(20rad)



Spectrogram

Scattering Arches



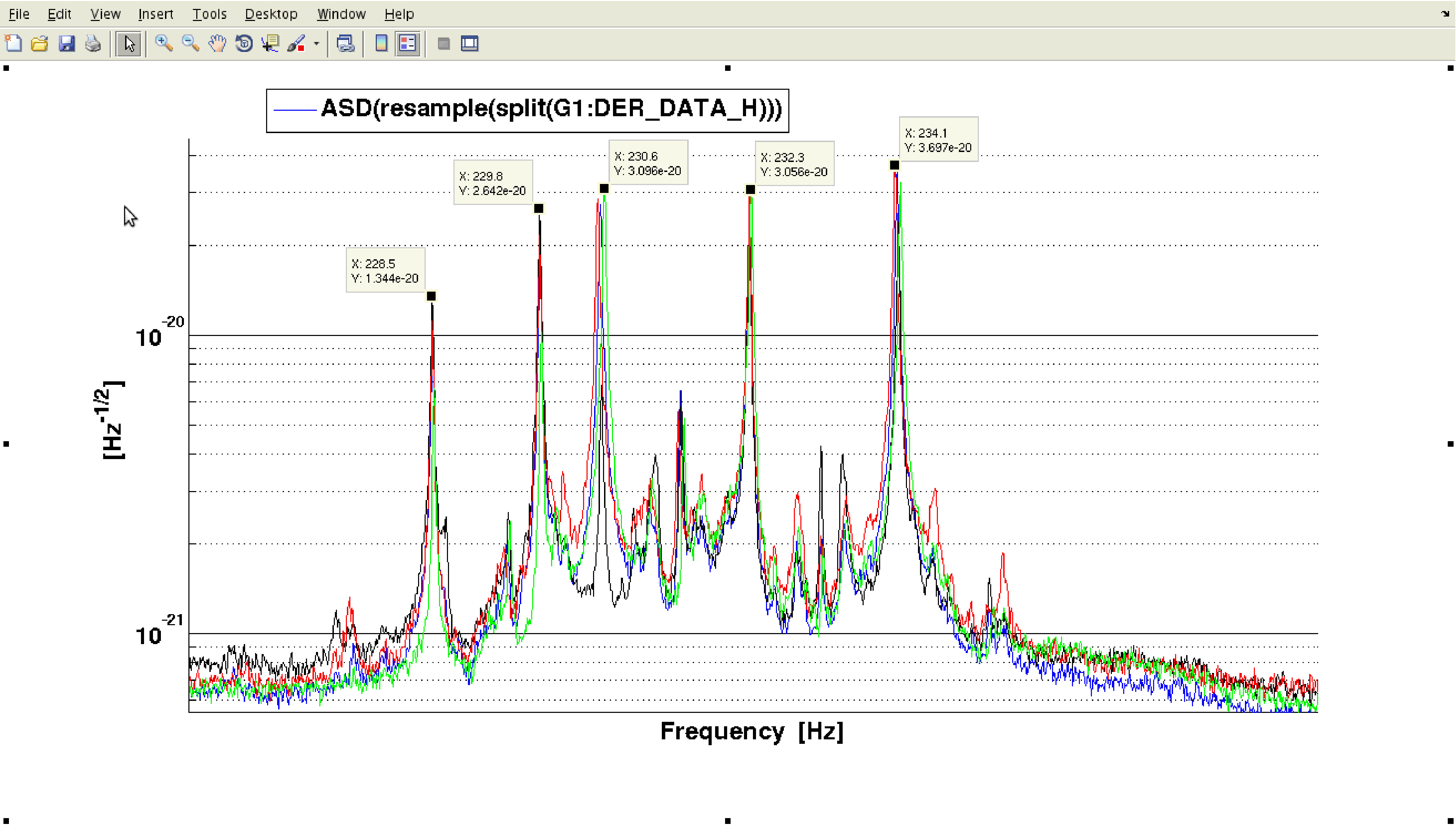


GEOでの実験

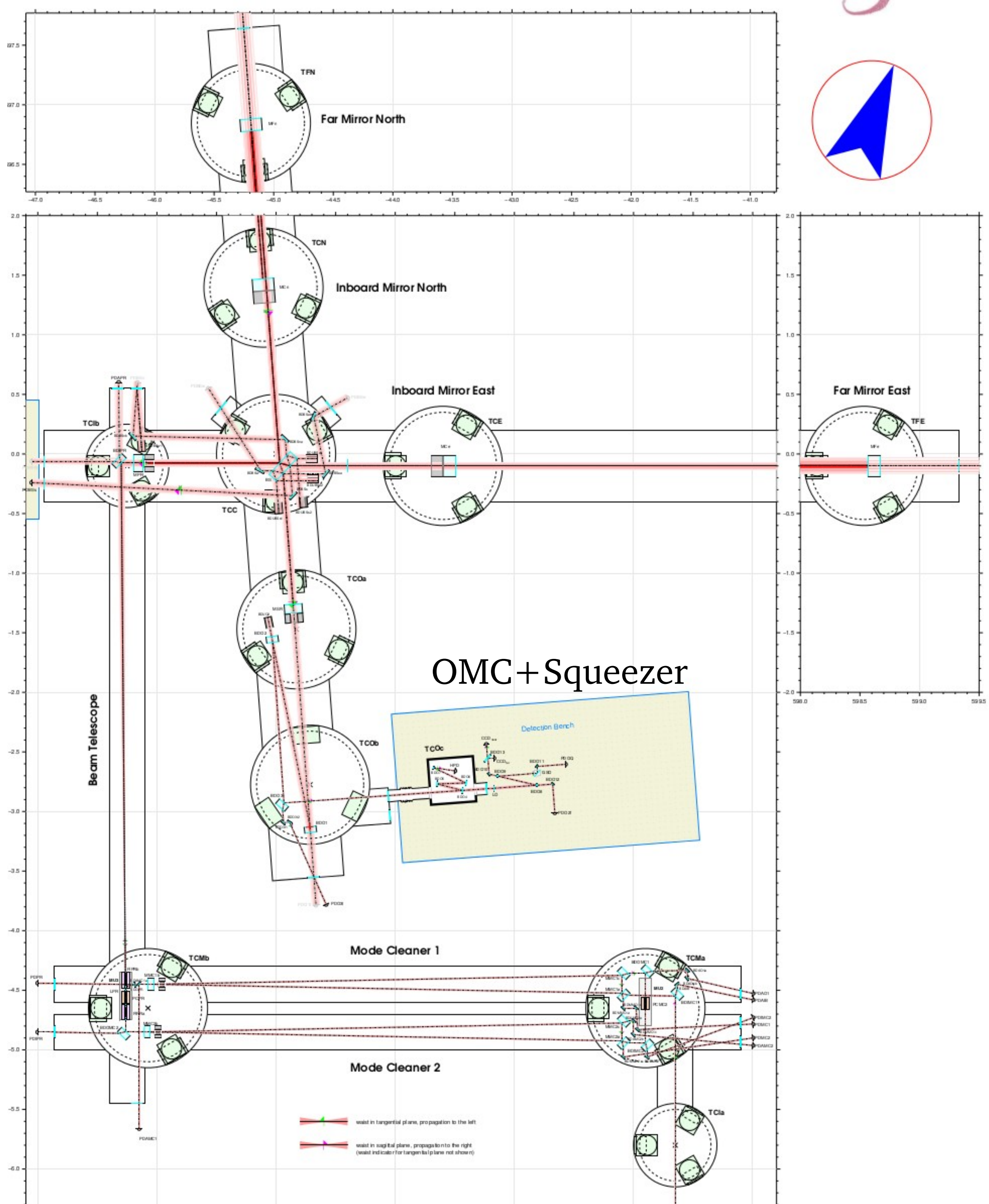
問題になっていた点

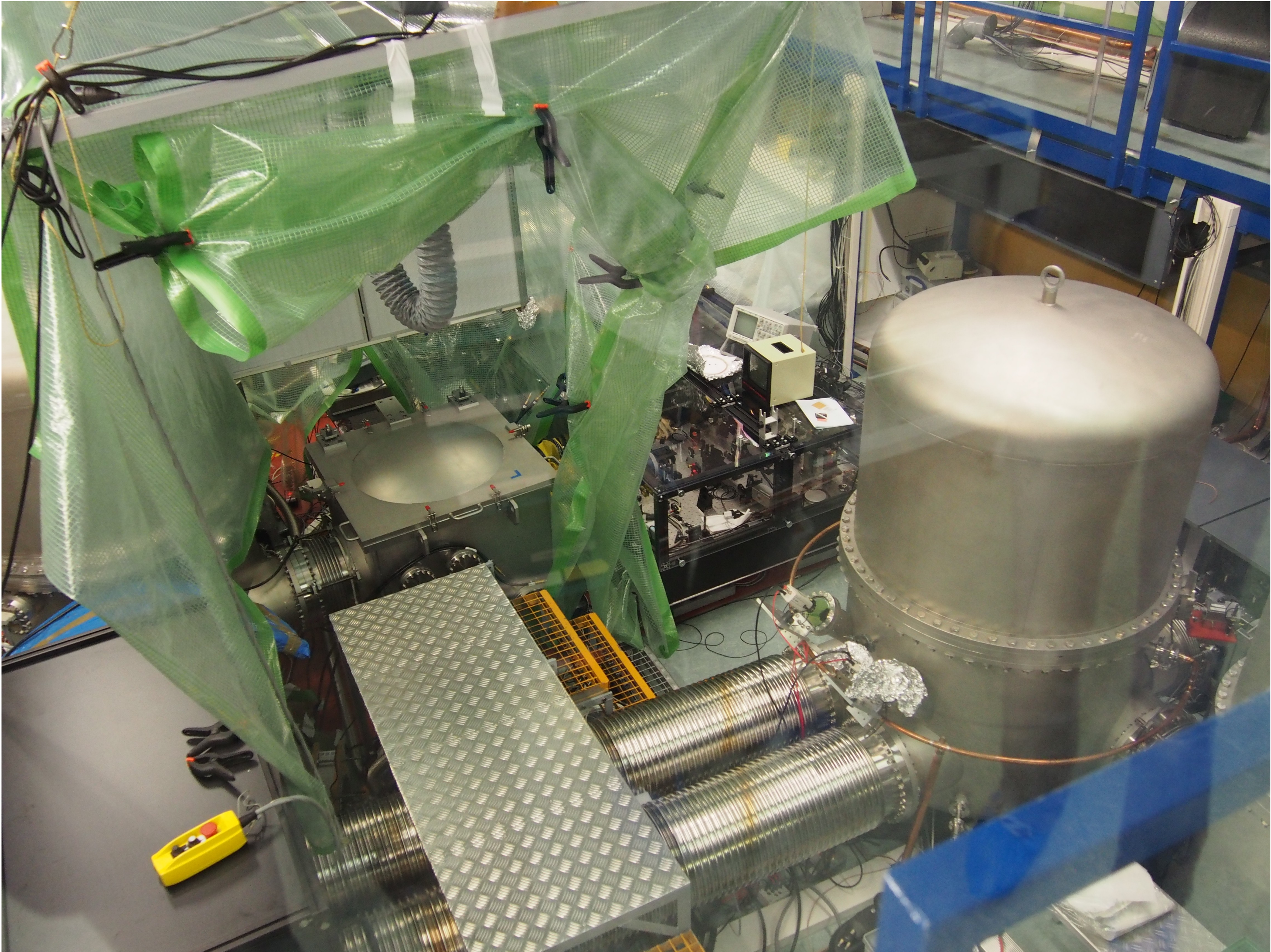
- 230Hz付近に地面振動とコヒーレンスのあるピークが多数ある
- OMCに手を入れた後、低周波にノイズの盛り上がりができた。
  - OMC Chamberの窓板への入射角が垂直に近くなった?
  - 角度を変えるとノイズが減る -> 散乱光が怪しい
- 現在、散乱光雑音が感度を制限しているのか、していないのならどのぐらいのマージンがあるのか、測定されていない。
- パワーを上げると低周波の雑音が増加する

230Hzピーク



File
Edit
View
Insert
Tools
Desktop
Window
Help
ASD(resample(split(G1:DER_DATA_H)))
X: 228.5
Y: 1.344e-20
X: 229.8
Y: 2.642e-20
X: 230.6
Y: 3.096e-20
X: 232.3
Y: 3.056e-20
X: 234.1
Y: 3.697e-20
10^{-20}
10^{-21}
[$Hz^{-1/2}$]
Frequency [Hz]


Far Mirror North
TFN
Inboard Mirror North
TCN
Inboard Mirror East
TCE
Far Mirror East
TFE
TClb
TCC
TCOa
TCOb
TCOc
OMC+Squeezer
Detection Bench
Beam Telescope
Mode Cleaner 1
TCMb
TCMa
Mode Cleaner 2
TCla
waist in tangential plane, propagation to the left
waist in sagittal plane, propagation to the right
(waist indicator for tangential plane not shown)



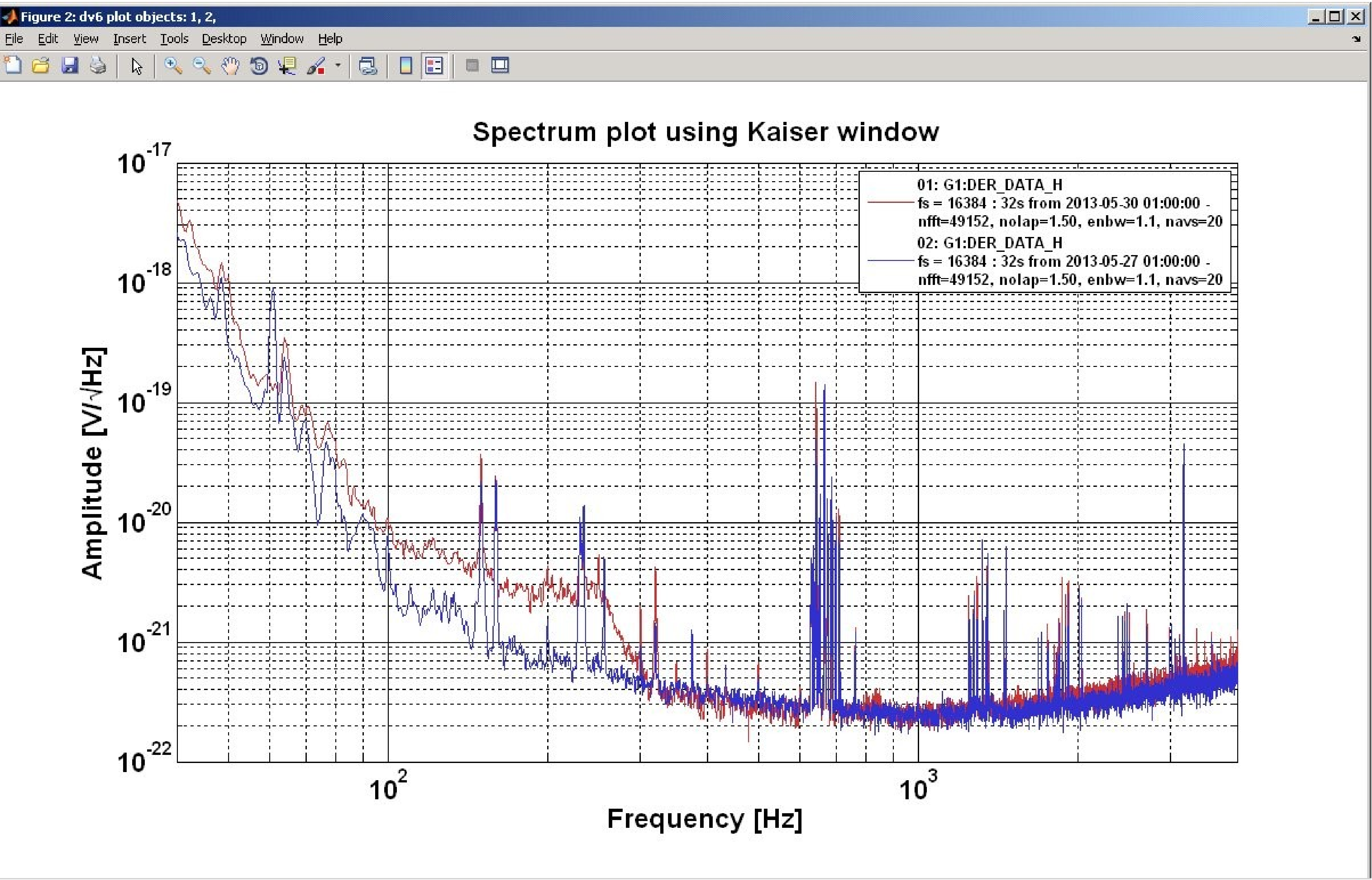


Figure 2: dv6 plot objects: 1, 2,
File Edit View Insert Tools Desktop Window Help
Spectrum plot using Kaiser window
01: G1:DER_DATA_H
fs = 16384 : 32s from 2013-05-30 01:00:00 -
nfft=49152, nolap=1.50, enbw=1.1, navs=20
02: G1:DER_DATA_H
fs = 16384 : 32s from 2013-05-27 01:00:00 -
nfft=49152, nolap=1.50, enbw=1.1, navs=20
Amplitude [V/√Hz]
Frequency [Hz]
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{2}
10^{3}

やった実験

- Shaking Tests
- Acoustic Injections
- Beam Tube Shaking
- Longitudinal Excitation of Input/Output Optics
- Squeezer Frequency Shift
- Folding Mirror Scattering Noise Estimate with FFT and Phase Map
- Running EXCAVATor on GEO Data

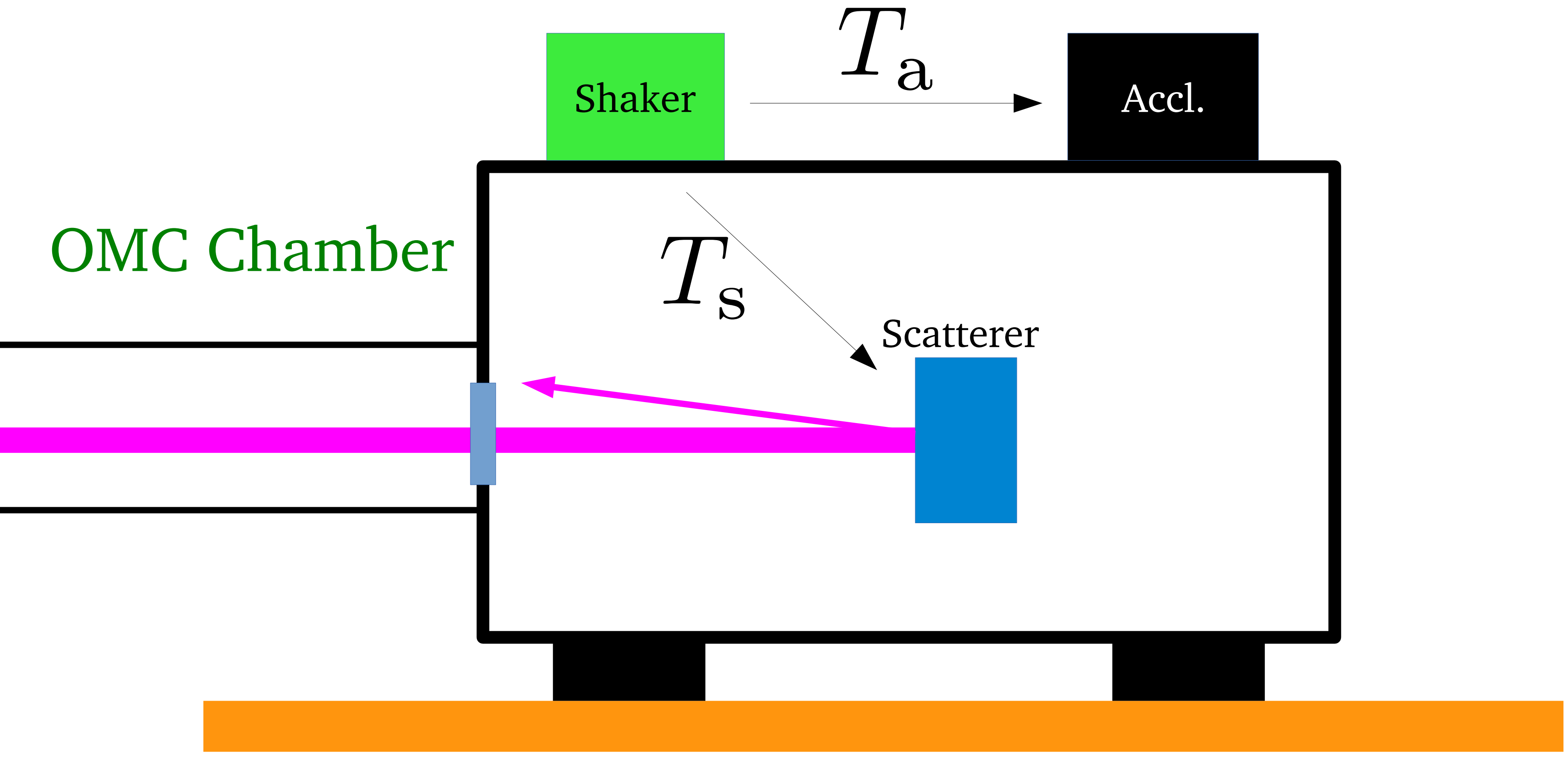
Shaker and an accelerometer are mounted on top of the OMC chamber

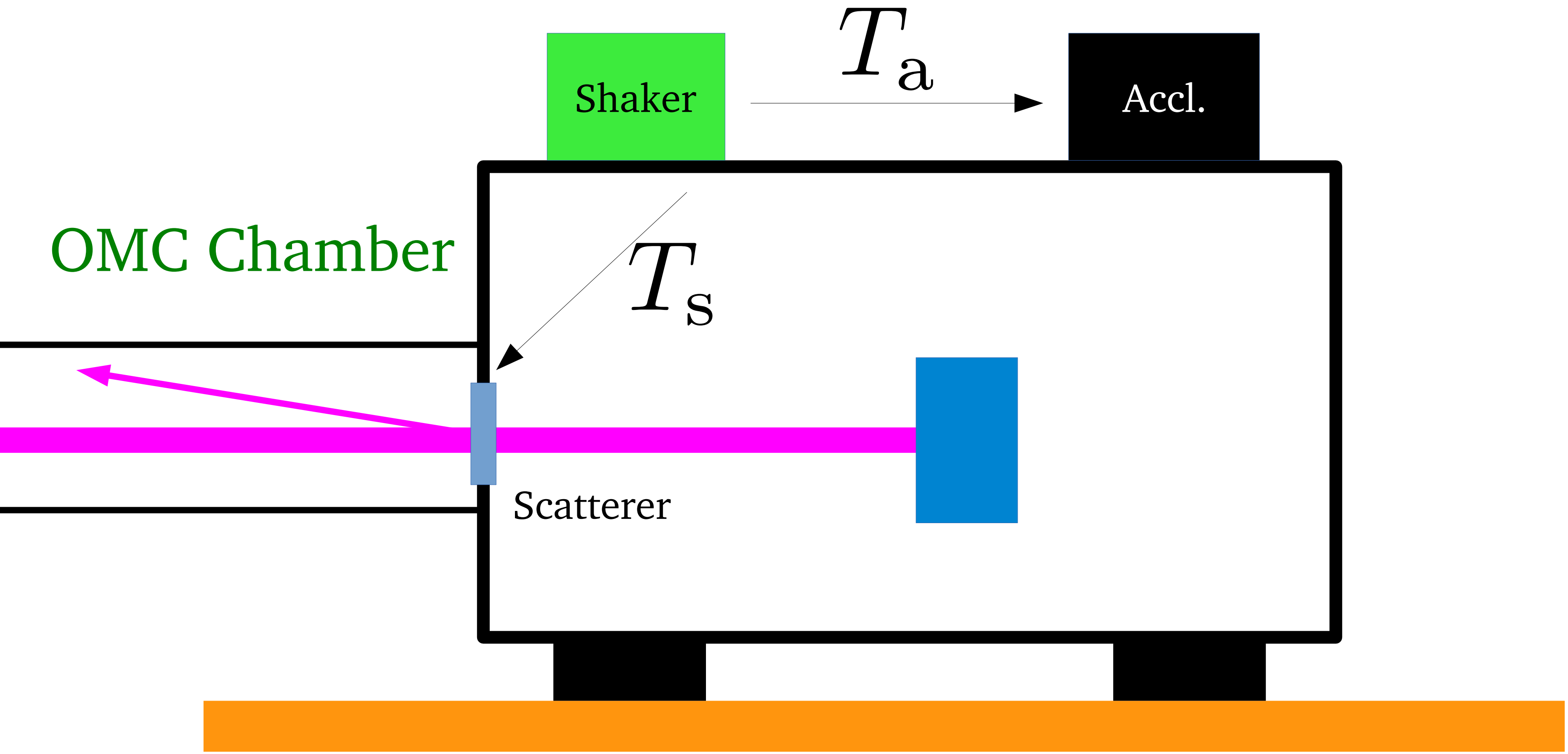
Accelerometer DAQ channels

X: LSC_MID_OPN
Y: G1:ASC_MID_FP-MCE-ESD1
Z: G1:LSC_MID_FP-MCE-MCN

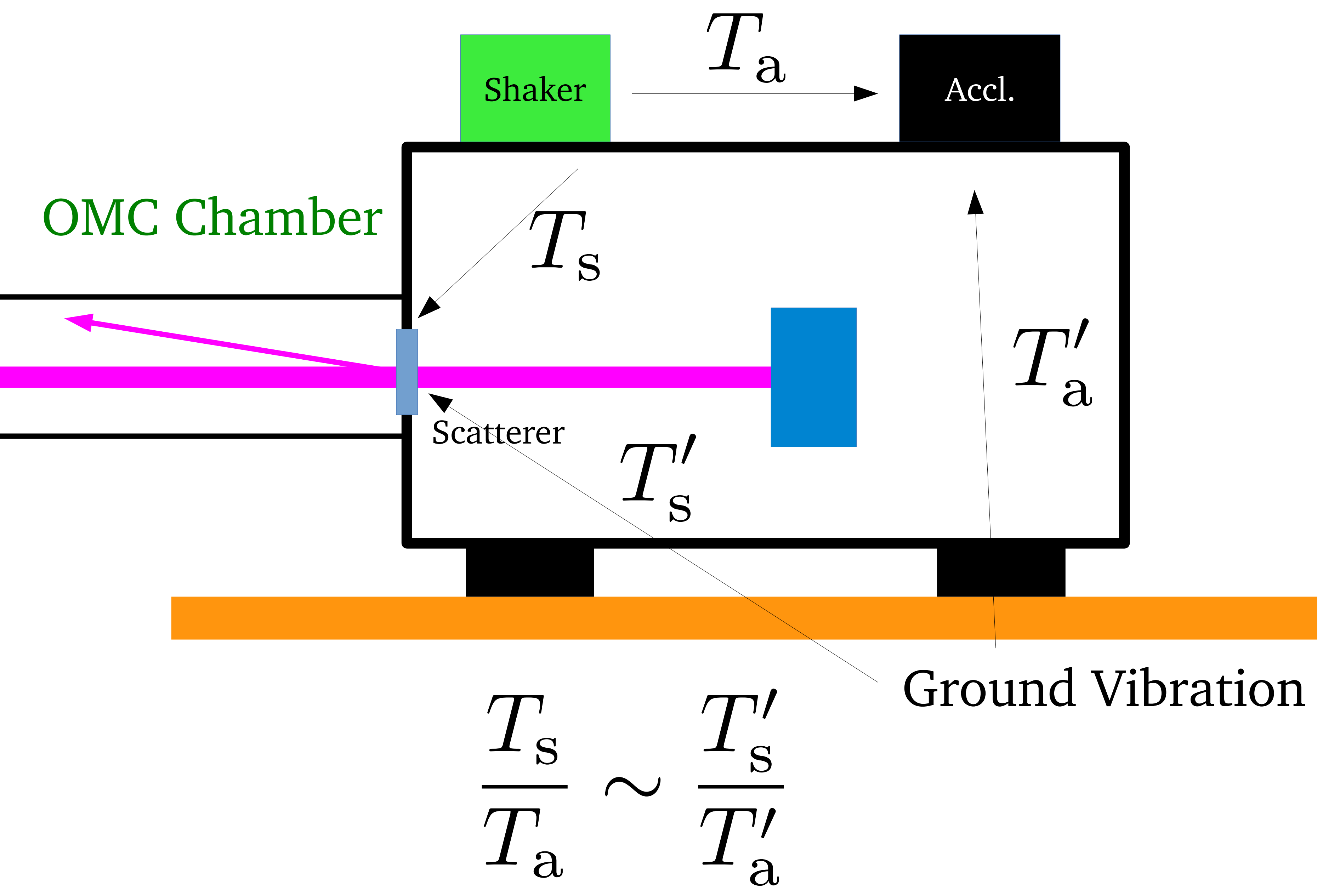
Accelerometer

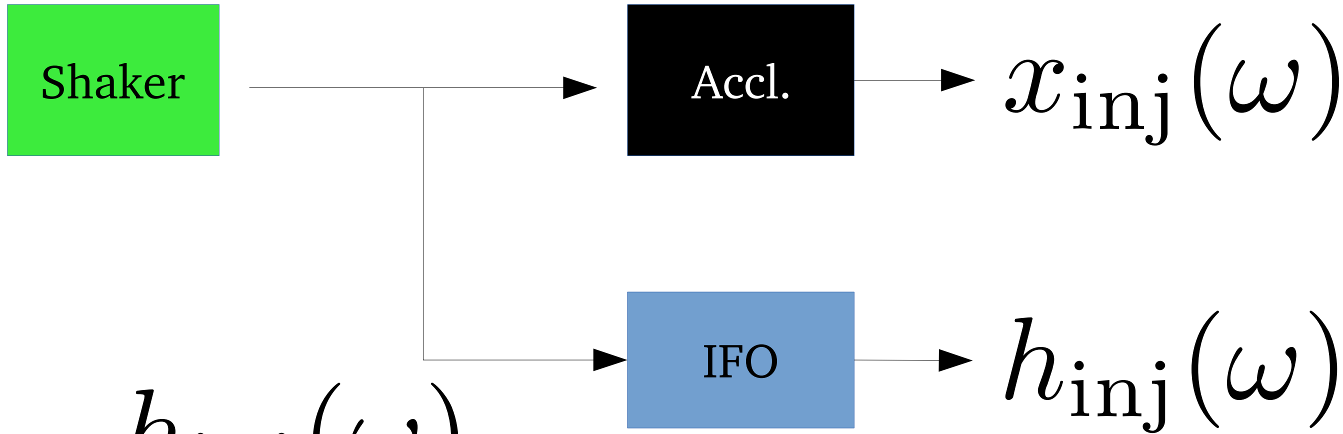
Shaker


T_{a}
Shaker
Accl.
OMC Chamber
T_{s}
Scatterer

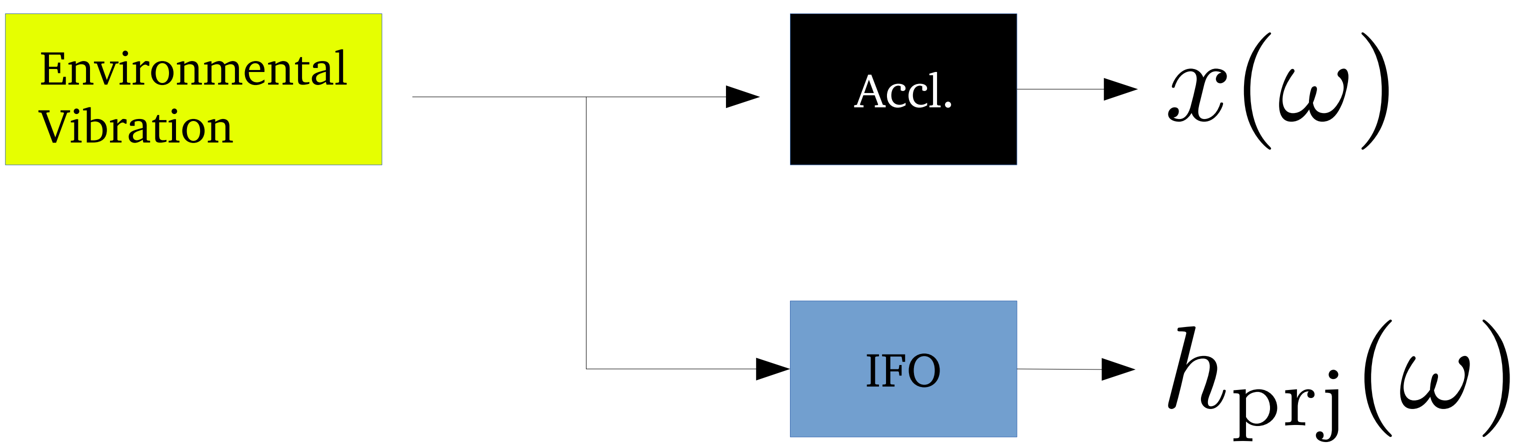


Shaker
T_a
Accl.
OMC Chamber
T_s
Scatterer


Shaker
T_a
Accl.
OMC Chamber
T_s
T'_a
Scatterer
T'_s
Ground Vibration
$\frac{T_s}{T_a} \sim \frac{T'_s}{T'_a}$



$$T_{\mathrm{i}}(\omega) = \frac{h_{\mathrm{inj}}(\omega)}{x_{\mathrm{inj}}(\omega)}$$



$$h_{\mathrm{prj}}(\omega) = T_{\mathrm{i}}(\omega) \cdot x(\omega)$$

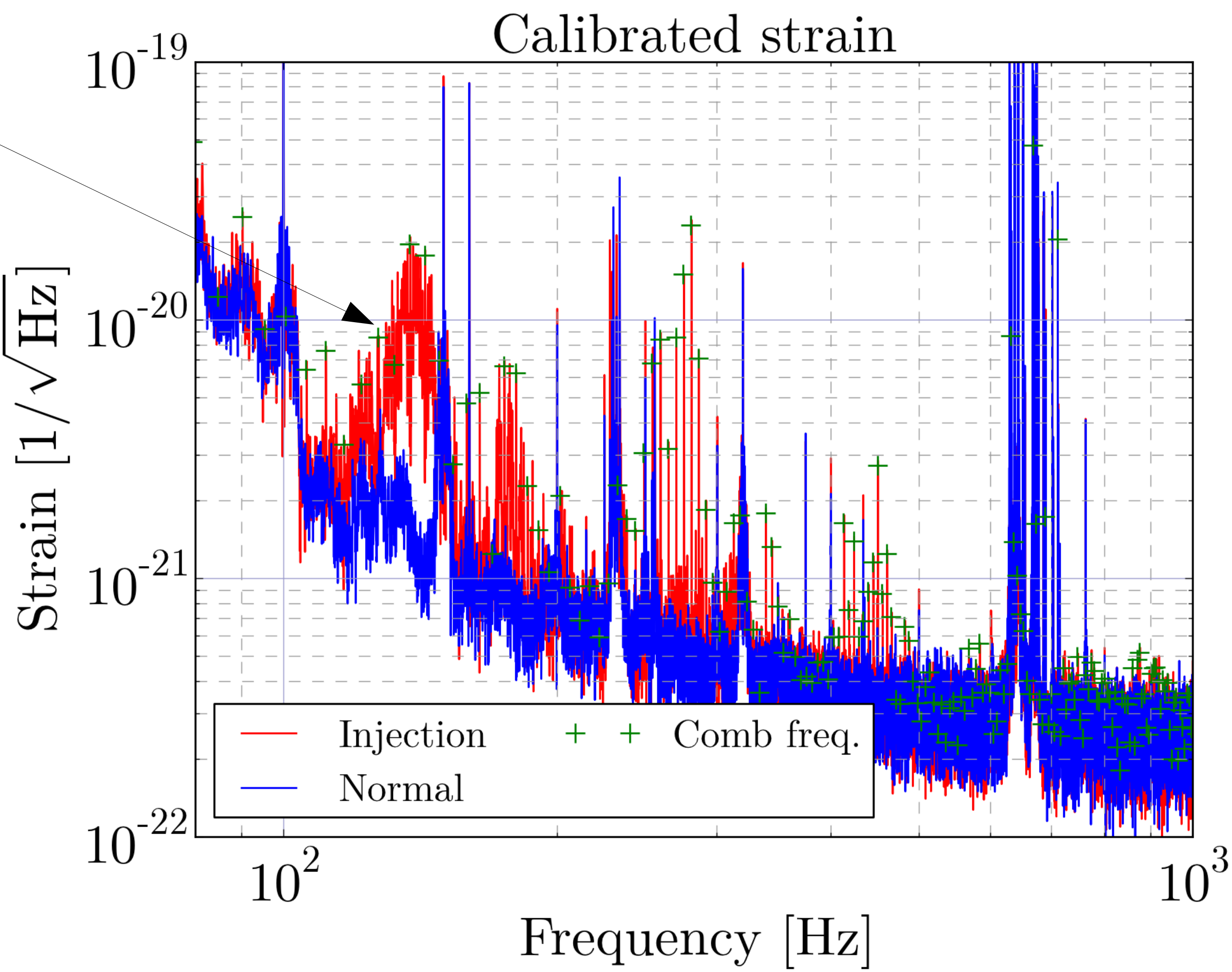
Saw Tooth Injection

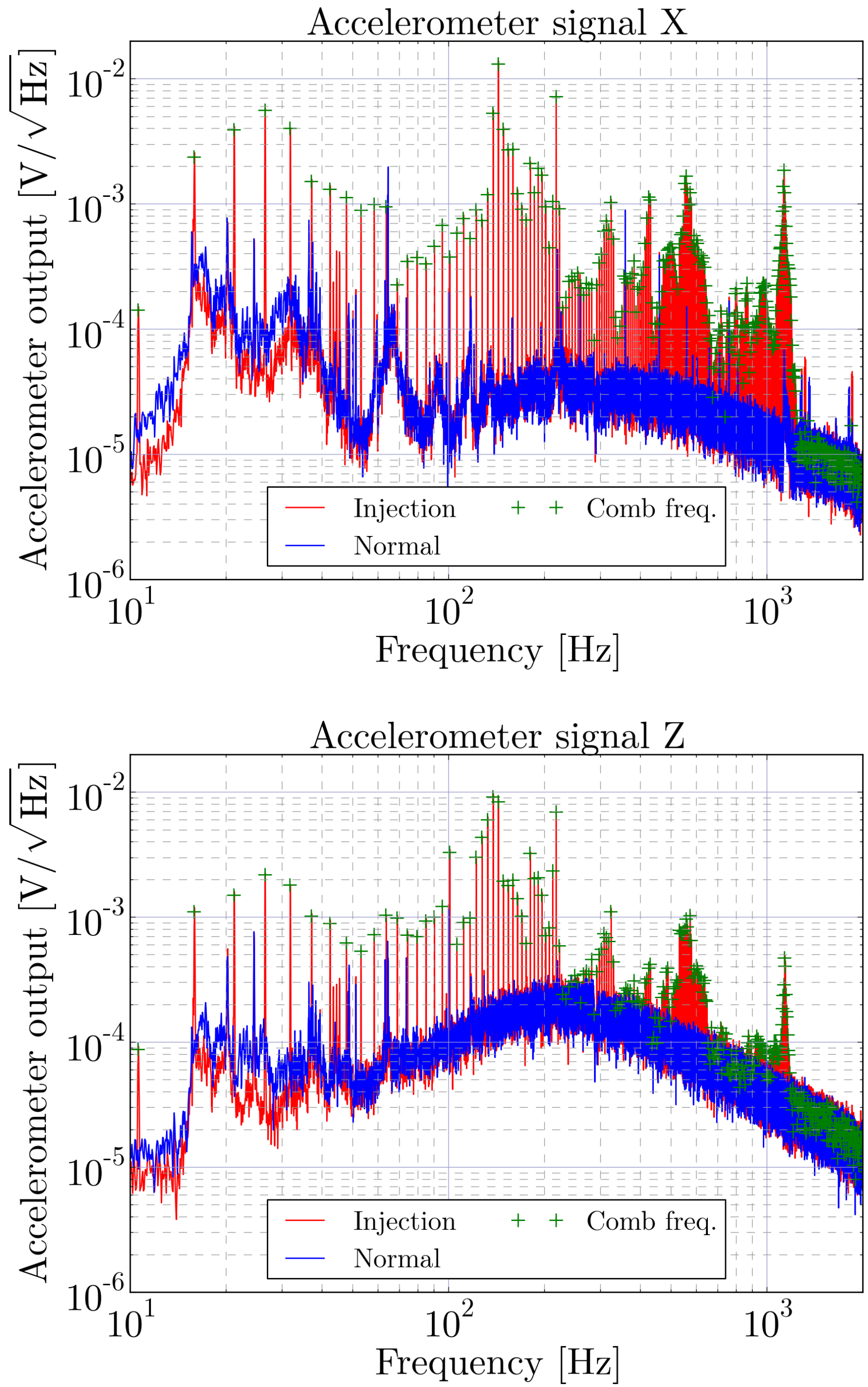
5.3Hz, 500mVpp to the shaker amplifier

13:34:40 – 13:38:00 (UTC)

Peaks appear in the strain noise

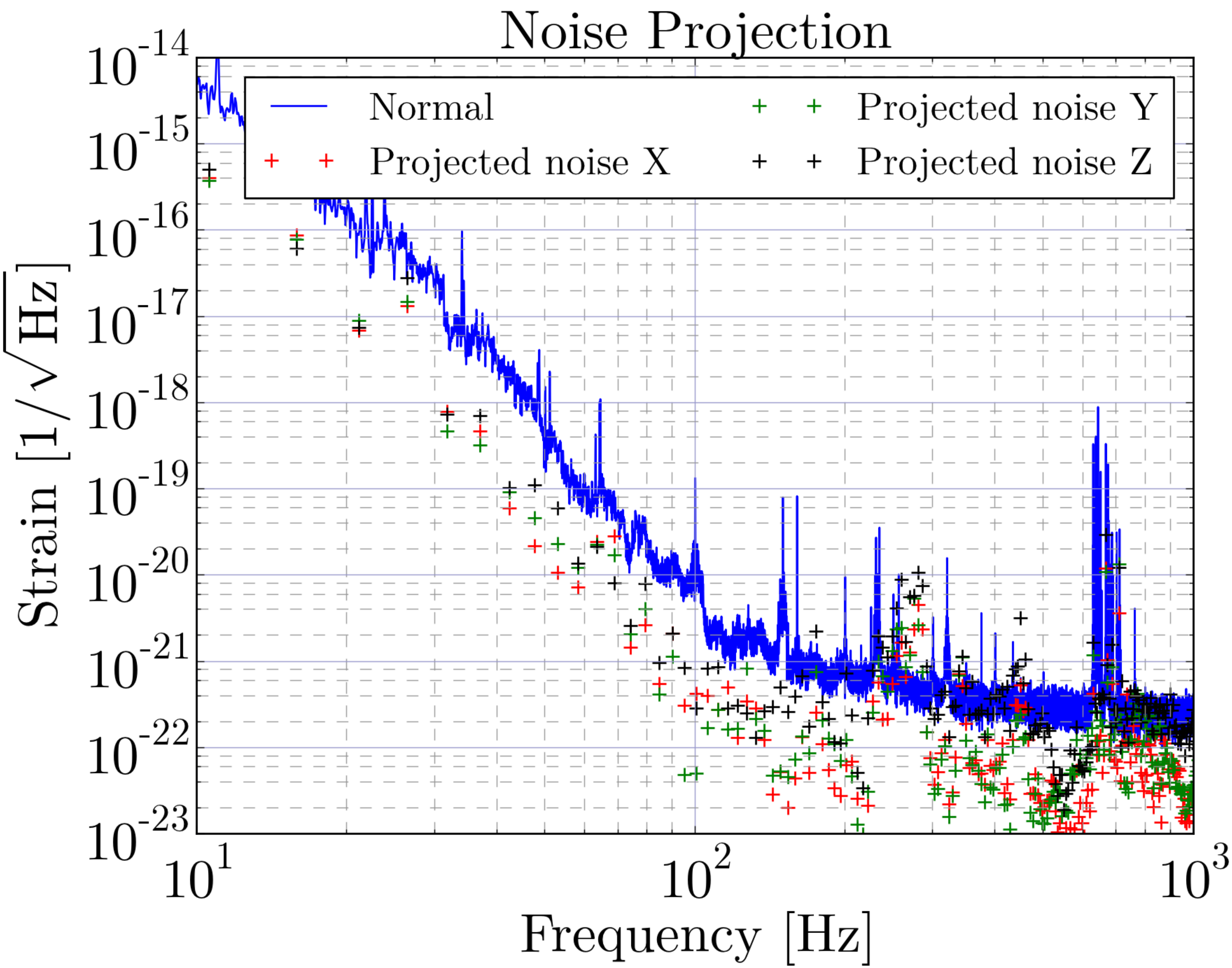
Broad noise





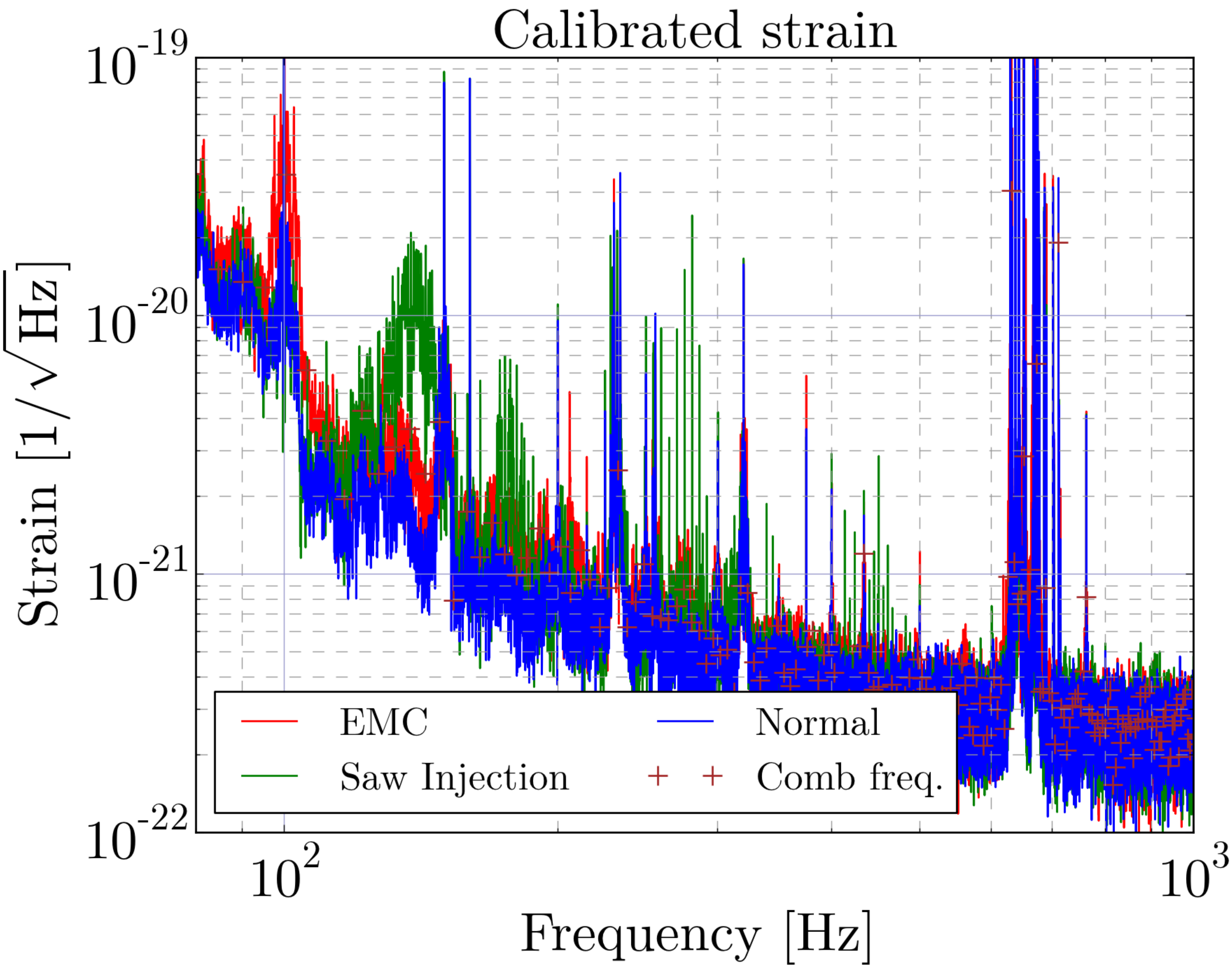
Comb appears in
the accelerometer signals

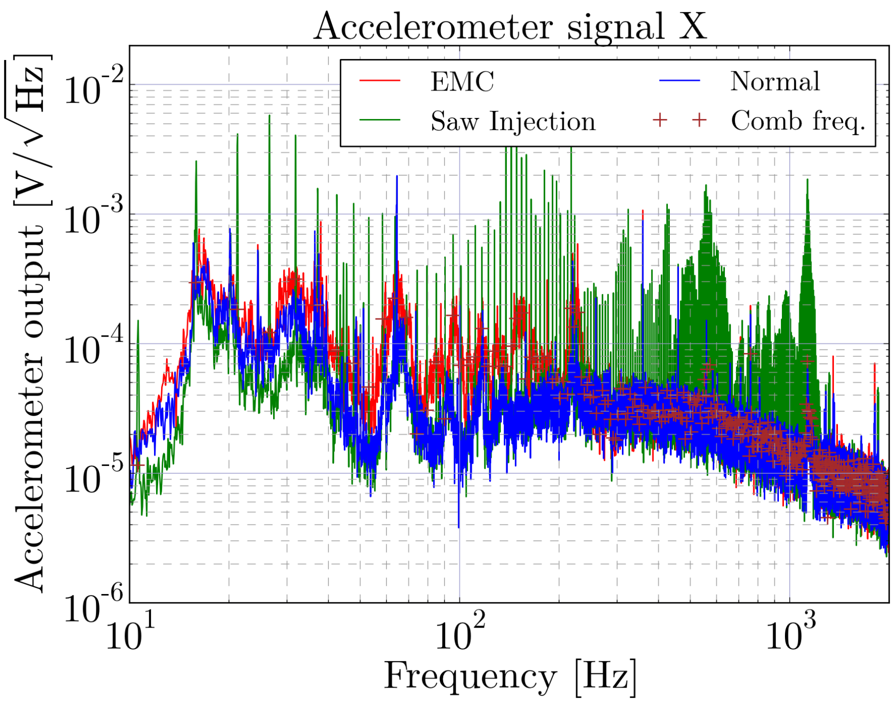
Projected noise

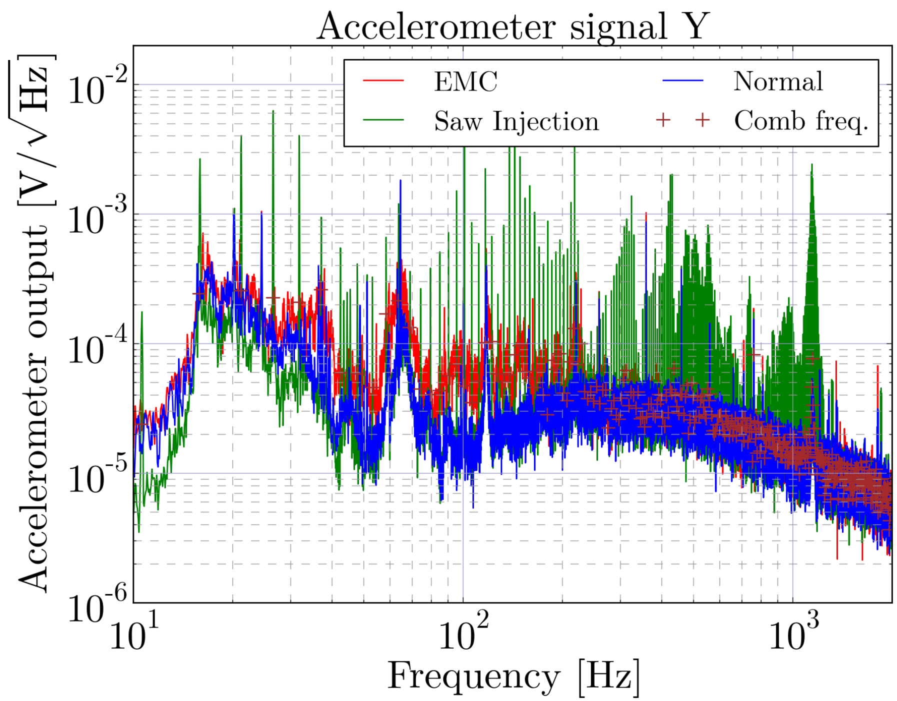


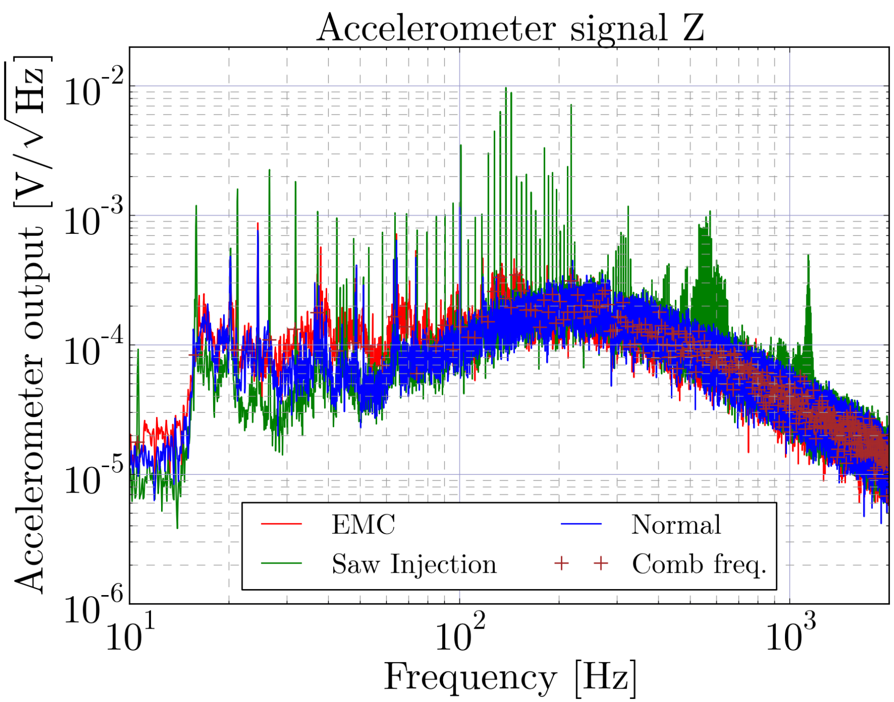
Electro-Magnetic Coupling (EMC)

Holding the shaker up in the air by hands

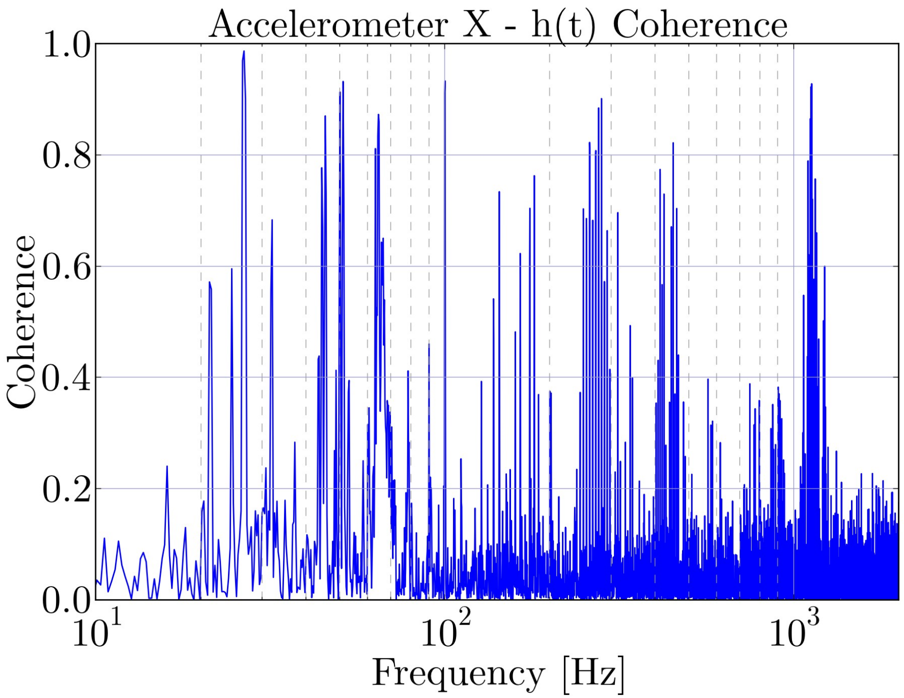


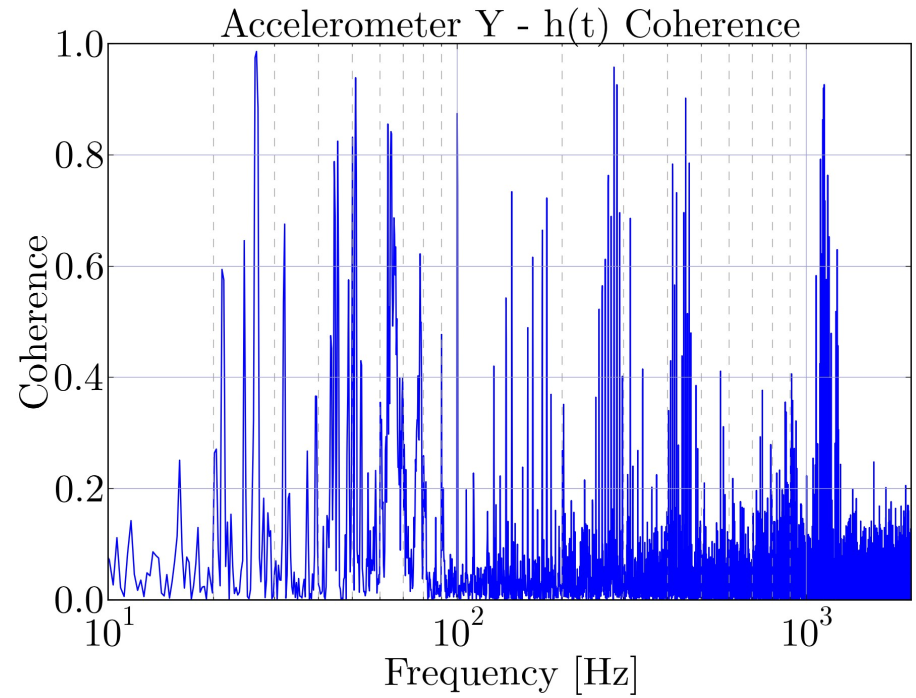


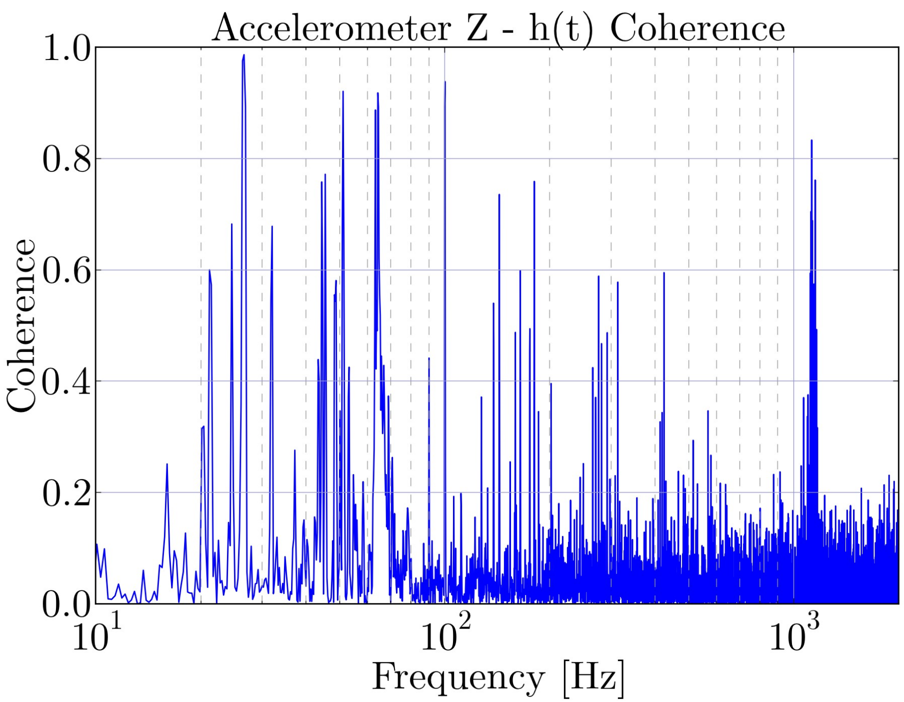




EMC for accelerometer signals

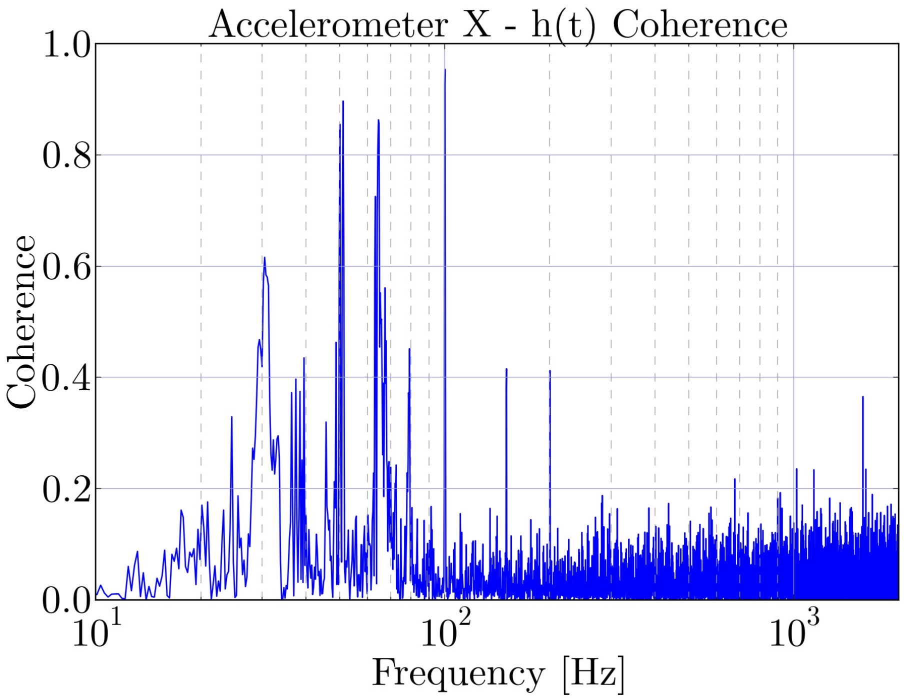


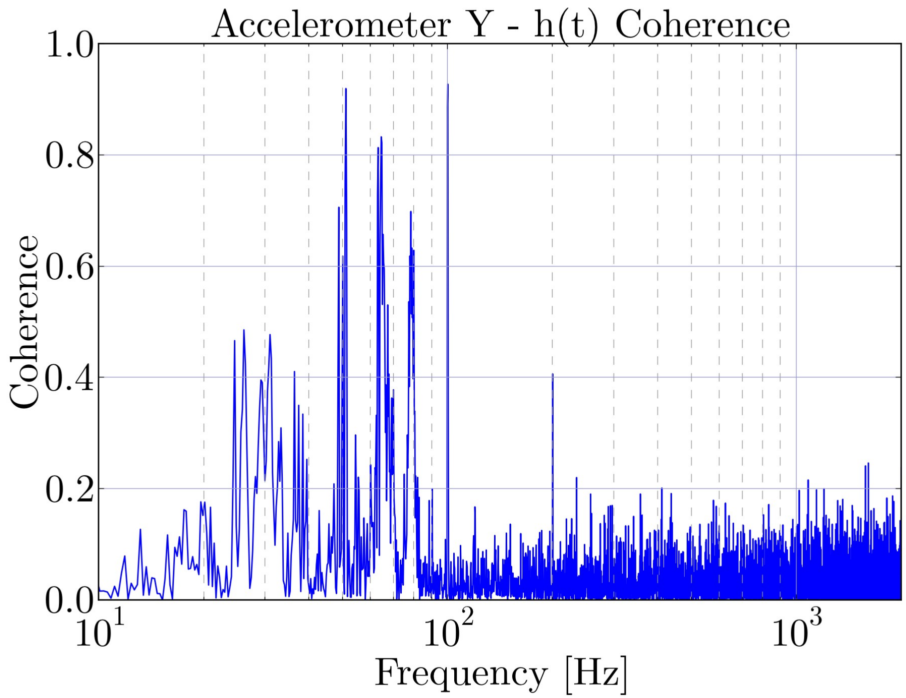


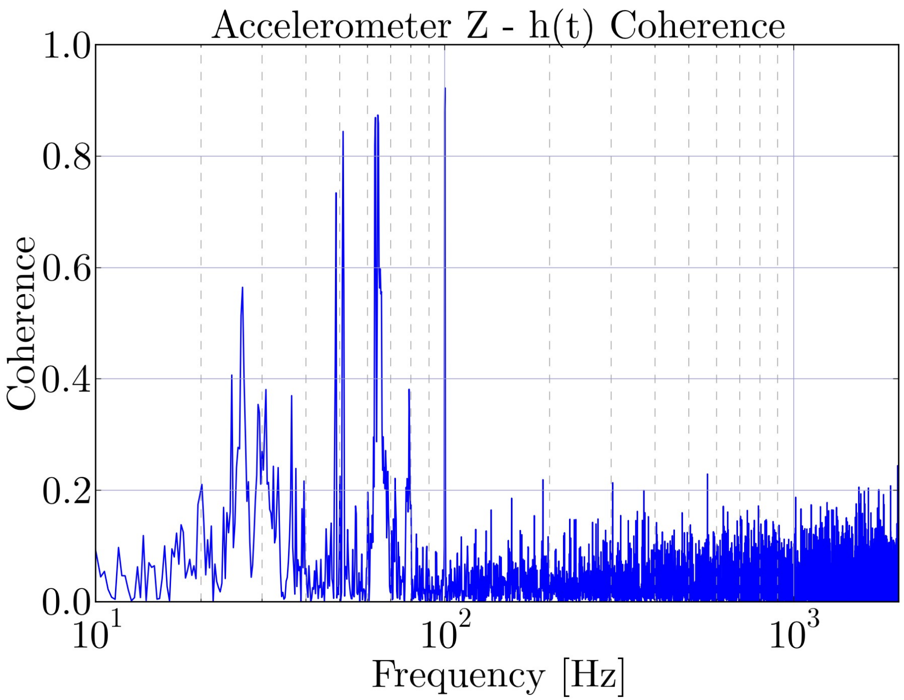


Coherence between accelerometers and h(t)

With Saw Tooth Injection







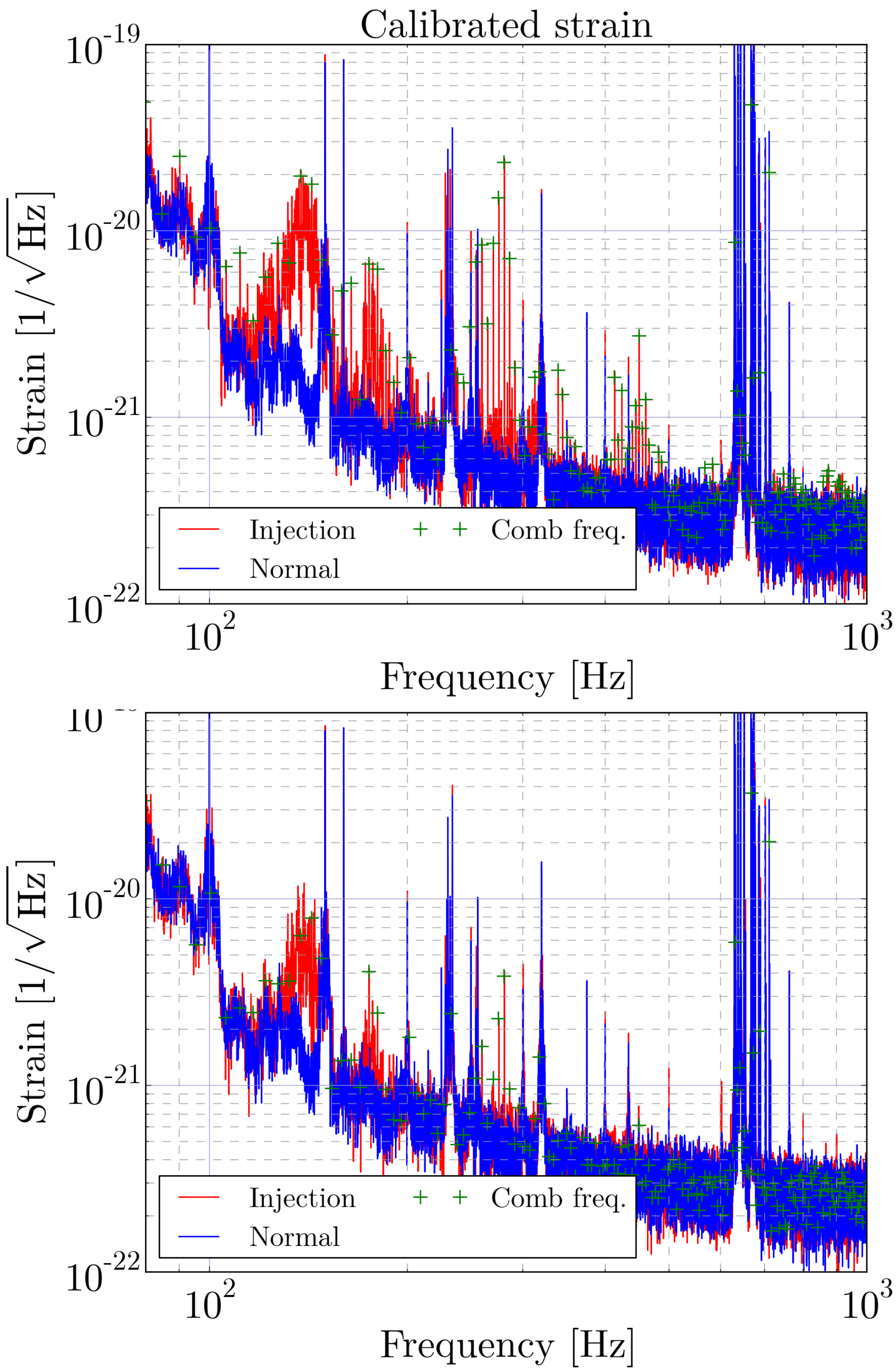
Coherence between accelerometers and h(t)

Quiet State

Saw Tooth Injection with different amplitudes

500mVpp

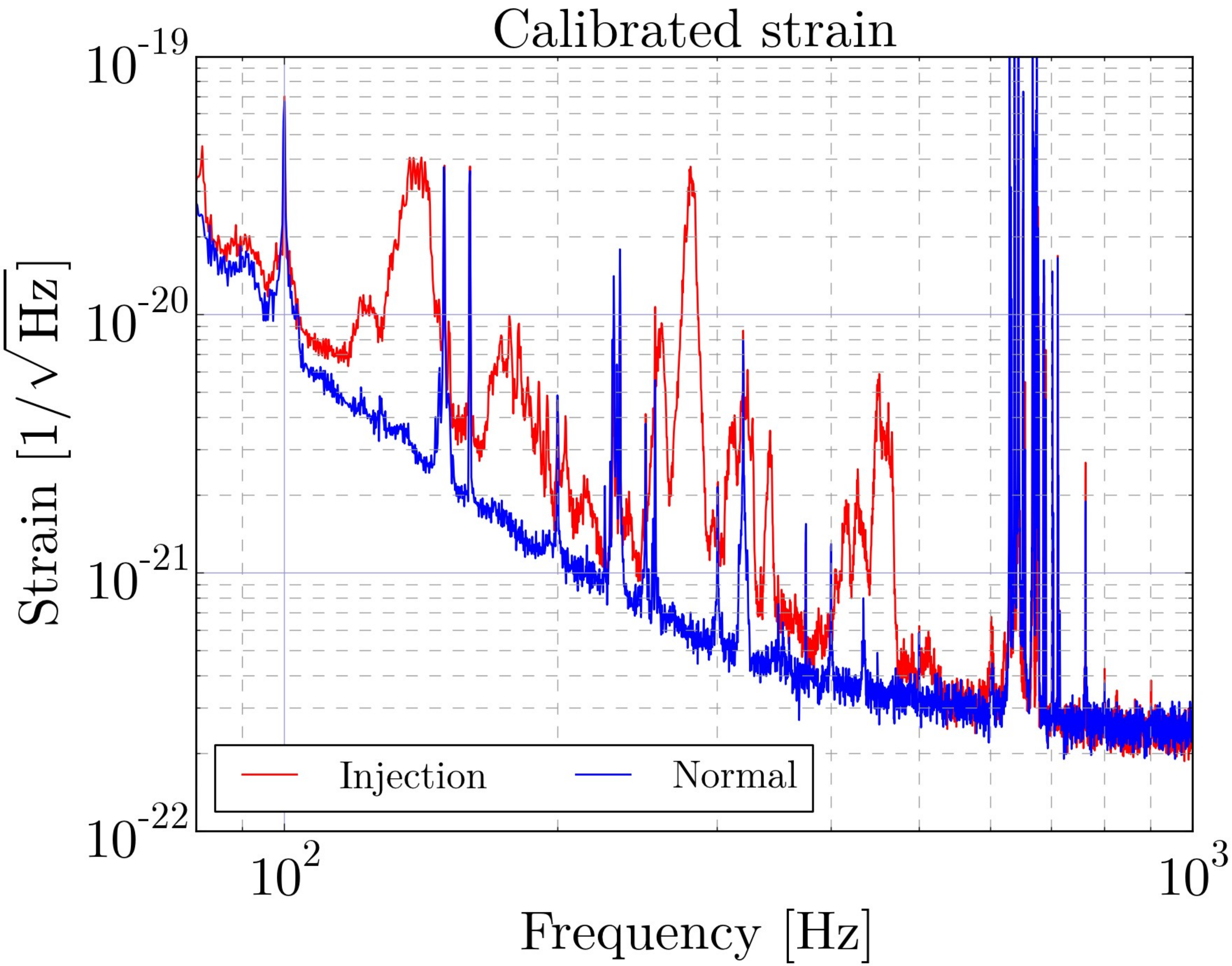
200mVpp

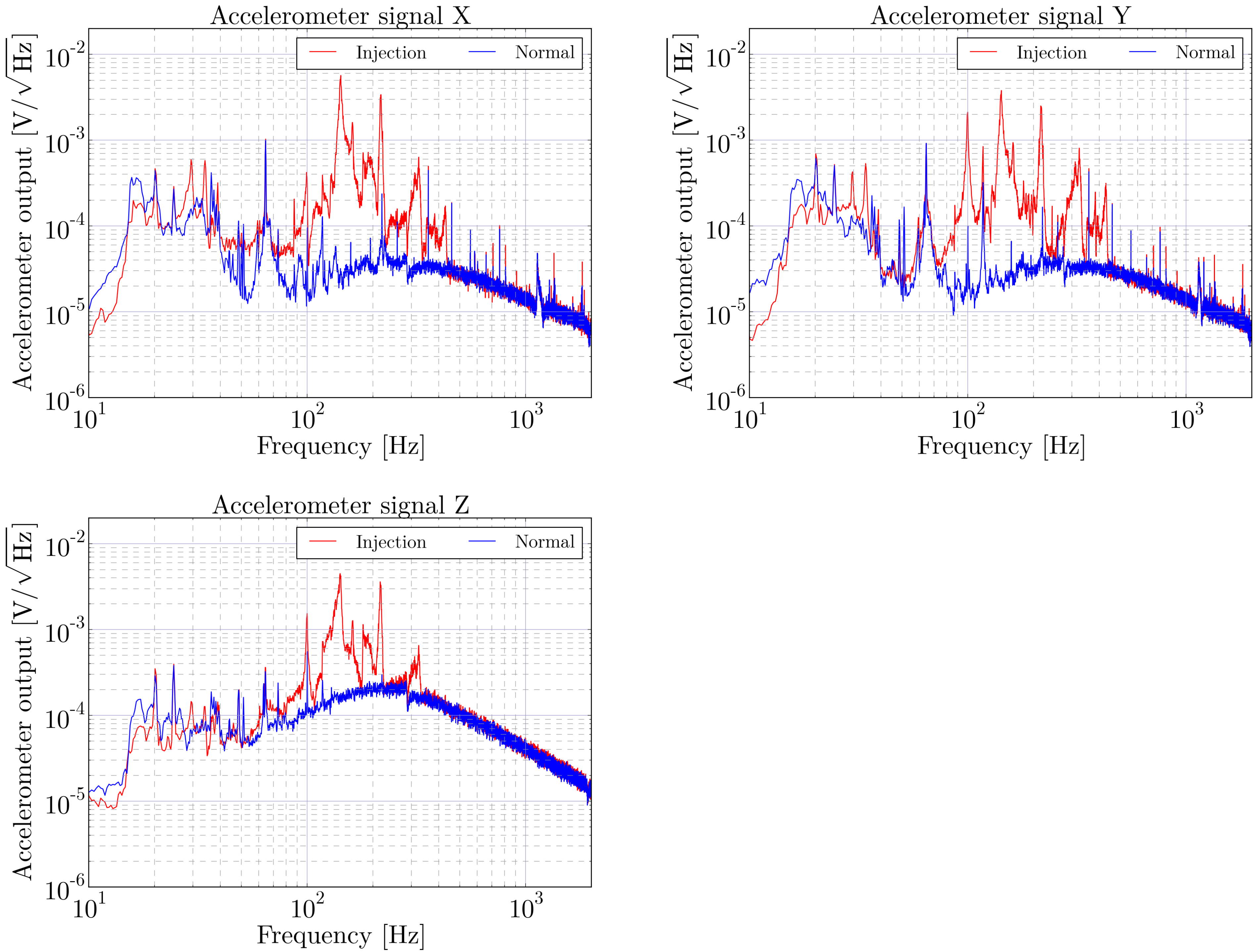


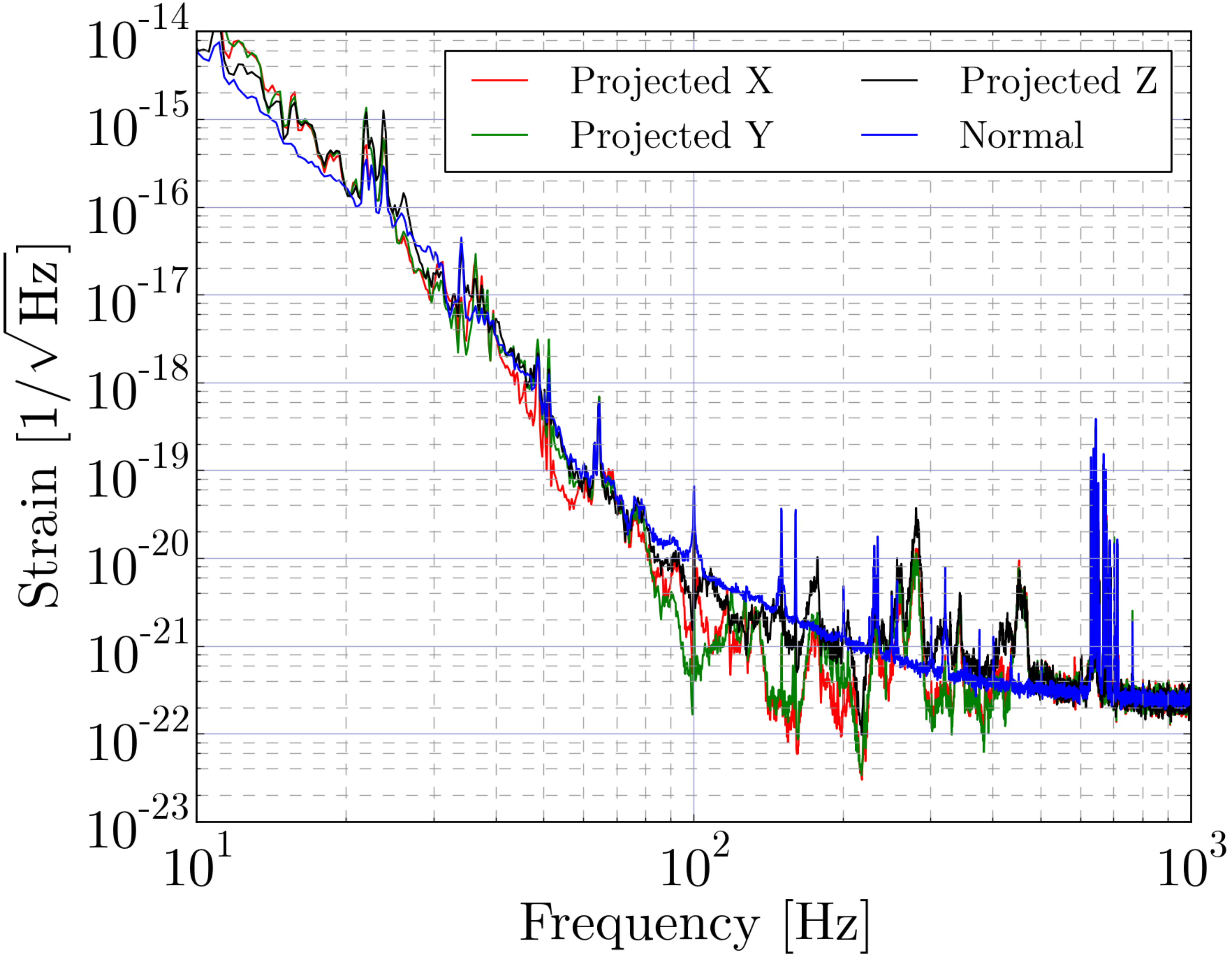
Band Limited White Noise (BLWN) Injection

100-300Hz, 500mVpp to the shaker amplifier

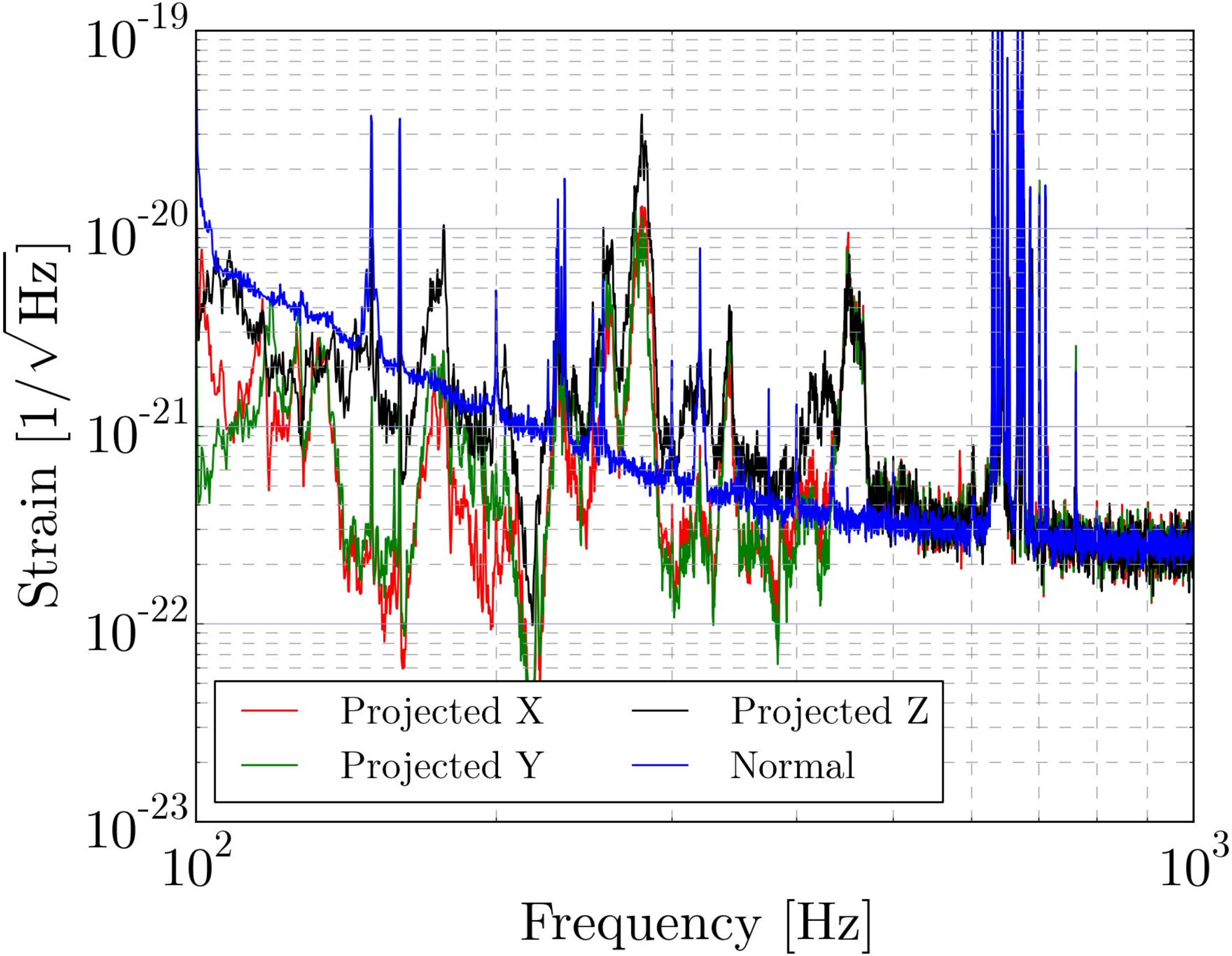
14:06:30 – 14:09:10 (UTC)




Accelerometer signal X
Injection
Normal
Accelerometer output [V/√Hz]
Frequency [Hz]
Accelerometer signal Y
Injection
Normal
Accelerometer output [V/√Hz]
Frequency [Hz]
Accelerometer signal Z
Injection
Normal
Accelerometer output [V/√Hz]
Frequency [Hz]

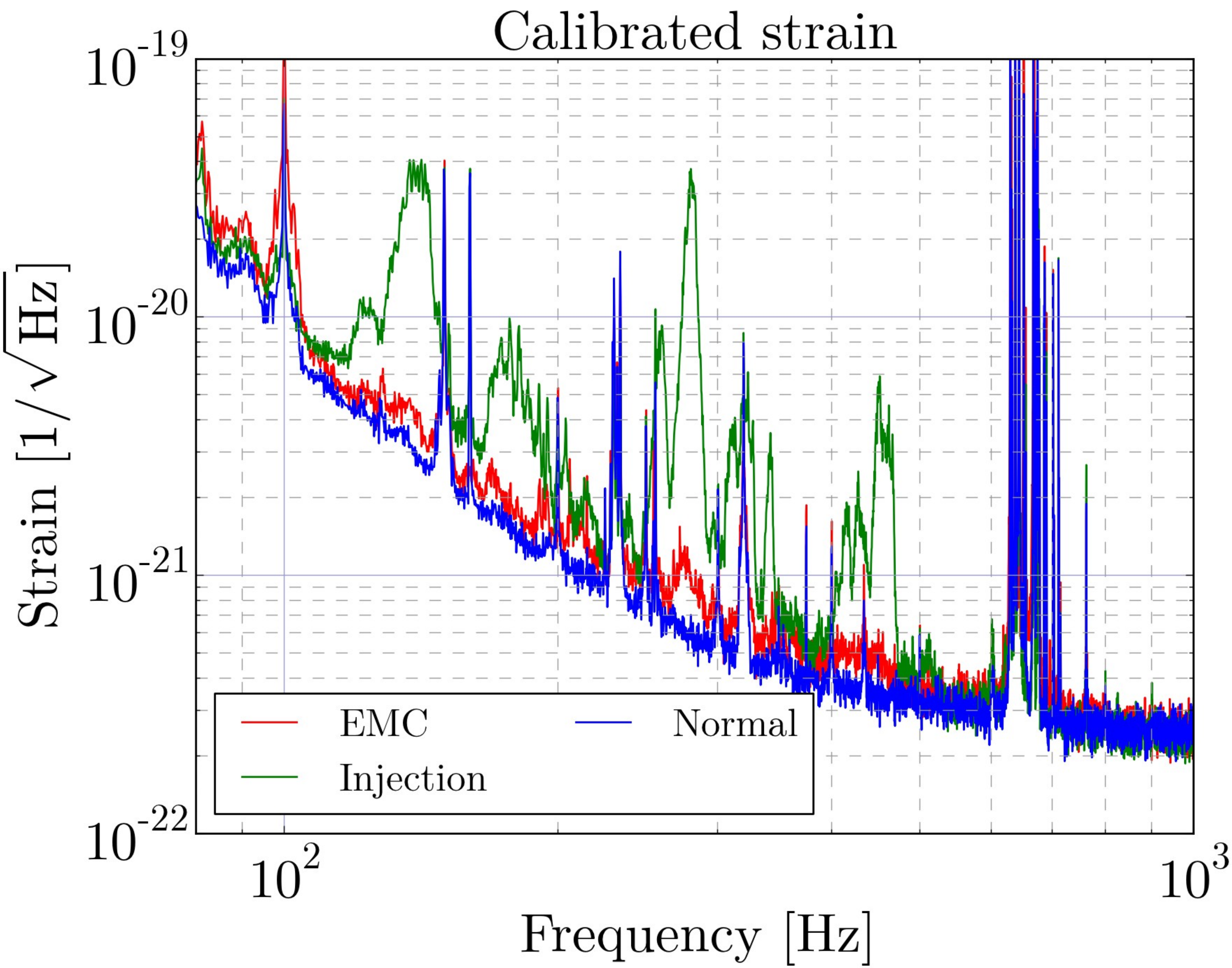


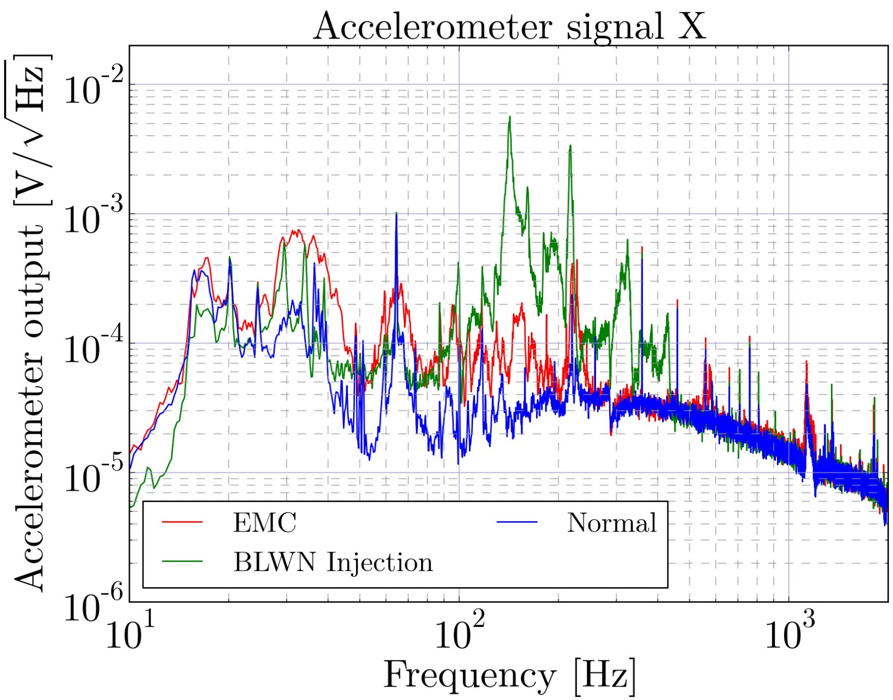
Projected X
Projected Y
Projected Z
Normal
Strain [1/√Hz]
Frequency [Hz]
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{1}
10^{2}
10^{3}

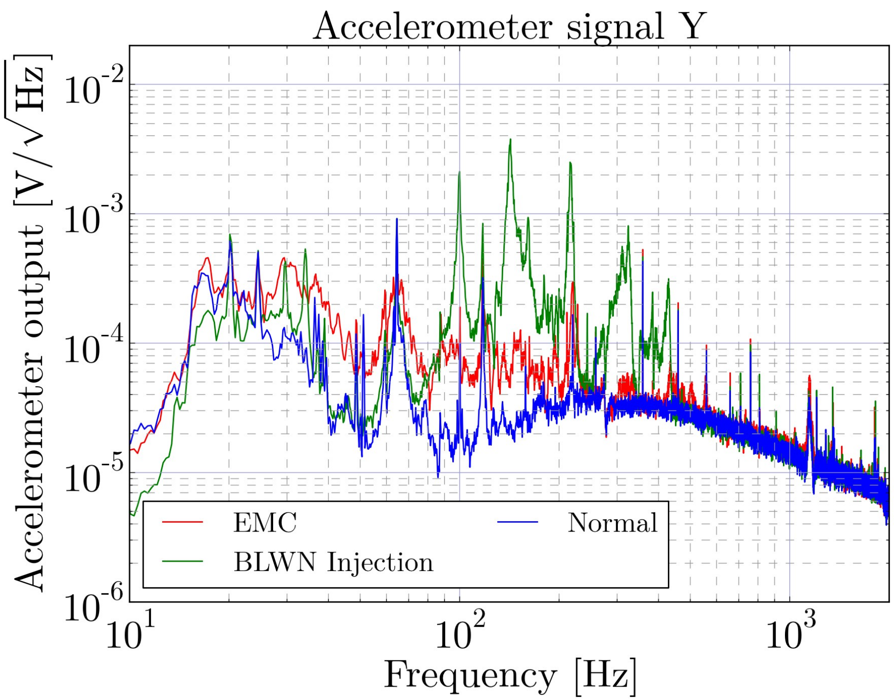


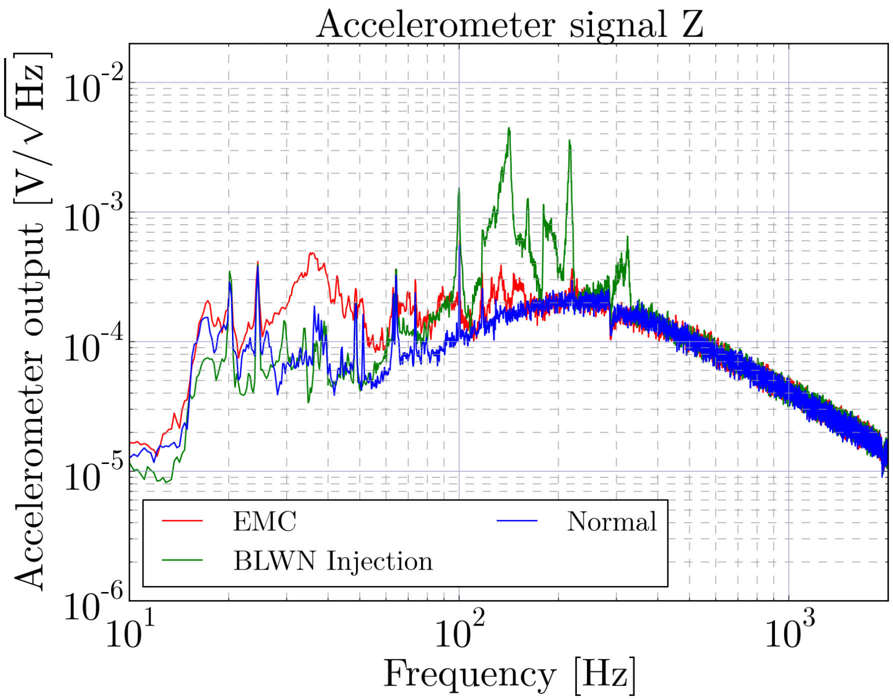
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{2}
10^{3}
Strain $[1/\sqrt{\mathrm{Hz}}]$
Frequency [Hz]
Projected X
Projected Y
Projected Z
Normal

Electro-Magnetic Coupling (EMC)

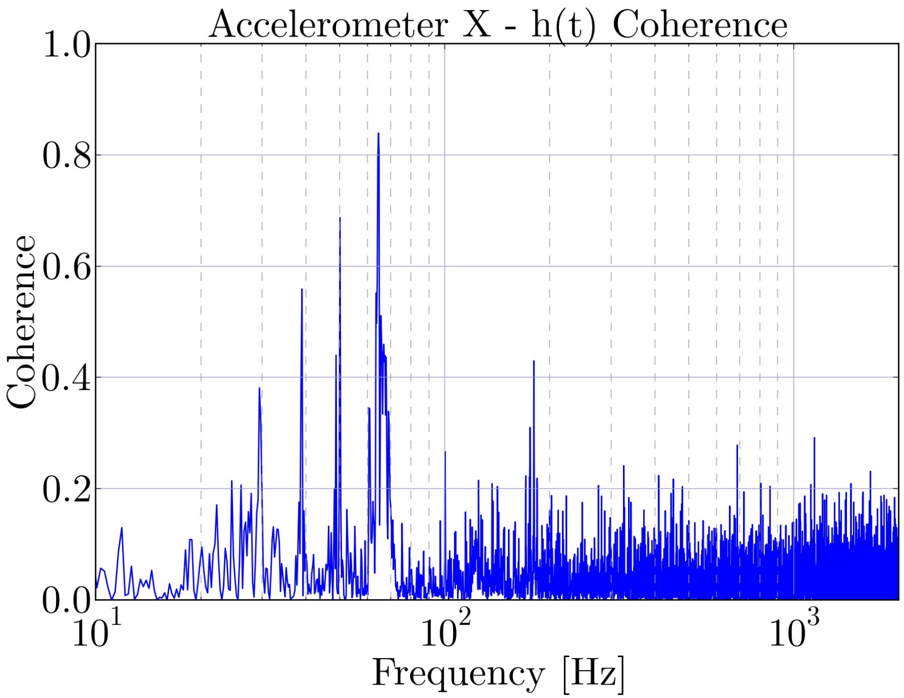


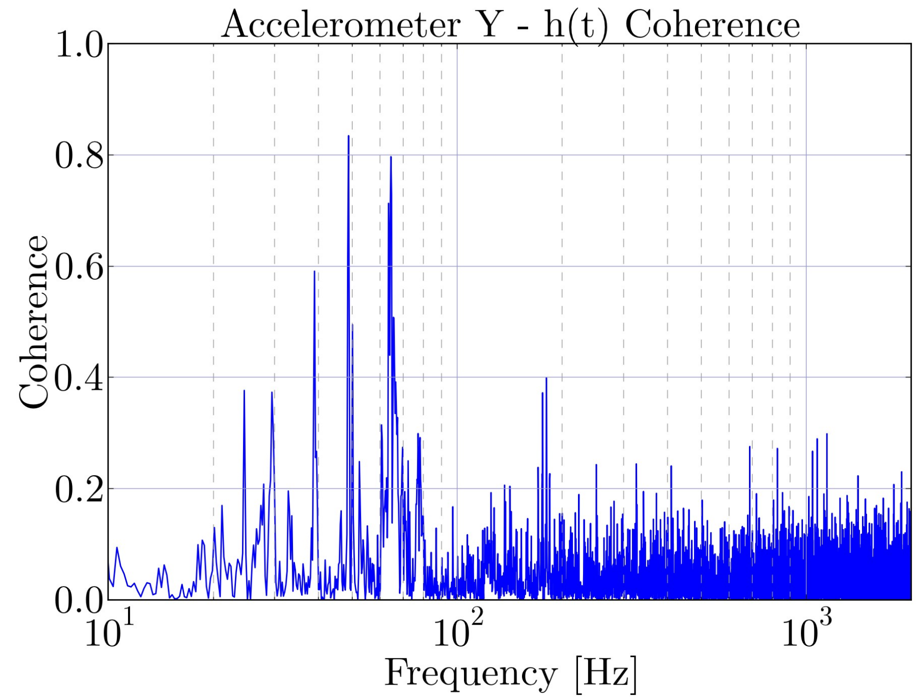


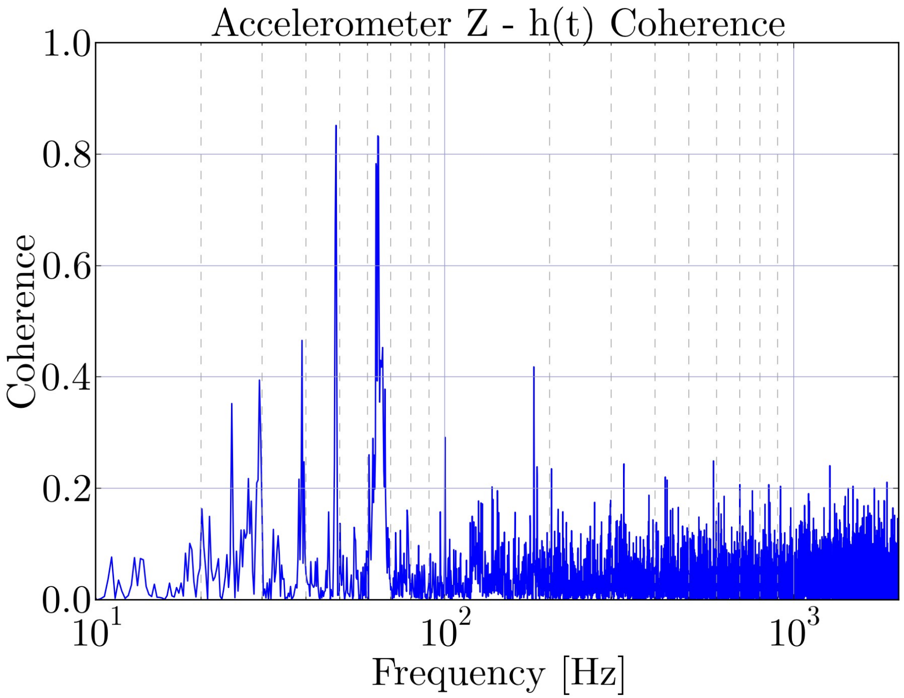




EMC for accelerometer signals

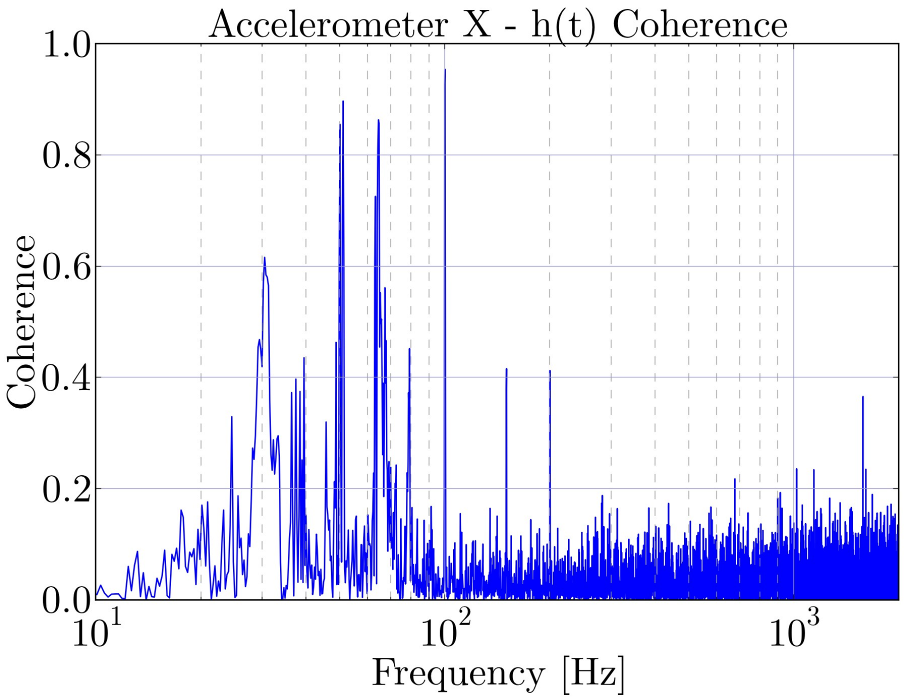


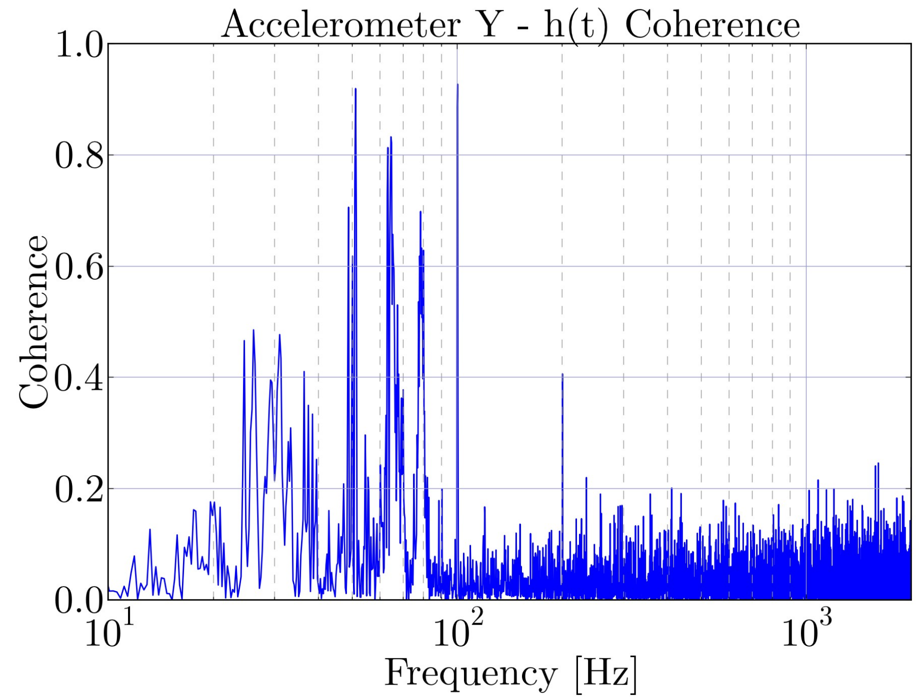


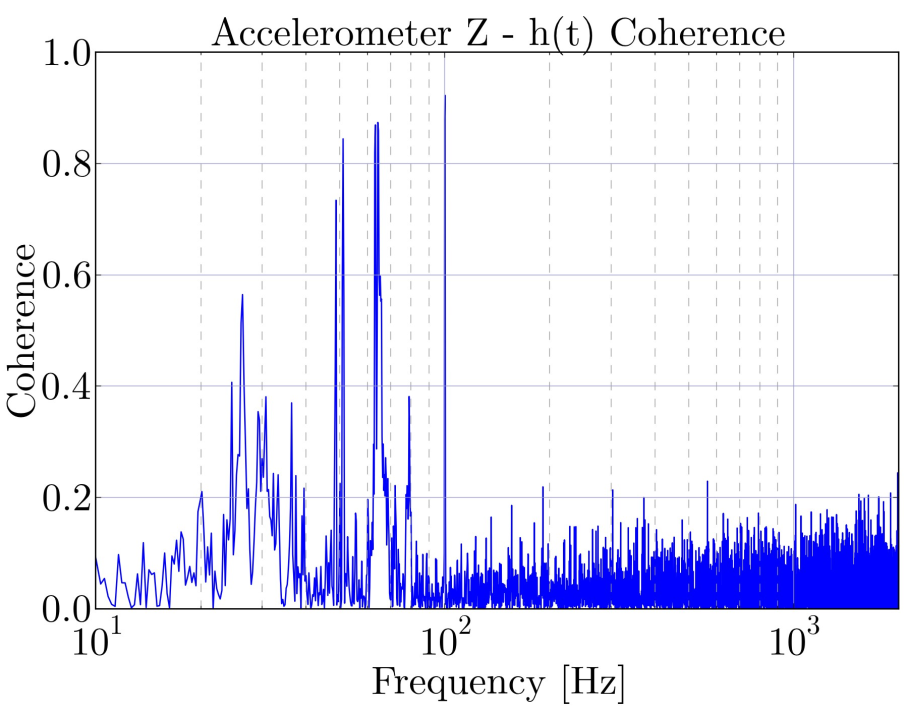


Coherence between accelerometers and h(t)

BLWN Injection





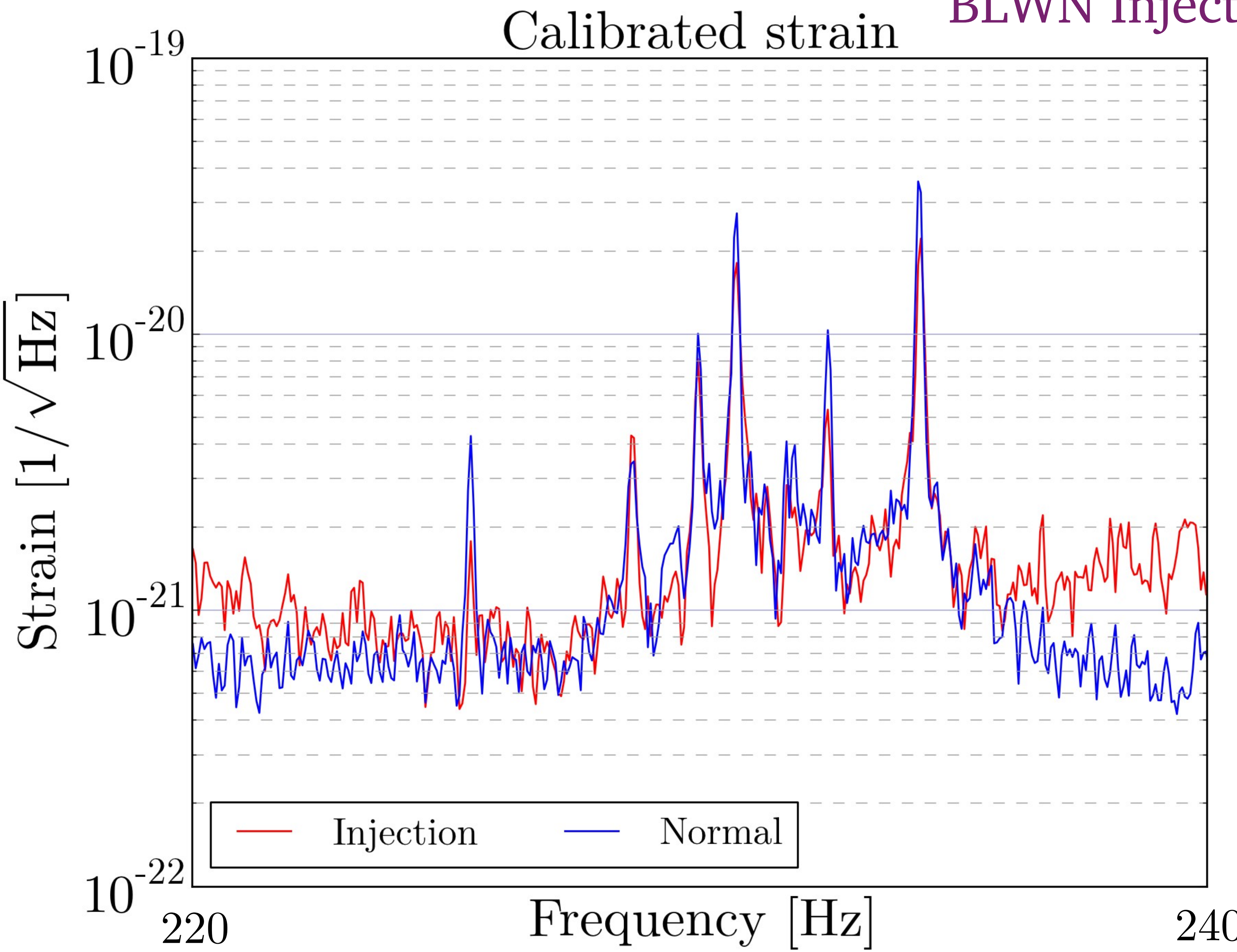


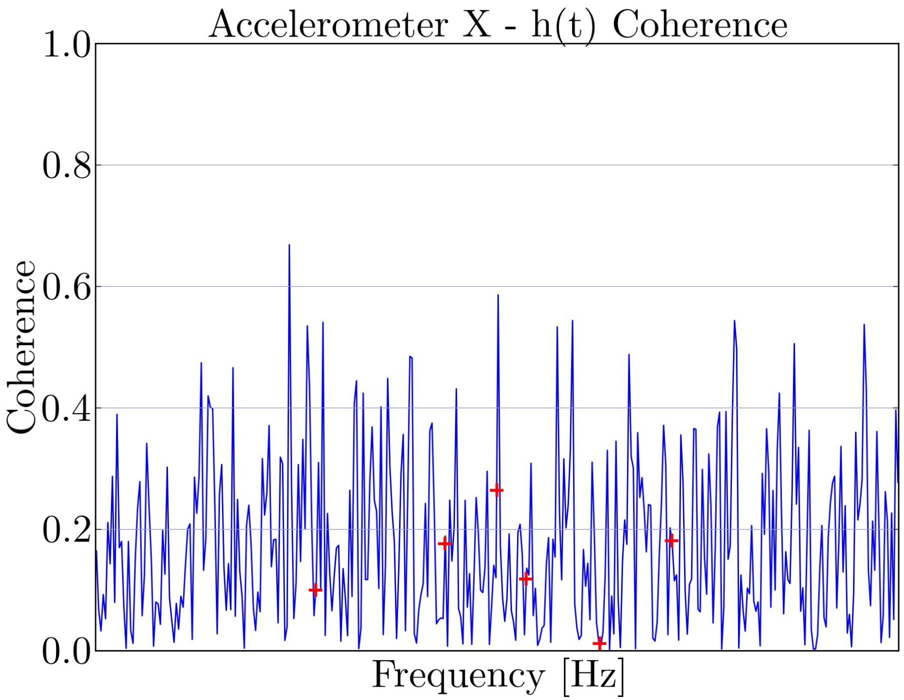
Coherence between accelerometers and h(t)

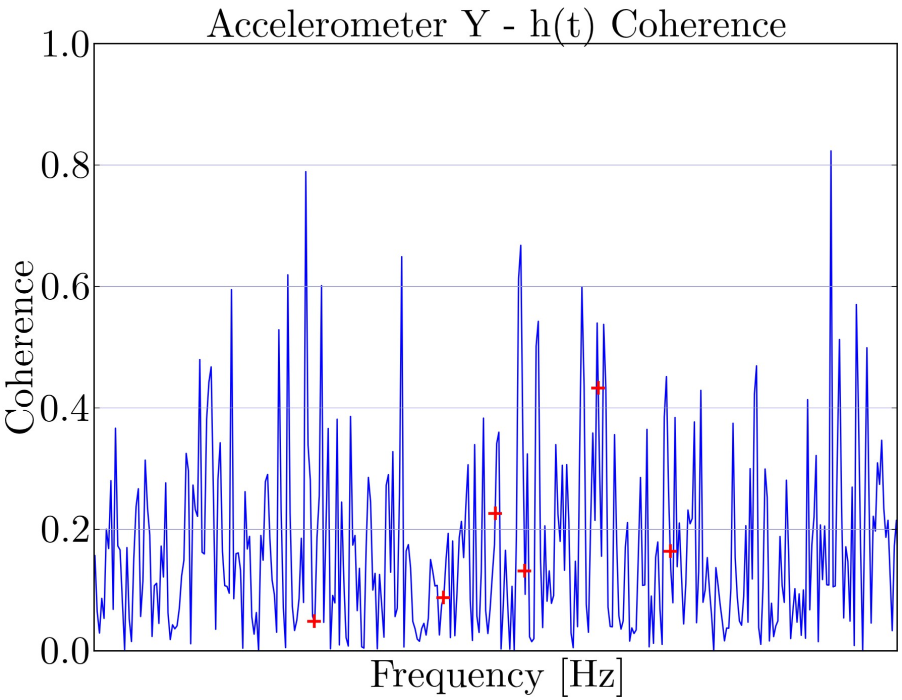
Quiet State

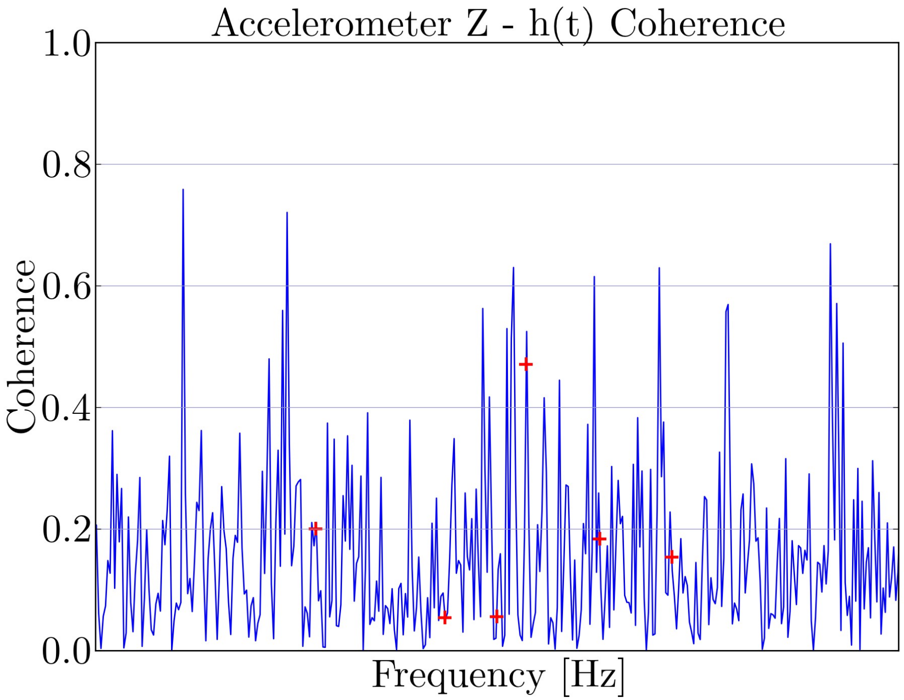
230Hz peaks

BLWN Injection









BLWN Injection

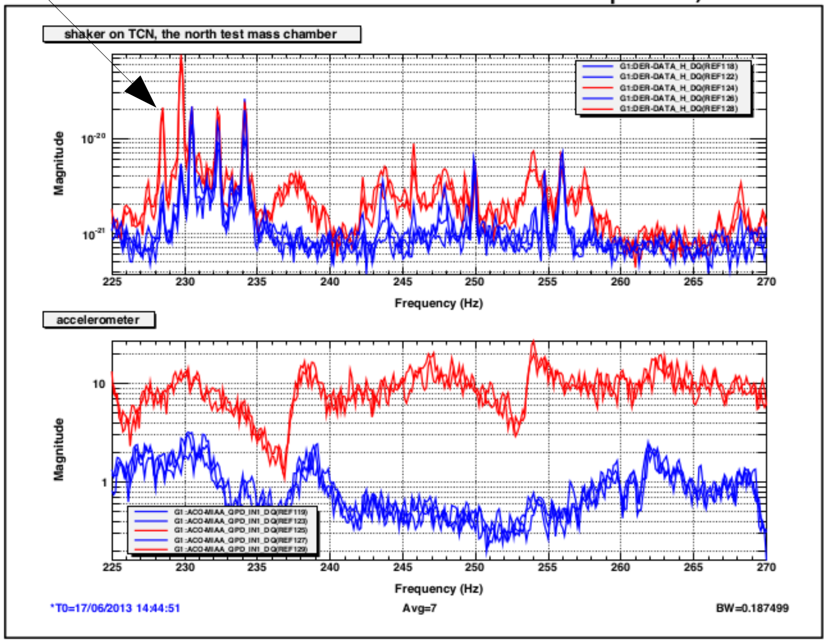
Coherence Zoom
220Hz - 240Hz

Clipping ?

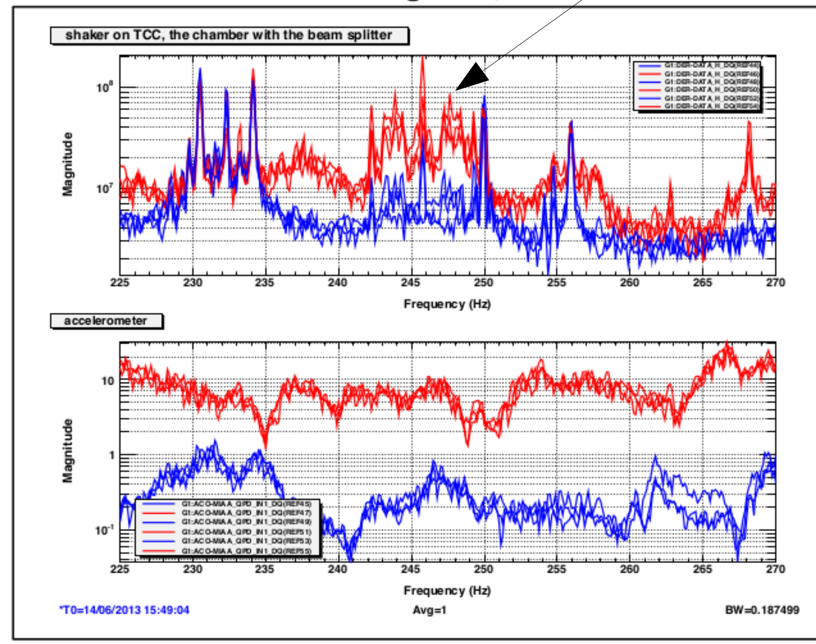
Continued Shaking Tests

Scattering ?

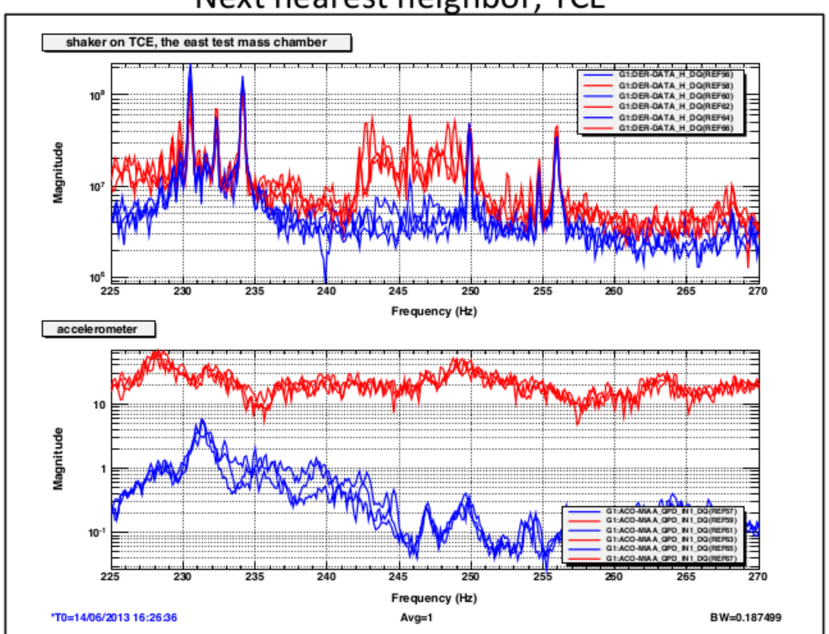
Chamber with 2 excitable 230 Hz peaks, TCN



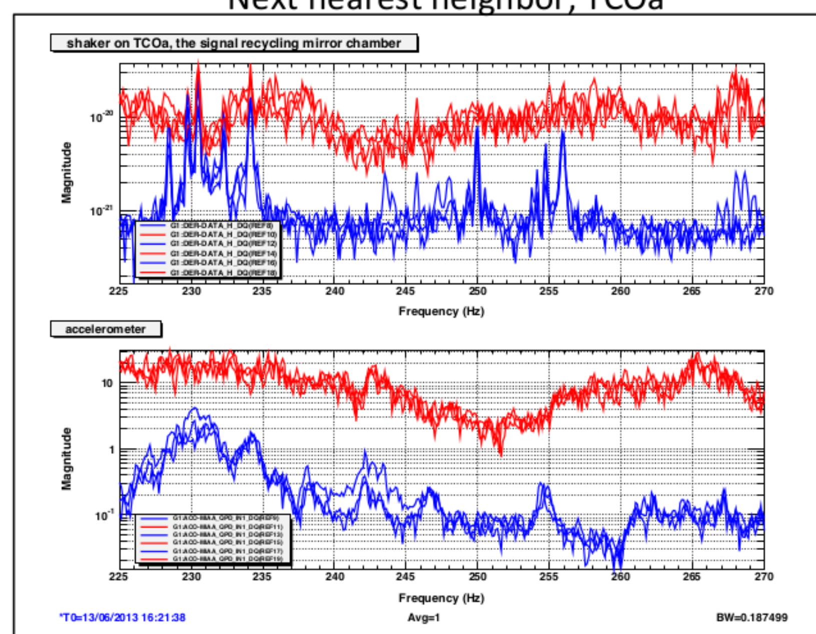
Nearest neighbor, TCC



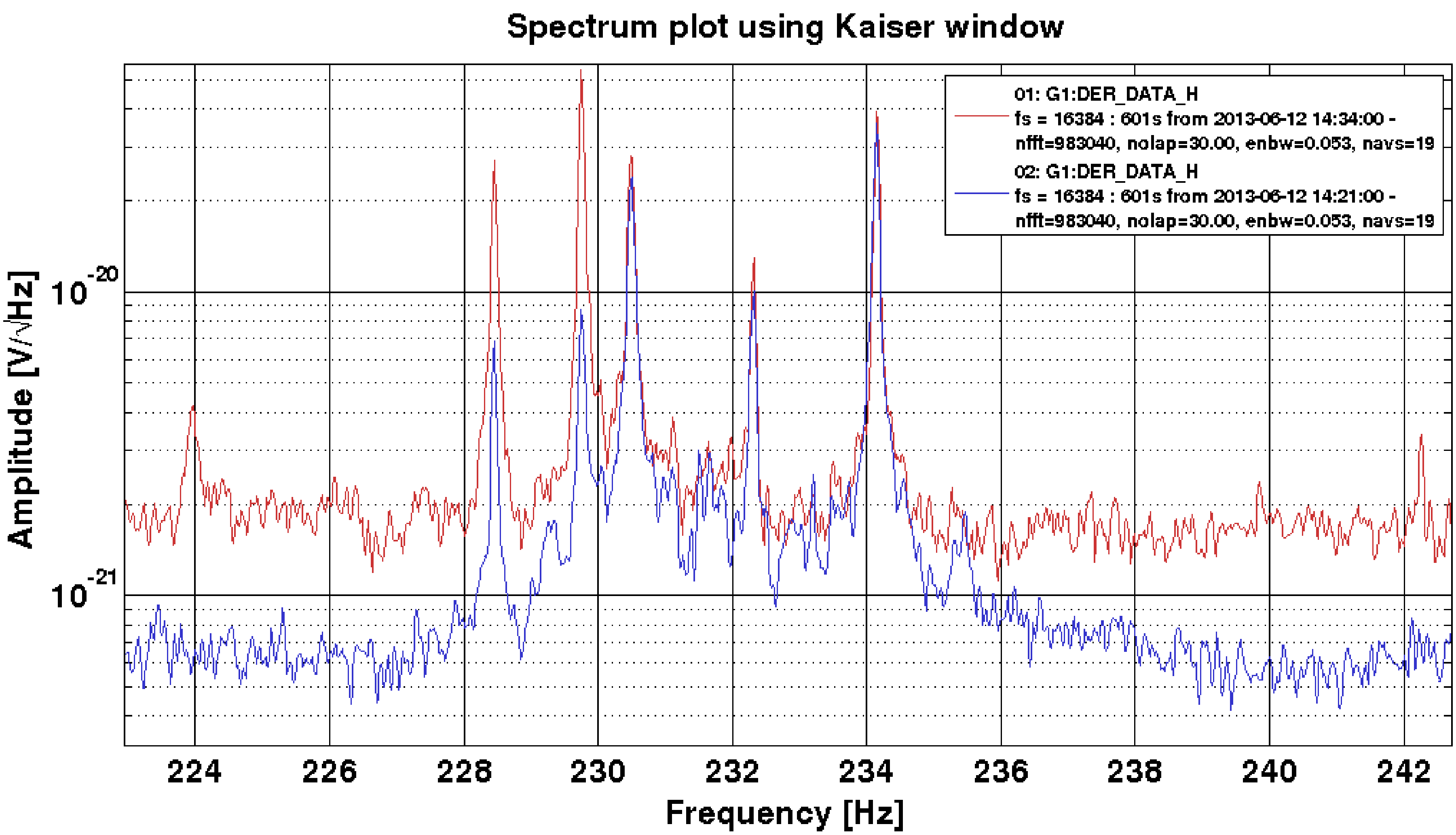
Next nearest neighbor, TCE



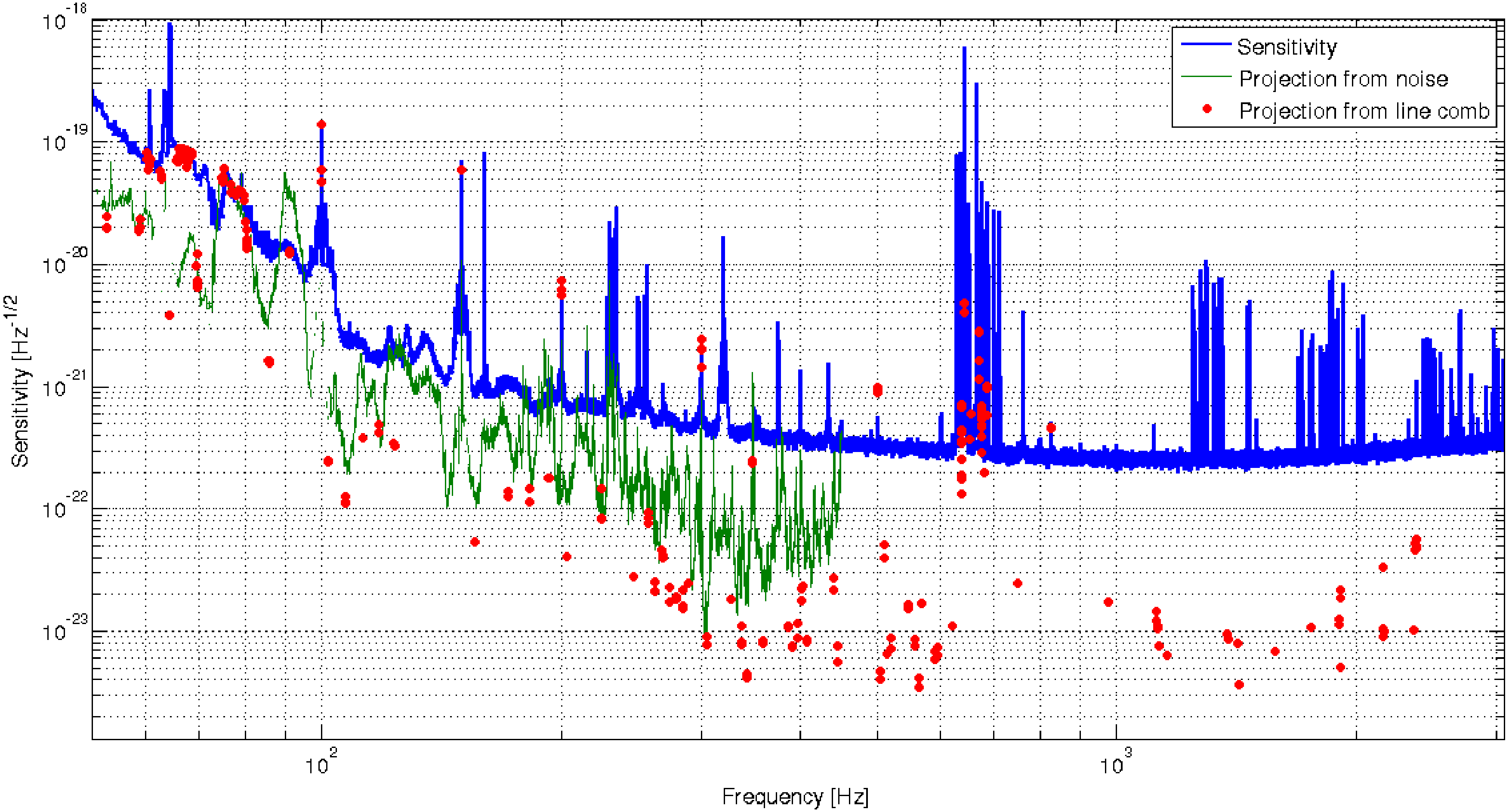
Next nearest neighbor, TCOa



Acoustic Injections

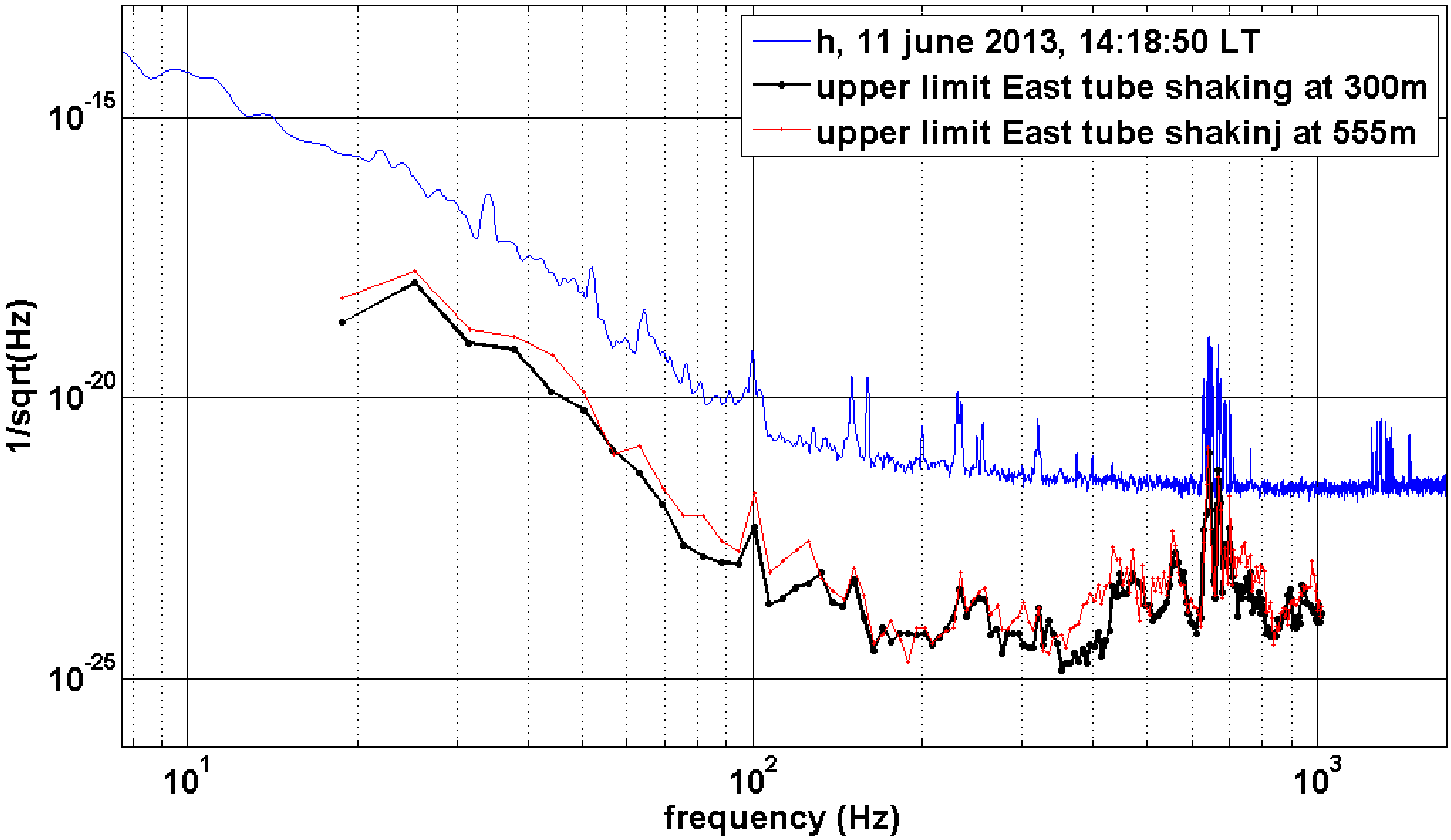


Acoustic Noise Projection

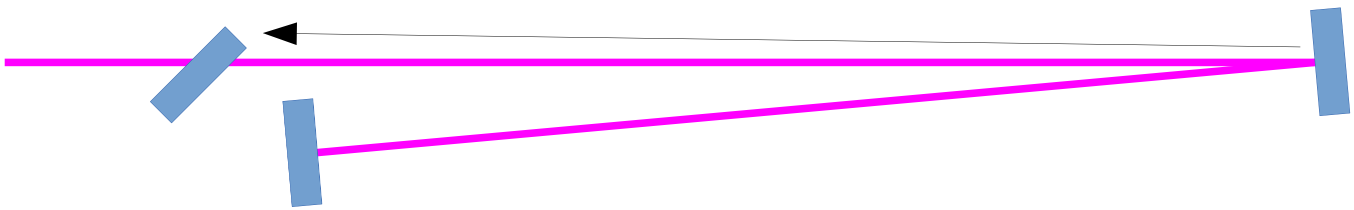


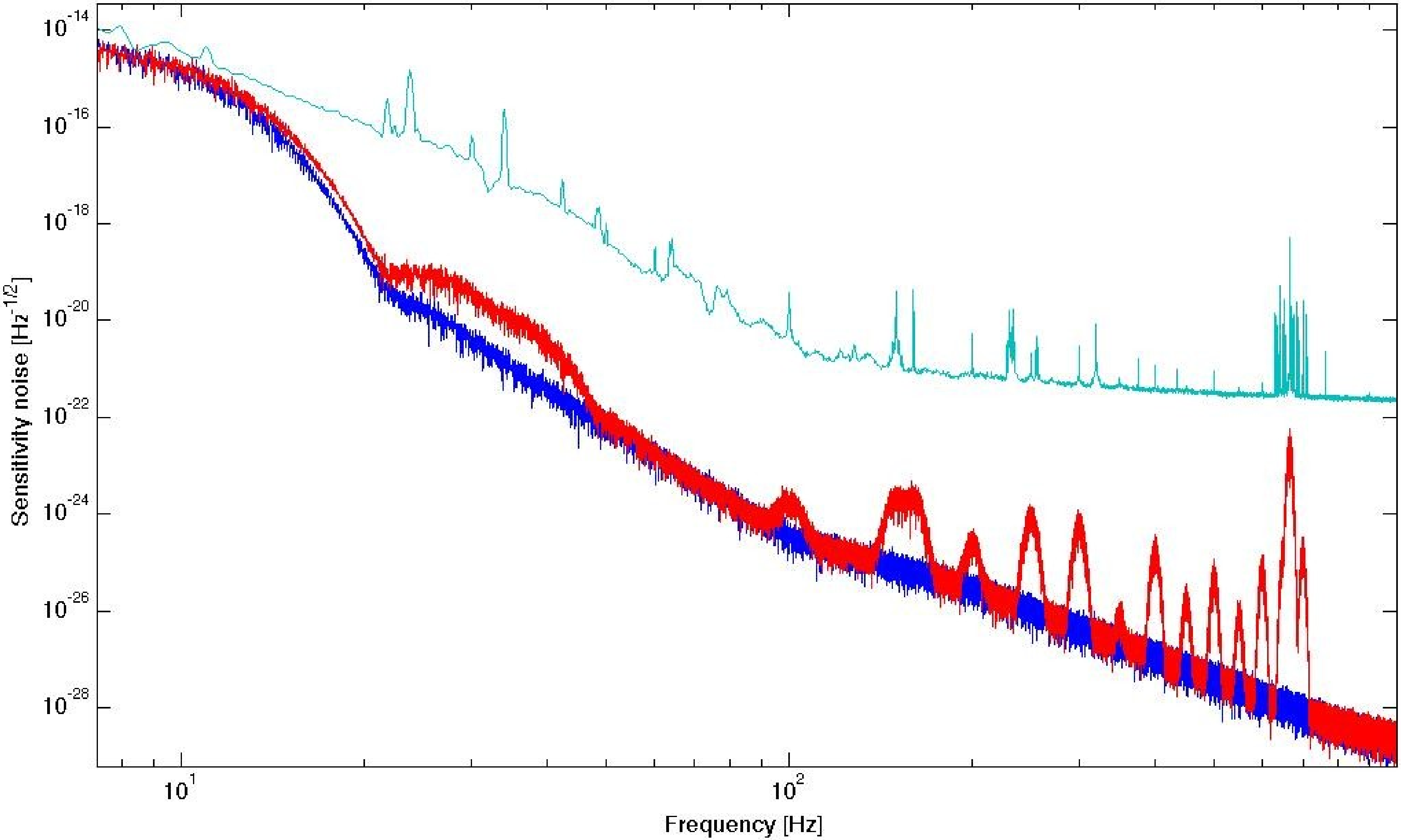
Beam Tube Shaking

Beam Tube Noise Projection



Folding Mirror Phase Map → Noise Projection

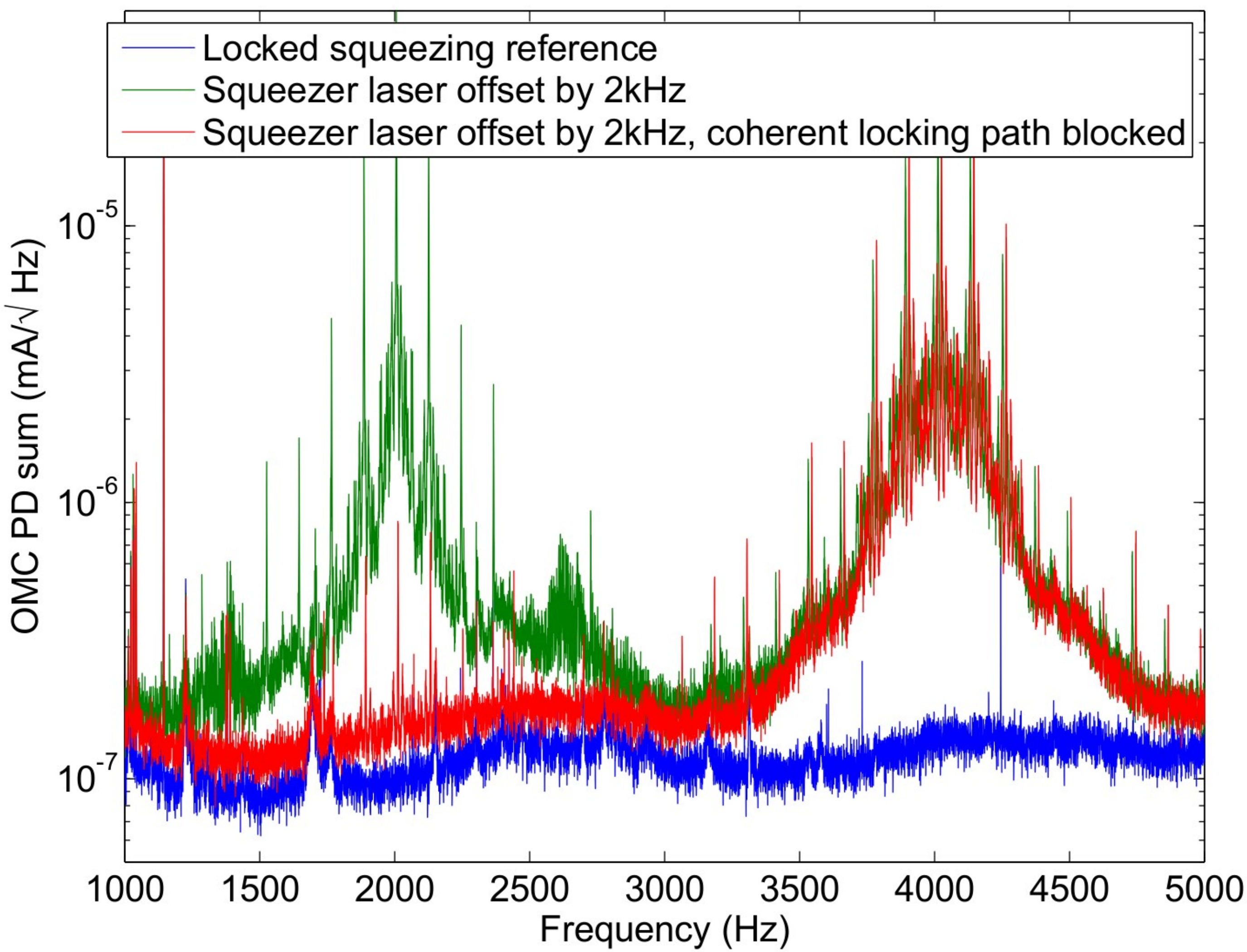




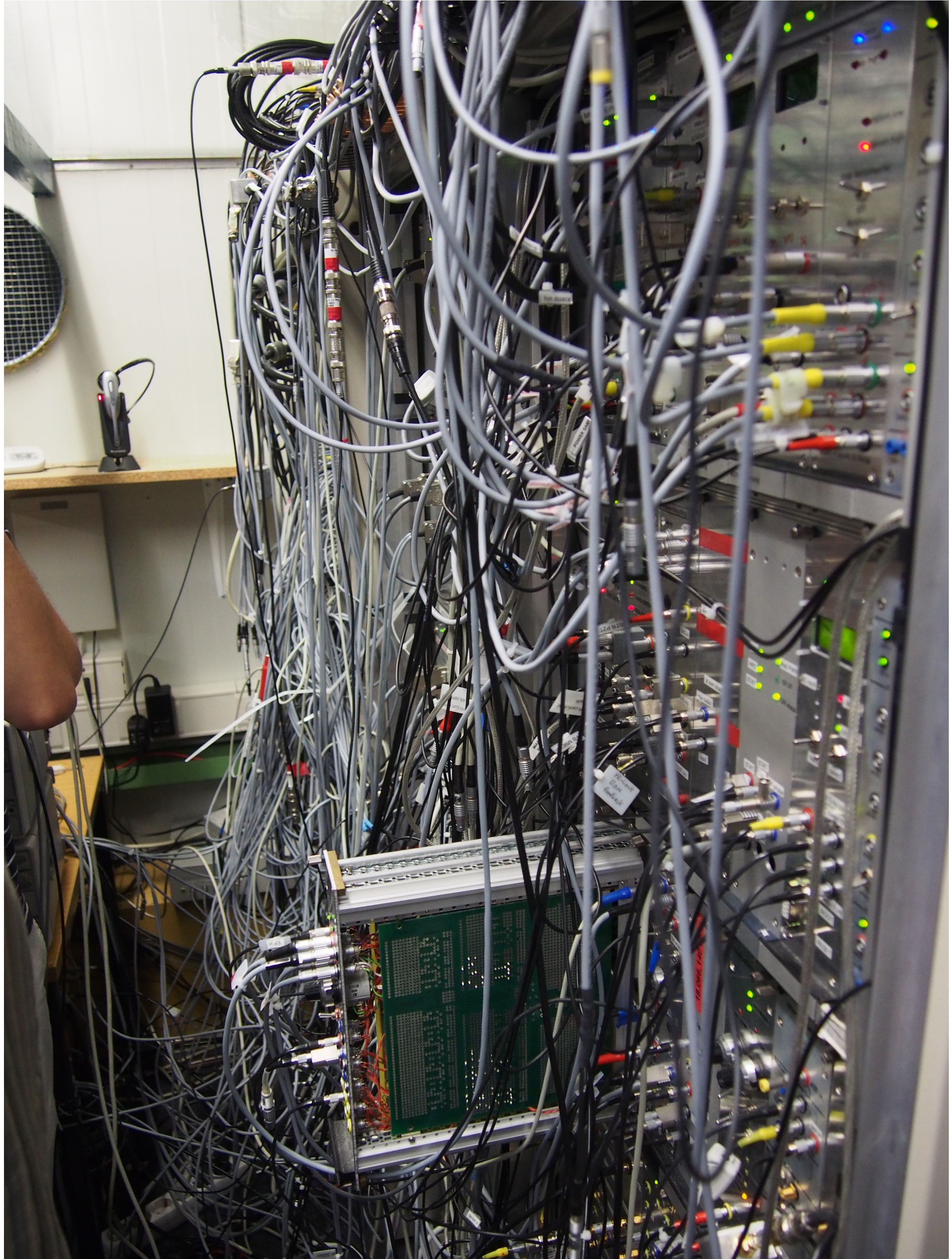
Input/Output Optics Longitudinal Excitation

Running EXCAVATor on GEO data

Squeezer Frequency Shift




E
O O
darkport
east vp
east
north vp
OMC
CAM6
north
CAM8
CAM9
LG
29.41
Inboard Mirror East
Beam Telescope
AUTOMATION




おしまい