

神岡地上・地下における シューマン共振磁場の測定

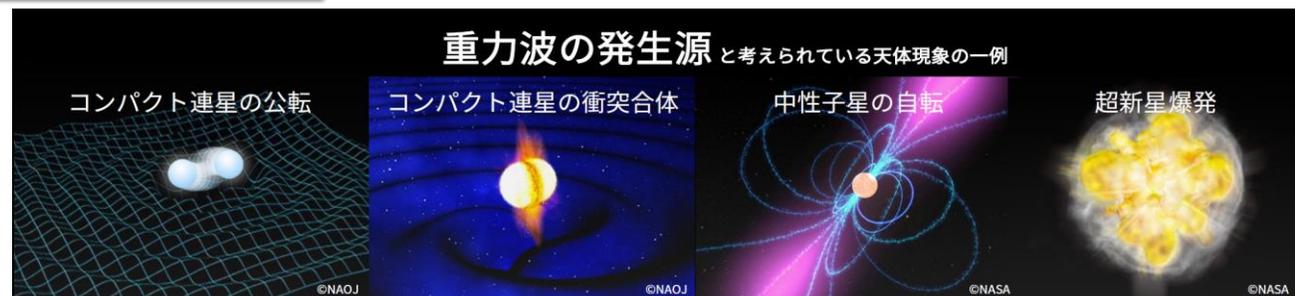
鷺見貴生 (国立天文台)

都丸隆行 (国立天文台), 横澤孝章 (東大宇宙線研),
横山順一, 西澤篤志 (東大ビッグバン),
樽家篤史 (京大基研), 姫本宣朗 (日大),
他KAGRA Collaboration

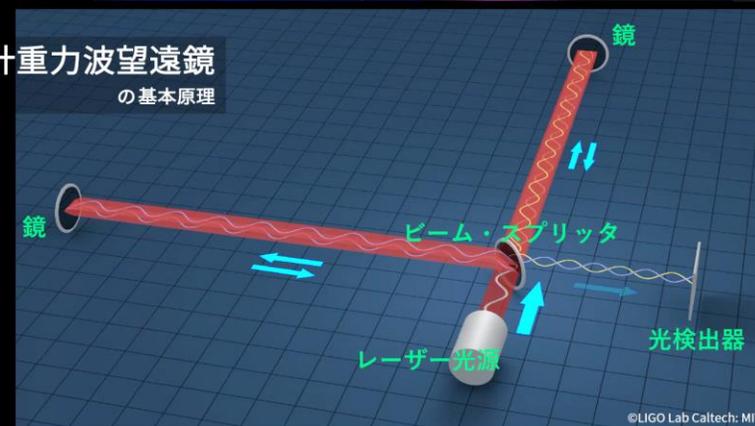
大型低温重力波望遠鏡KAGRA

重力波は「時空のさざなみ」

- 典型的な大きさは、地球と太陽の距離が水素原子1個分だけの伸縮
 - あらゆる雑音を極限まで低減する必要がある
- キロメートルの腕を持つレーザー干渉計で検出
- 2015年にアメリカのLIGOが初検出



レーザー干渉計重力波望遠鏡
の基本原理

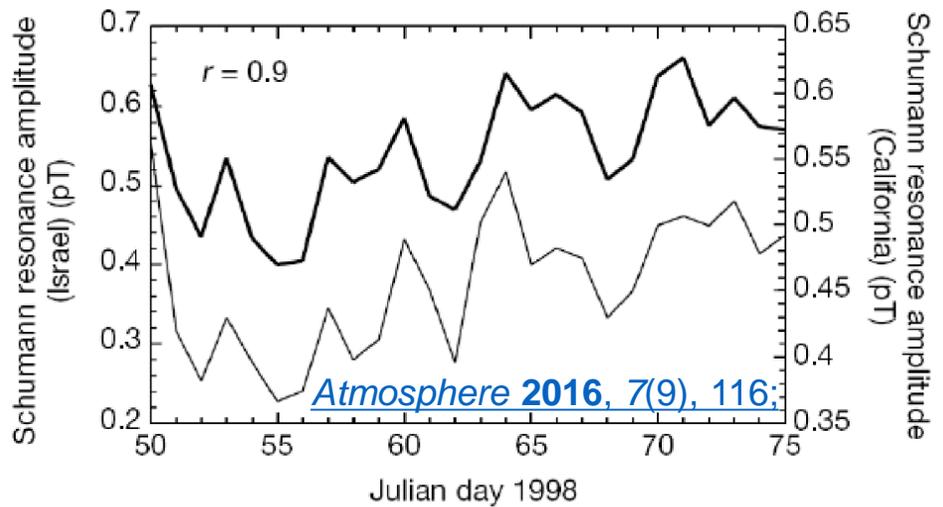
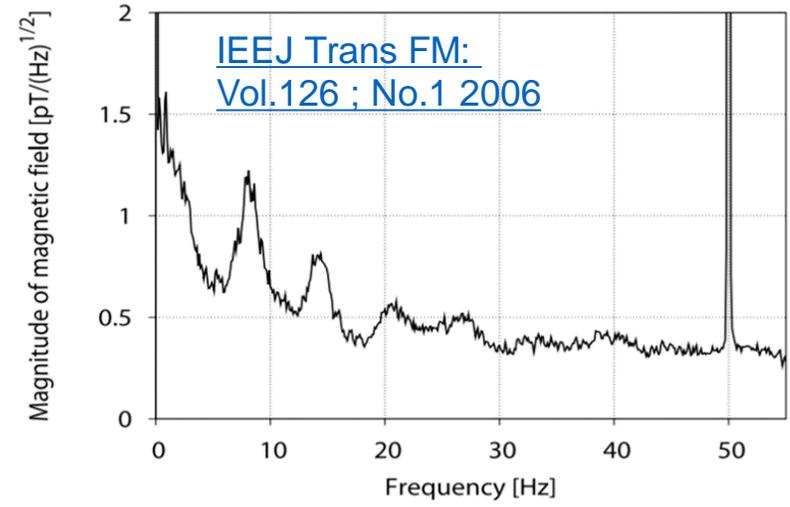
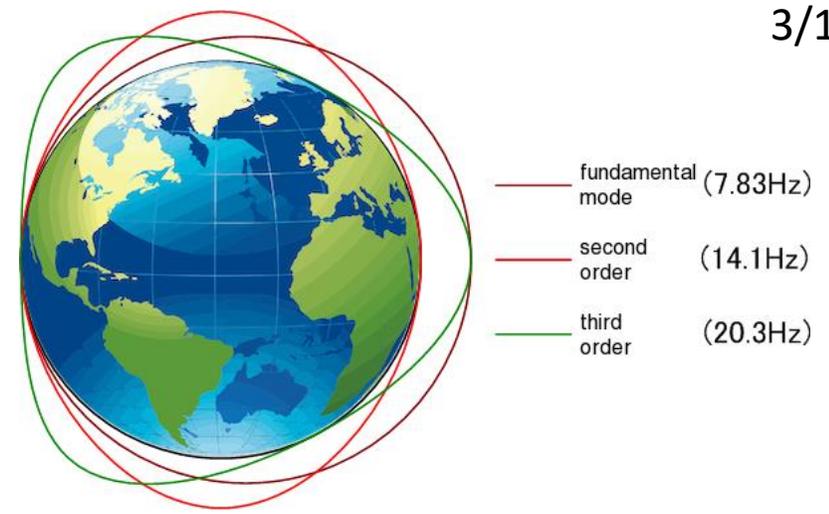


KAGRAの詳細は、宇宙線・宇宙物理領域

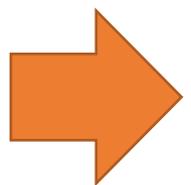
- 14pW3-1 大型低温重力波望遠鏡KAGRAの現状 (大阪市大 澤田崇広)
 - 17aW1-6 KAGRA 実験による重力波観測が拓く マルチメッセンジャー天文学 (大阪市大 神田展行)
- などを参照

シューマン共振

- 地球の地面と電離層の間で共鳴状態となる電磁場
- 雷や太陽風などによって励起される
- 共振周波数 $f_n = \frac{c}{2\pi R_{\oplus}} \sqrt{n(n+1)} = 7.8 \text{ Hz}, 14.1 \text{ Hz}, 20.3 \text{ Hz}, \dots$
- 振幅 $\sim 1 \text{ pT}/\sqrt{\text{Hz}}$



- 地球上全体で相関を持つ
- 振幅・位相・方向などが時間とともに変化する



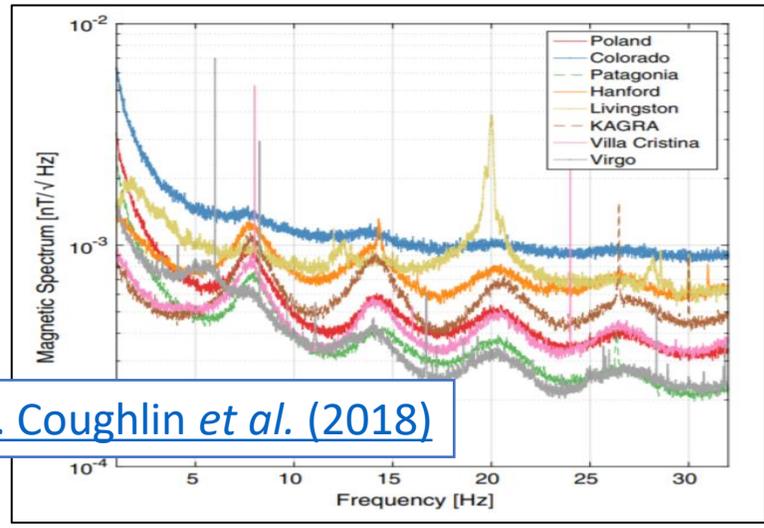
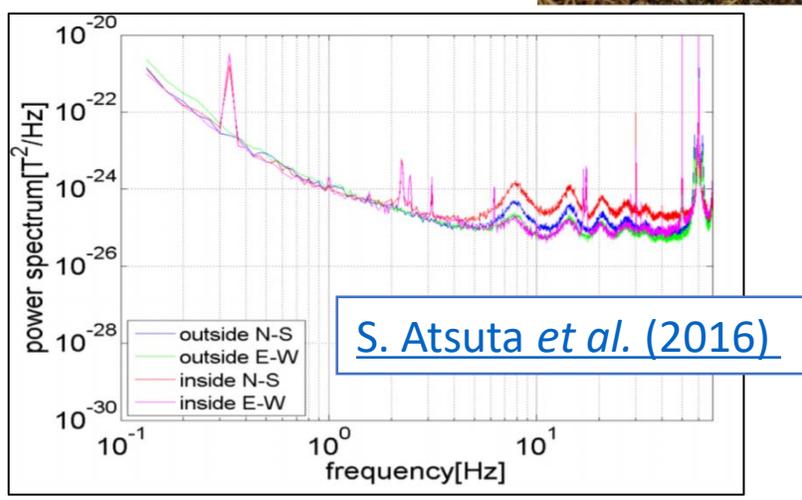
重力波観測では離れた観測地点(日米欧)で相関のある信号を探索するため、シューマン共振磁場がやっかいな雑音となる

- 特に背景重力波と呼ばれる重力波を探索する場合

KAGRAにおける過去の磁場測定 (2014, 2016)

2014/12/1 ~ 3

2016/7/21 ~ 22



いづれもレンタル機材を用いた短期測定

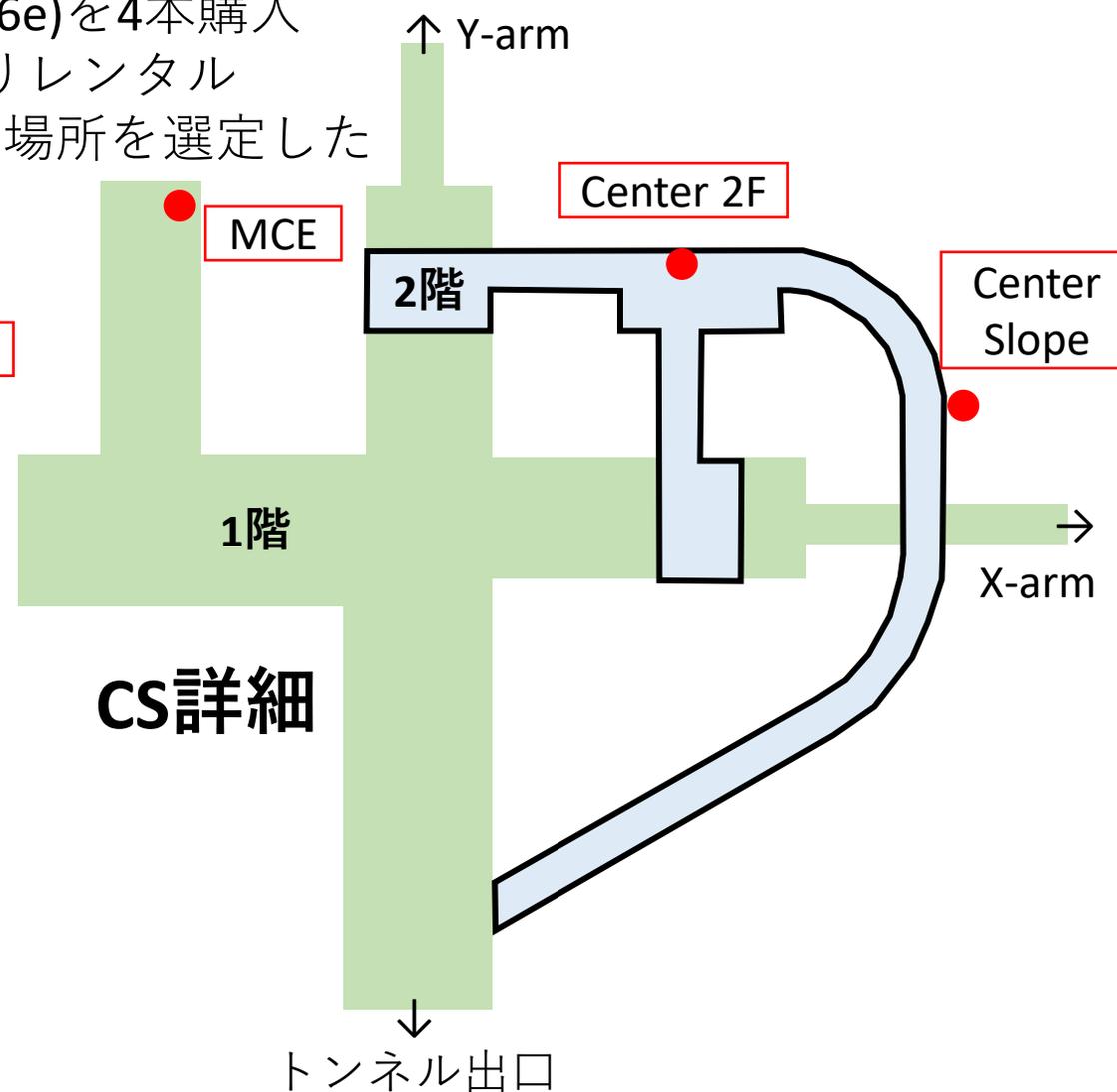
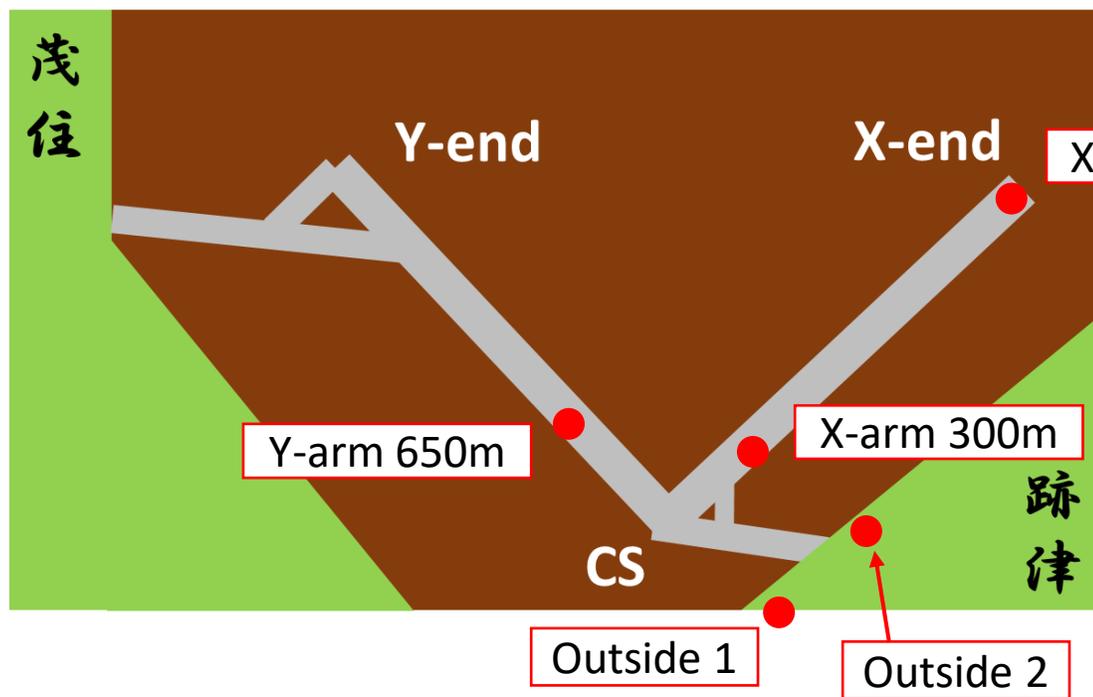


常時観測に向けた予備調査

今回

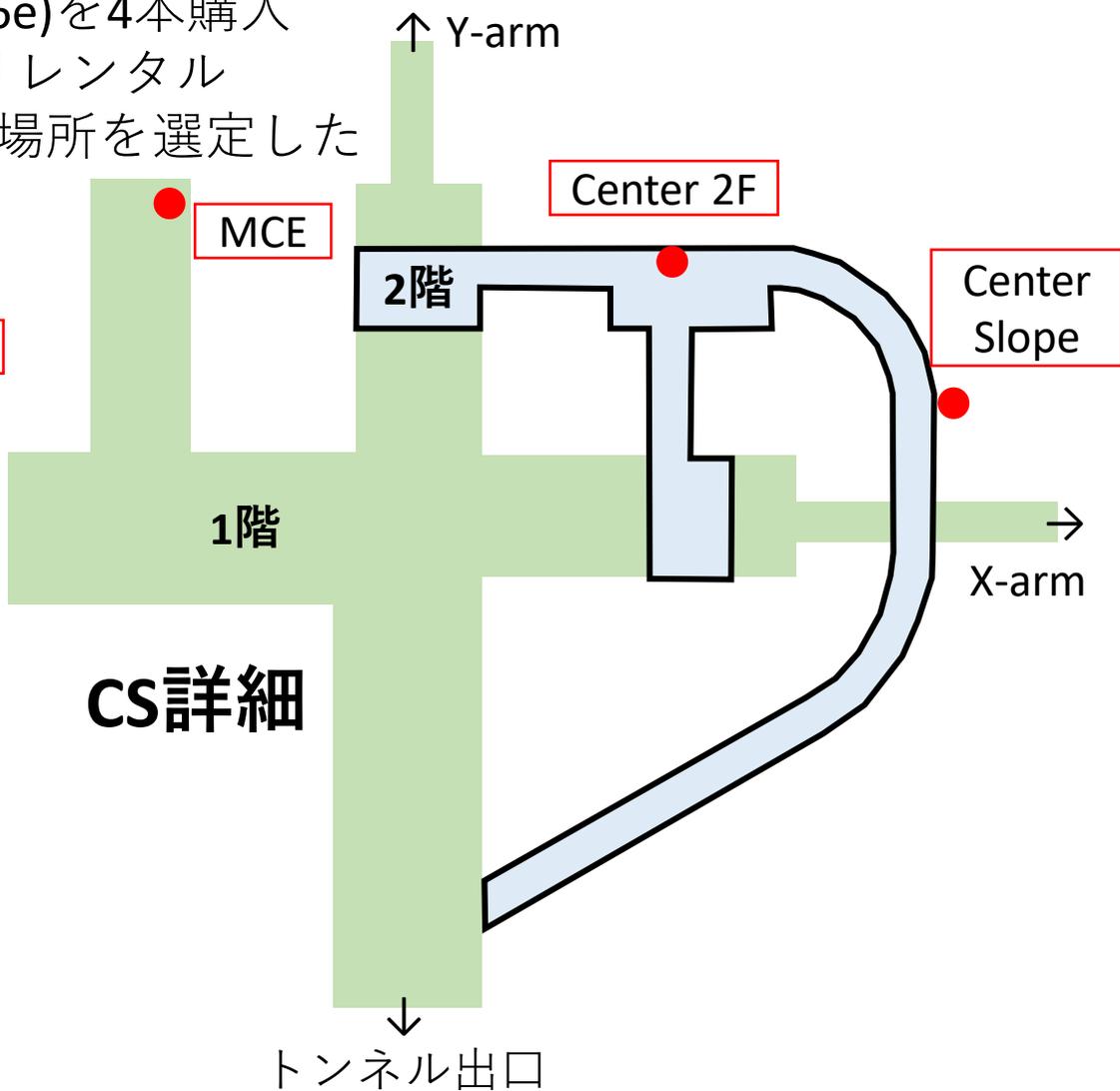
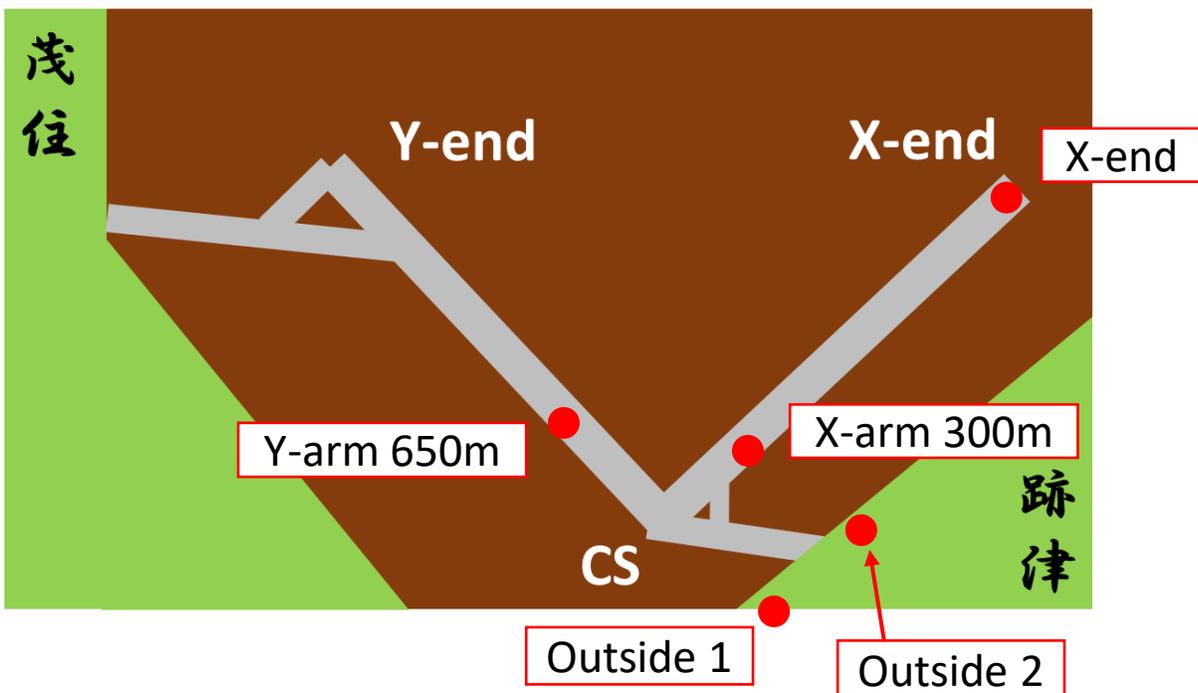
今回の磁場測定 (2021/3/31 ~ 4/15)

- 東大と国立天文台で高感度磁力計(Metronix MFS-06e)を4本購入
- DAQは地熱技術開発株式会社(長谷様、小泉様)よりレンタル
- 様々な場所で測定を行い機器からの雑音が少ない場所を選定した



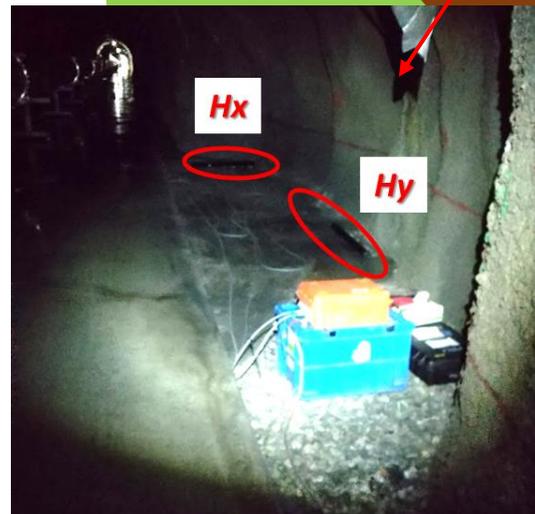
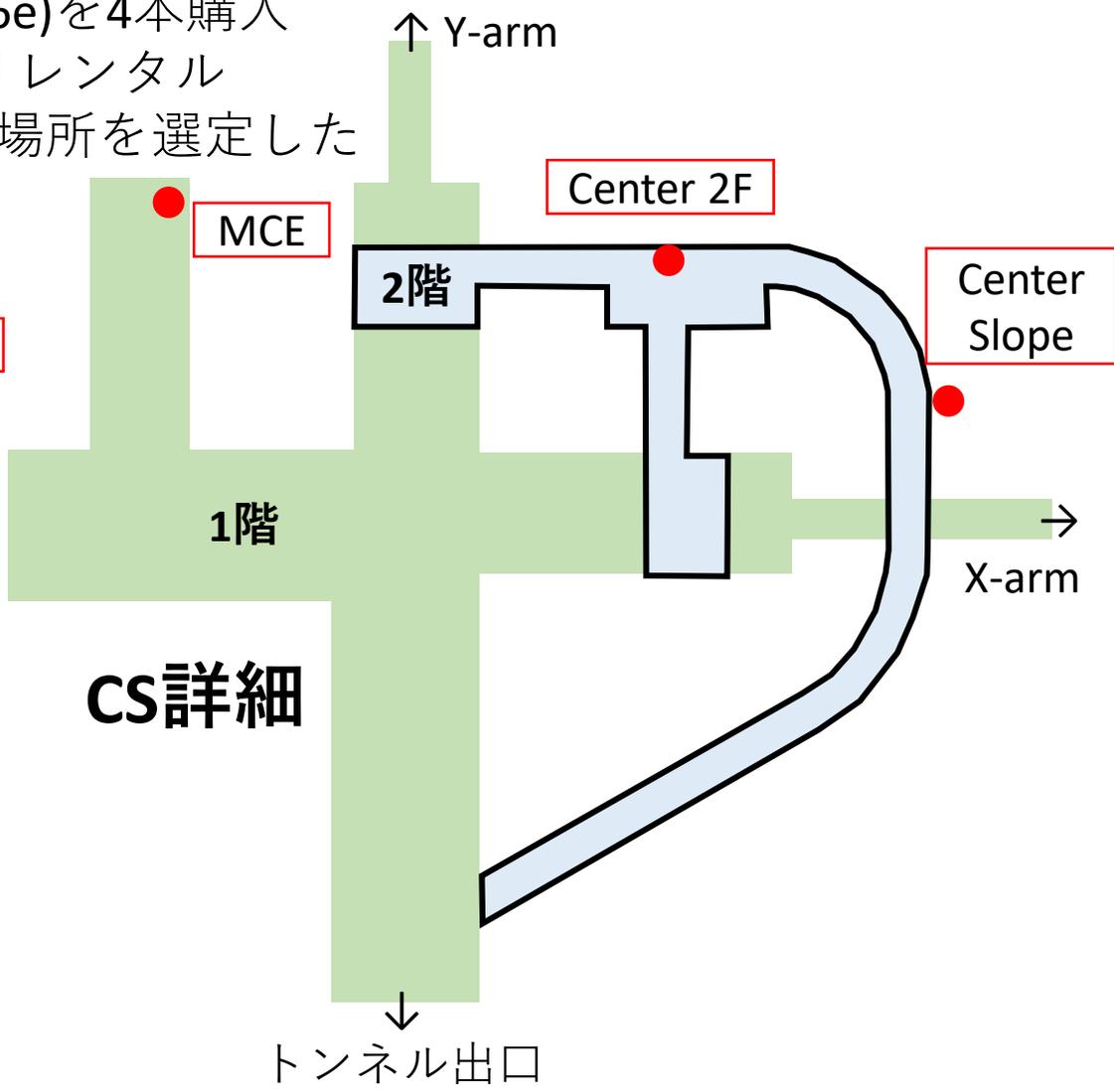
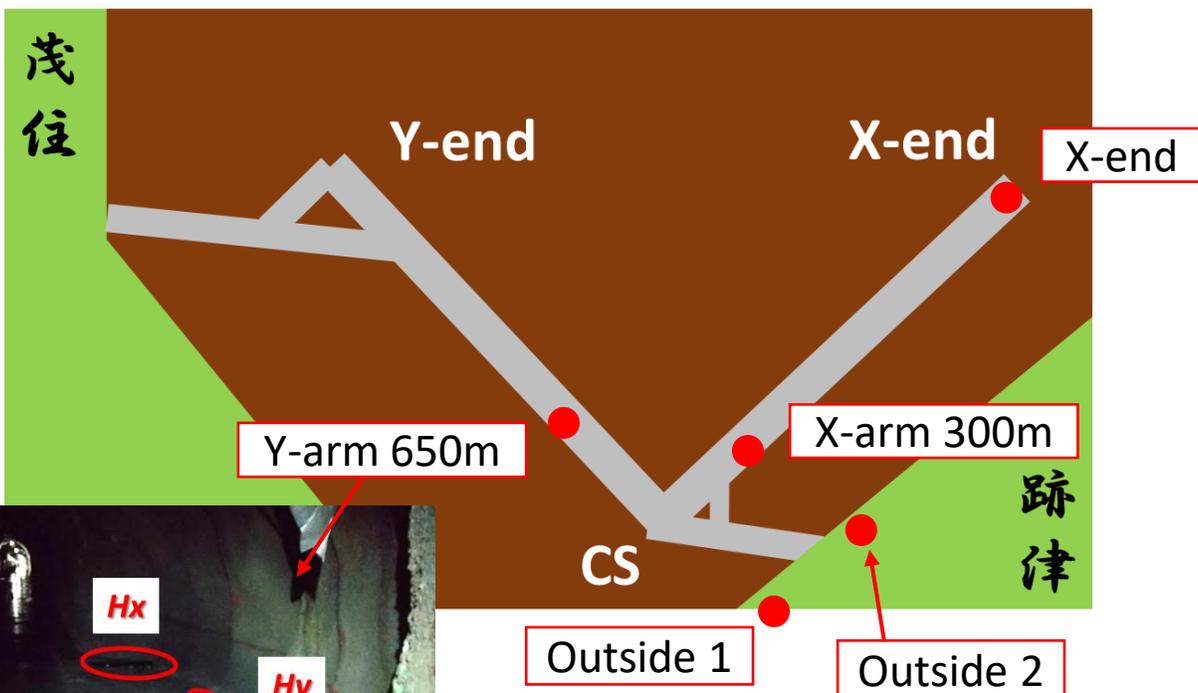
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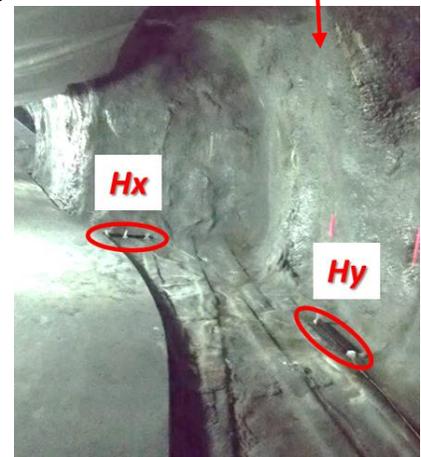
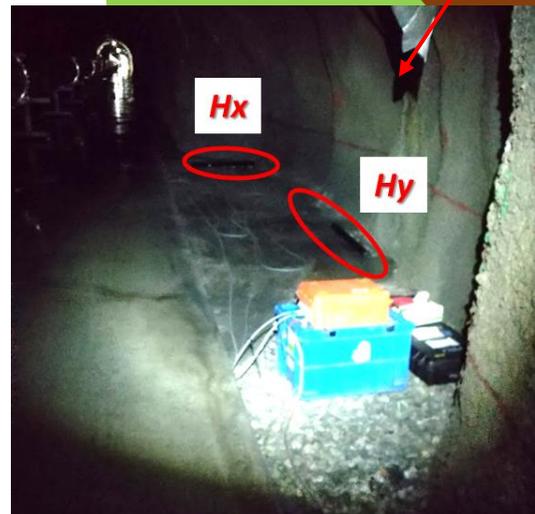
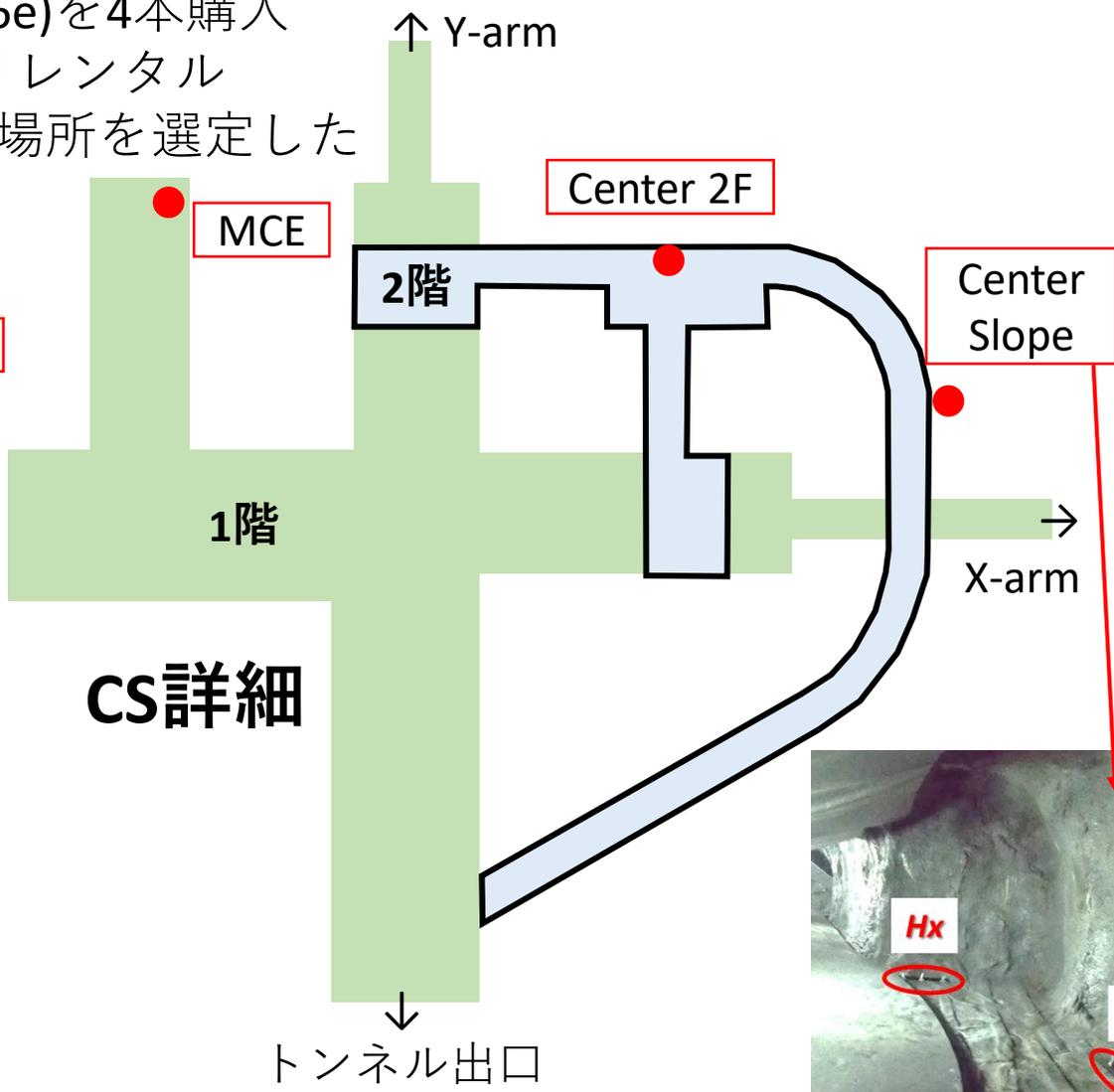
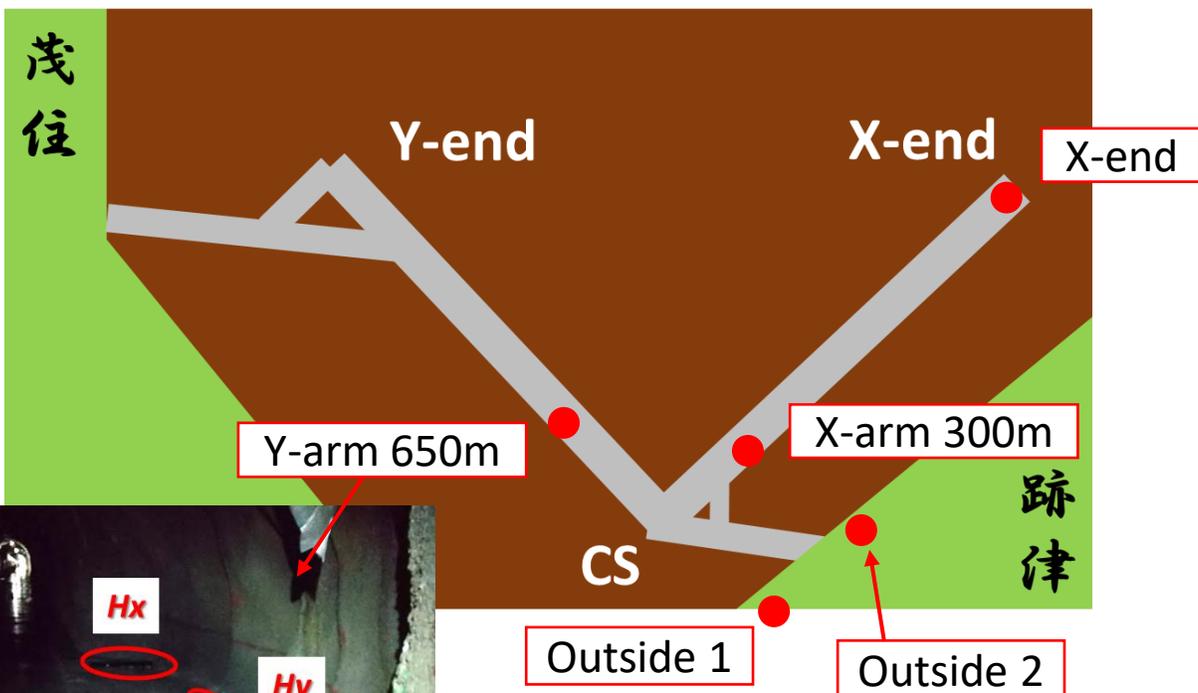
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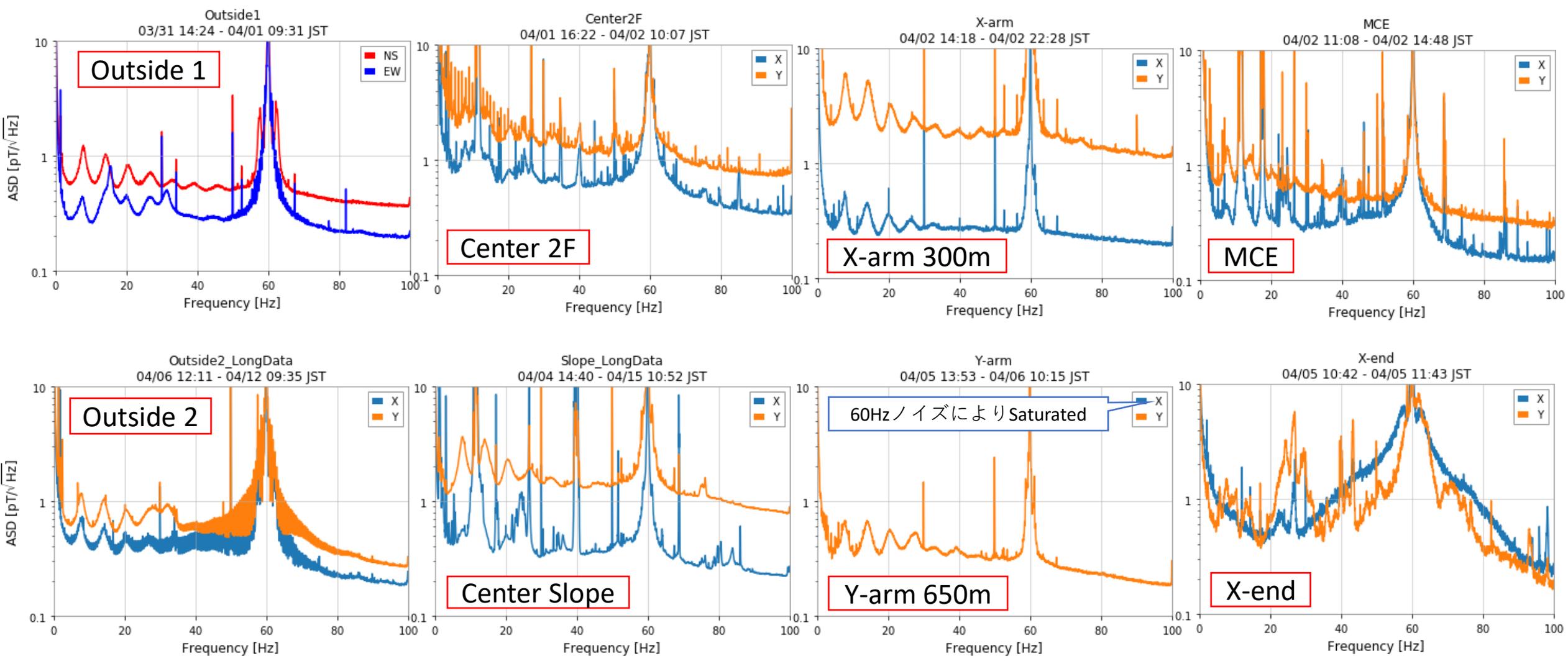


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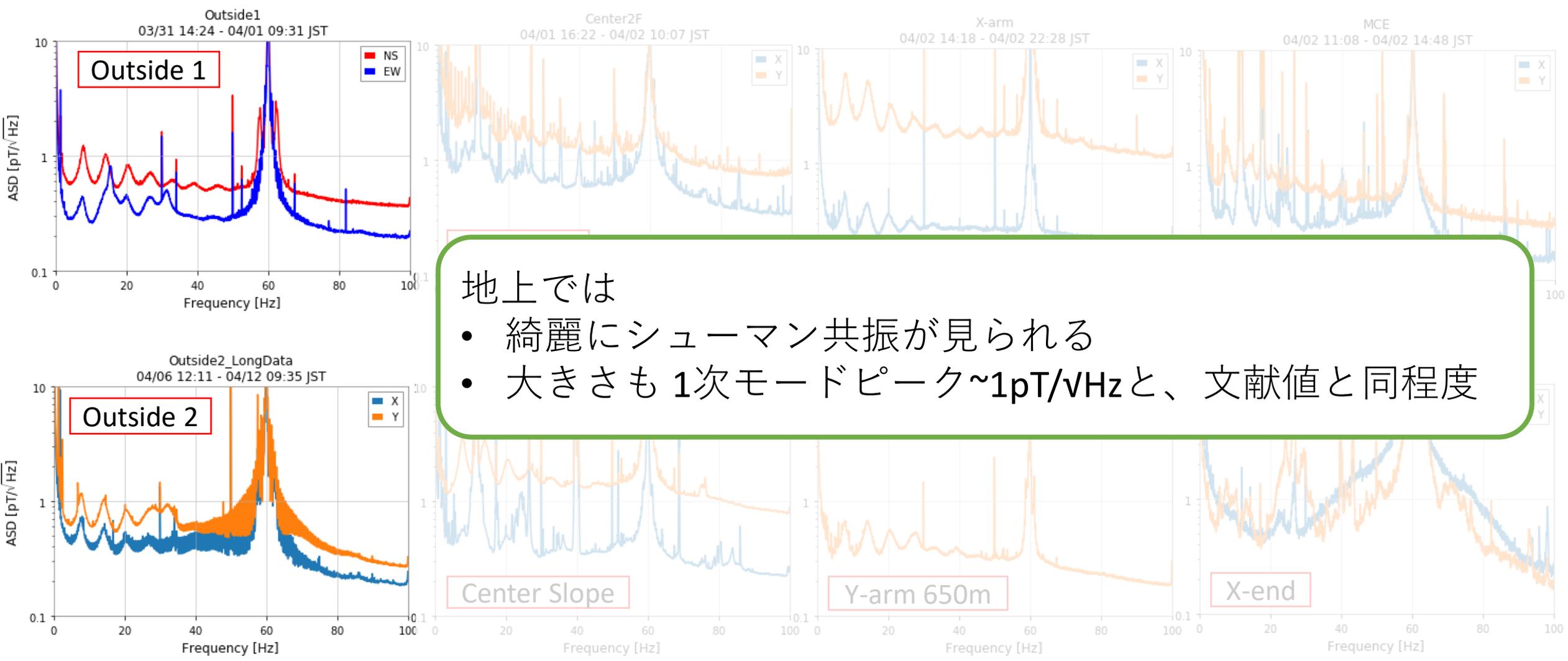
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各場所での磁場スペクトル



各場所での磁場スペクトル



地上では

- 綺麗にシューマン共振が見られる
- 大きさも1次モードピーク~1pT/√Hzと、文献値と同程度

各場所での磁場スペクトル

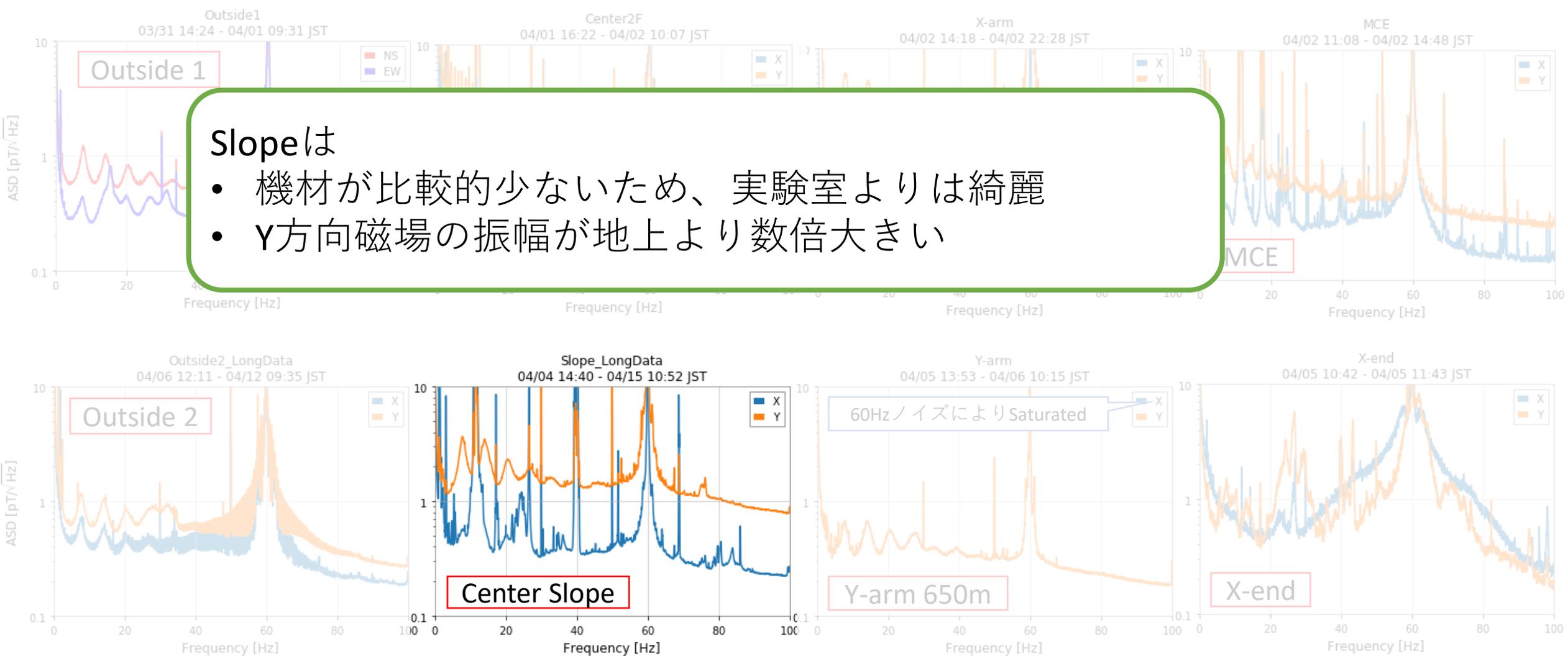


- 地下の実験室内は機材からの雑音が多く
シューマン共振のモニターには不向き

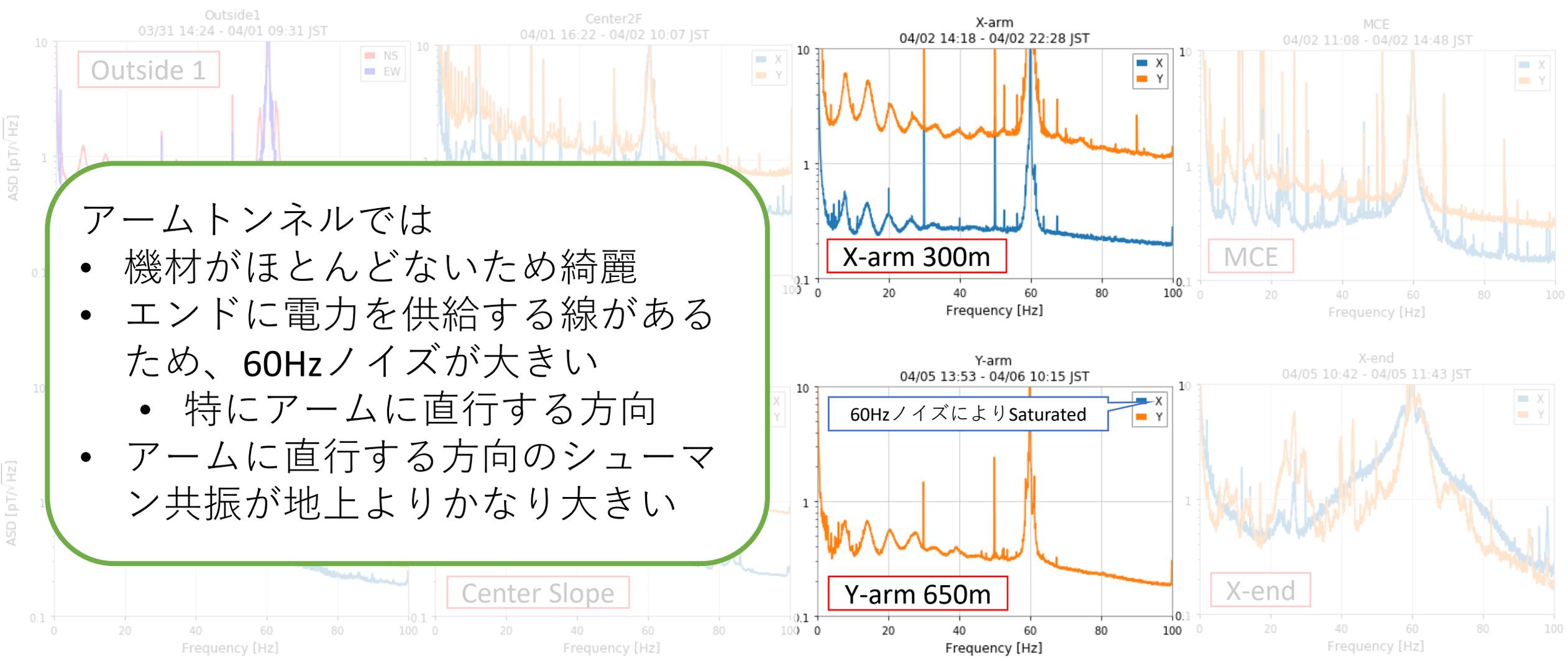
各場所での磁場スペクトル

Slopeは

- 機材が比較的少ないため、実験室よりは綺麗
- Y方向磁場の振幅が地上より数倍大きい



各場所での磁場スペクトル



アームトンネルでは

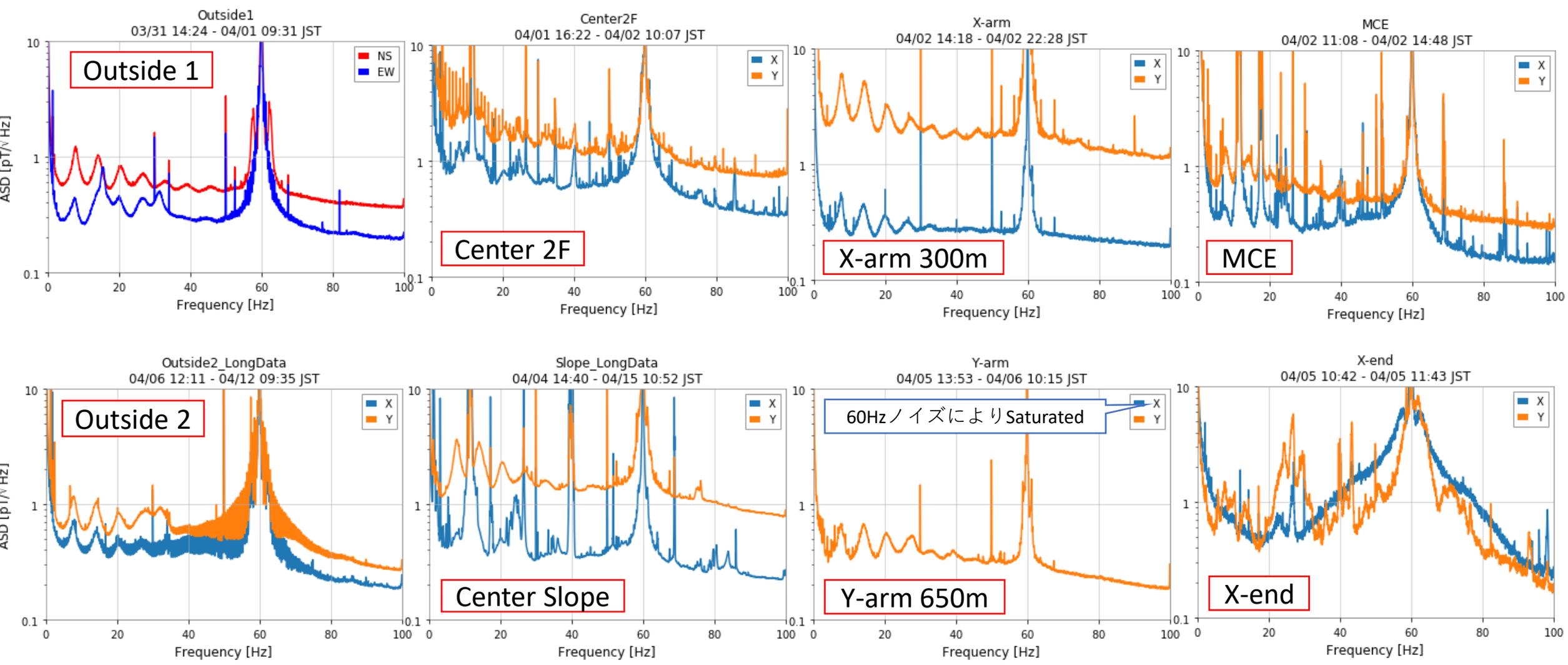
- 機材がほとんどないため綺麗
- エンドに電力を供給する線があるため、60Hzノイズが大きい
 - 特にアームに直行する方向
- アームに直行する方向のシューマン共振が地上よりかなり大きい

Center Slope

Y-arm 650m

X-end

各場所での磁場スペクトル



理論モデルによるFit

Himemoto & Taruya, PRD (2017, 2019)

$$P_{\text{SR}}(f) = P_{\text{B}}(f) \sum_{\ell} \frac{[f'_{\ell}/(2Q)]^2}{(f - f'_{\ell})^2 + [f_{\ell}/(2Q)]^2}$$

$$P_{\text{B}}(f) = A \left(\frac{f}{10 \text{ Hz}} \right)^{-\alpha} \quad (\text{typically } \alpha = 0.88)$$

$$f_{\ell} = \frac{\sqrt{\ell(\ell+1)} c}{2\pi a} \quad f'_{\ell} = s \times f_{\ell}$$

(typically $s=0.78$)

a : Earth radius

Q : Q value (typically ~ 5)

4 free
parameters

地上データ

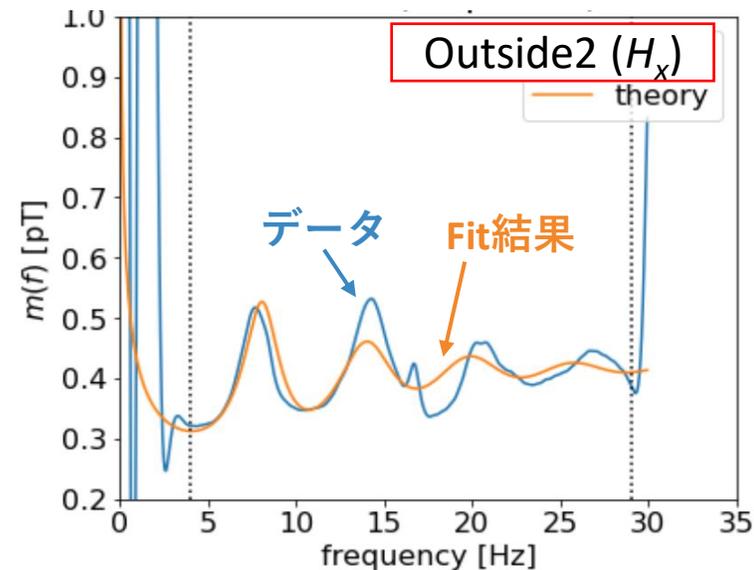
シューマン共振の理論モデルでFit

➤ Best fitのパラメタ :

$$A = 0.3 \text{ pT}^2/\text{Hz} \quad Q = 4.8$$

$$\alpha = 0.72 \quad s = 0.77$$

典型値と consistent な結果



理論モデルによるFit

Himemoto & Taruya, PRD (2017, 2019)

$$P_{SR}(f) = P_B(f) \sum_l \frac{[f'_l/(2Q)]^2}{(f - f'_l)^2 + [f_l/(2Q)]^2}$$

$$P_B(f) = A \left(\frac{f}{10 \text{ Hz}} \right)^{-\alpha} \quad (\text{typically } \alpha = 0.88)$$

$$f_l = \frac{\sqrt{l(l+1)} c}{2\pi a} \quad f'_l = s \times f_l$$

(typically s=0.78)

a : Earth radius

Q : Q value (typically ~5)

4 free parameters

地上データ

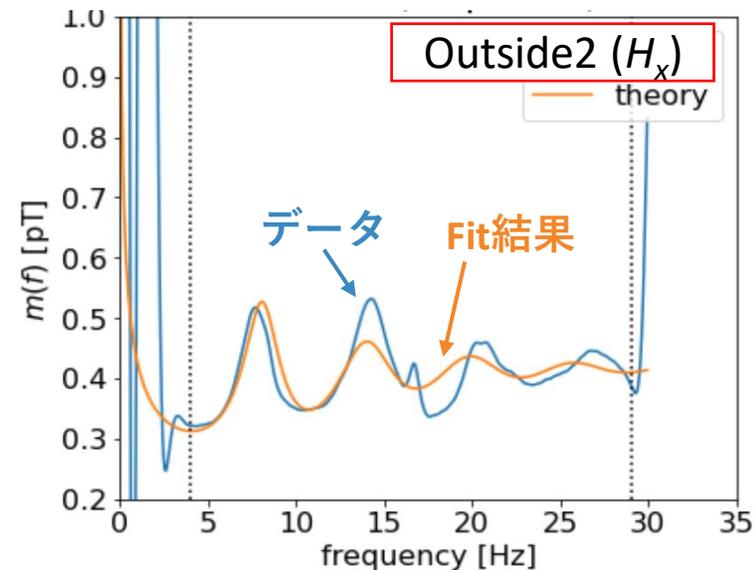
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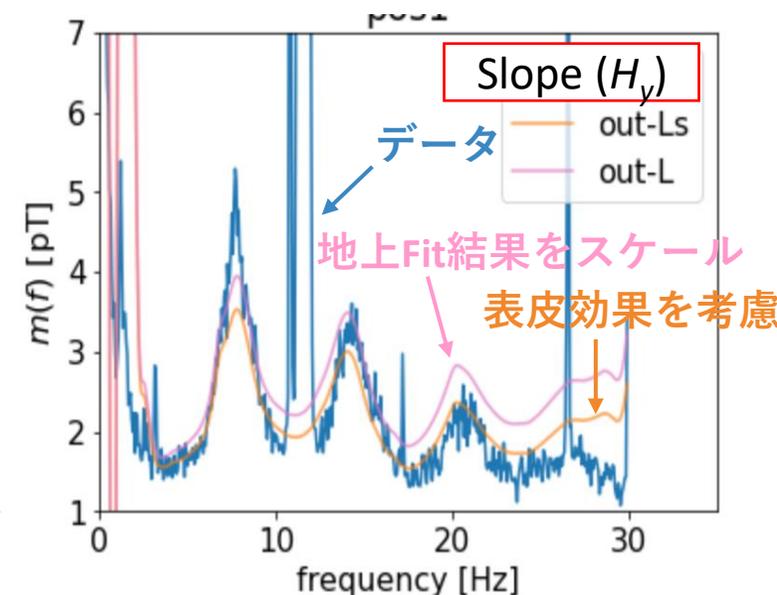
地下データ

地上Fit結果に、スケールと表皮効果を考慮してFit

➤ Best fitのパラメタ :

$$\sqrt{\pi\mu\sigma z} = 0.045 \text{ Hz}^{-1/2}$$

地抵抗に直すと、50~150 Ωm
文献値* (~300 Ωm)より小さめの値



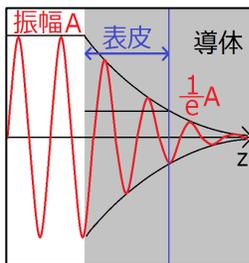
地面の表皮効果

$$H(z, t) = H_0 e^{-z/\delta} \cos(z/\delta - \omega t)$$

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} \quad \text{: 表皮厚さ}$$

μ : 地盤の透磁率

σ : 地盤の伝導率



各場所での磁場測定結果の考察

- ✓ 地上で測定されたシューマン共振磁場スペクトル(大きさ、形)は文献値と consistent
- ✓ 地下で測定されたシューマン共振磁場は、地上よりも大きい傾向がある
 - 場所と向きによっては最大5倍程度
 - スペクトルの形(周波数)自体は表皮効果で説明できる
- ✓ 常時観測を行うのに適した場所を検討
 - 信号雑音比：機器からの磁場雑音にシューマン共振が埋もれてしまわないか
 - 60Hz ノイズ：AC電源線からの強い磁場によダイナミックレンジが耐えられるか
 - データ取得のしやすさ：KAGRAのデジタルシステム(GPS同期)まで配線できるか

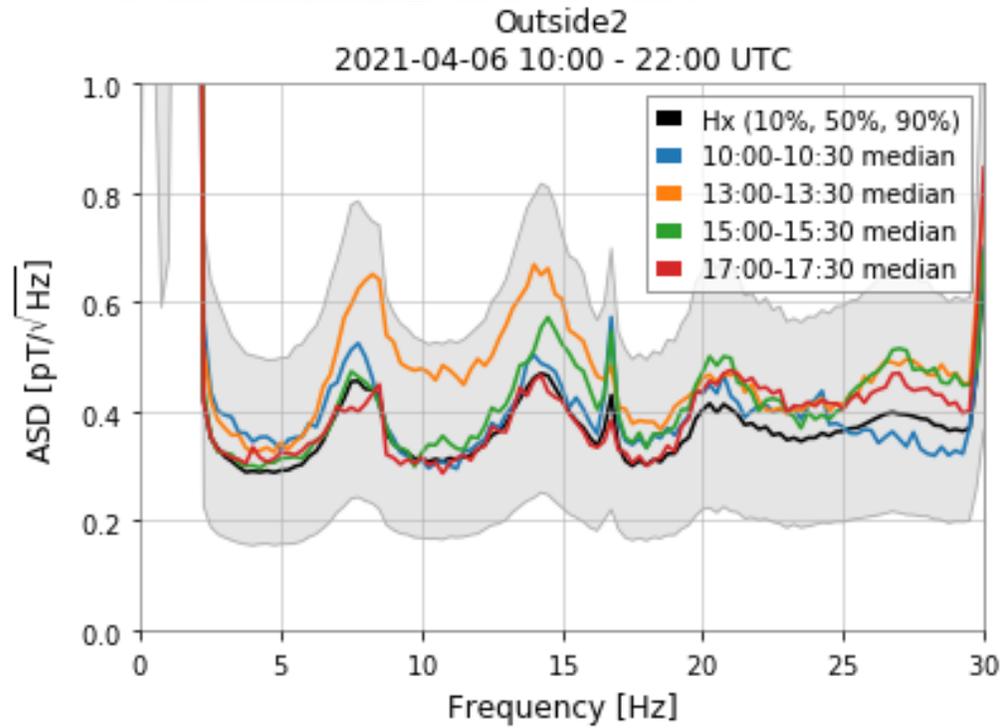
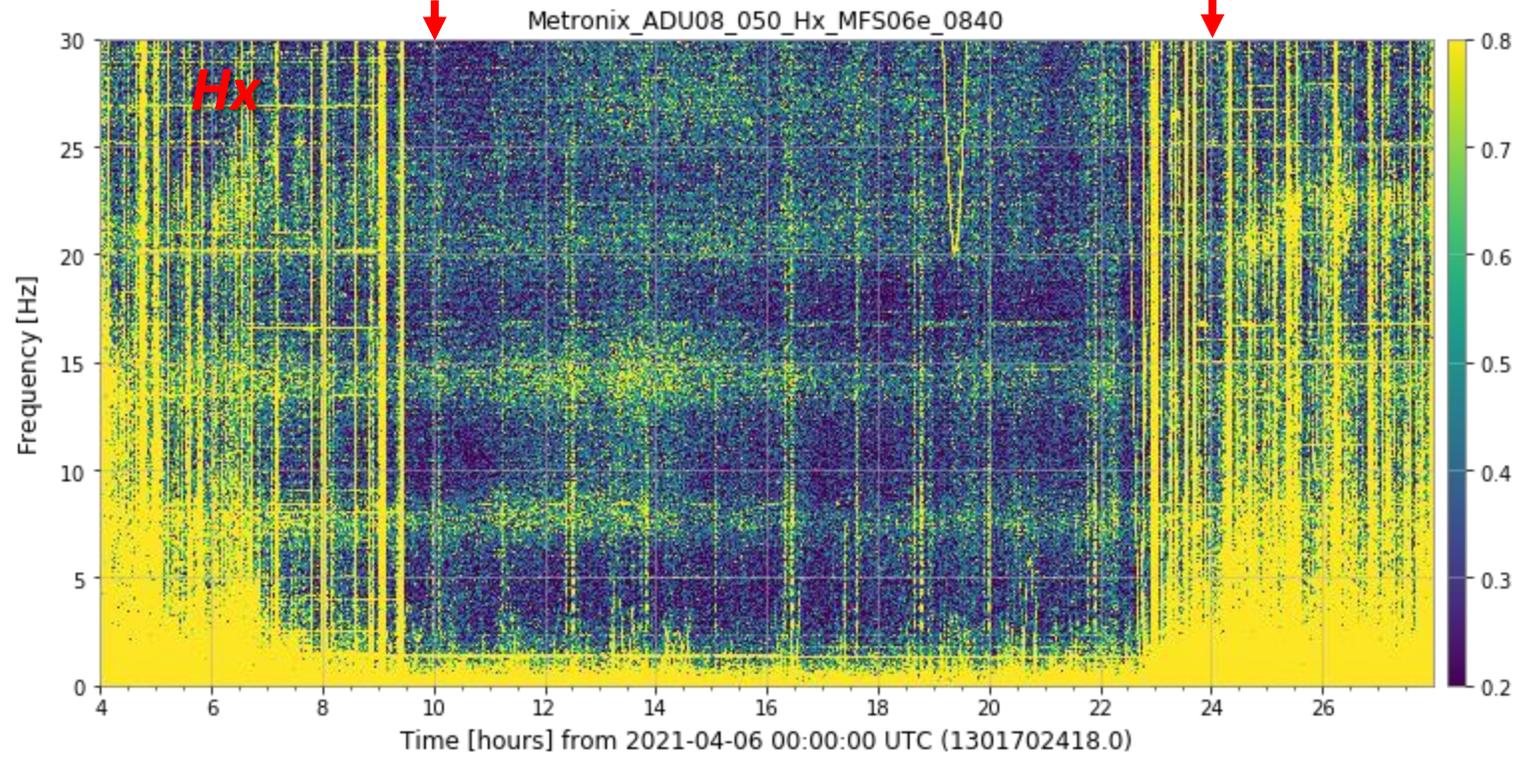
	信号雑音比	60Hzノイズ	DAQのしやすさ
地上	良(夜間) 悪(日中)	小	難しい
Slope	良	小	可能
実験室	悪	大	簡単
アームトンネル	良	特大	非常に難しい

- 地下ではSlopeが最も現実的
- 地上での測定には別途DAQを用意する必要がある (例：Metronix ADU-08e)

地上データの時間変動



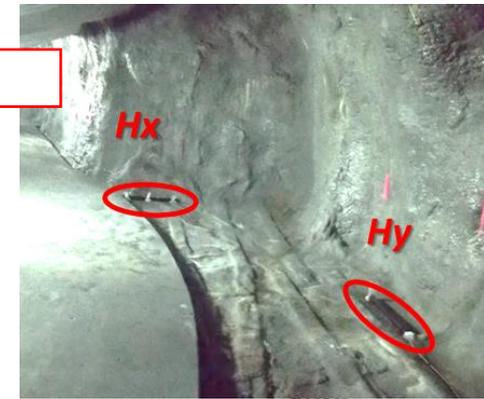
19:00 JST
9:00 JST



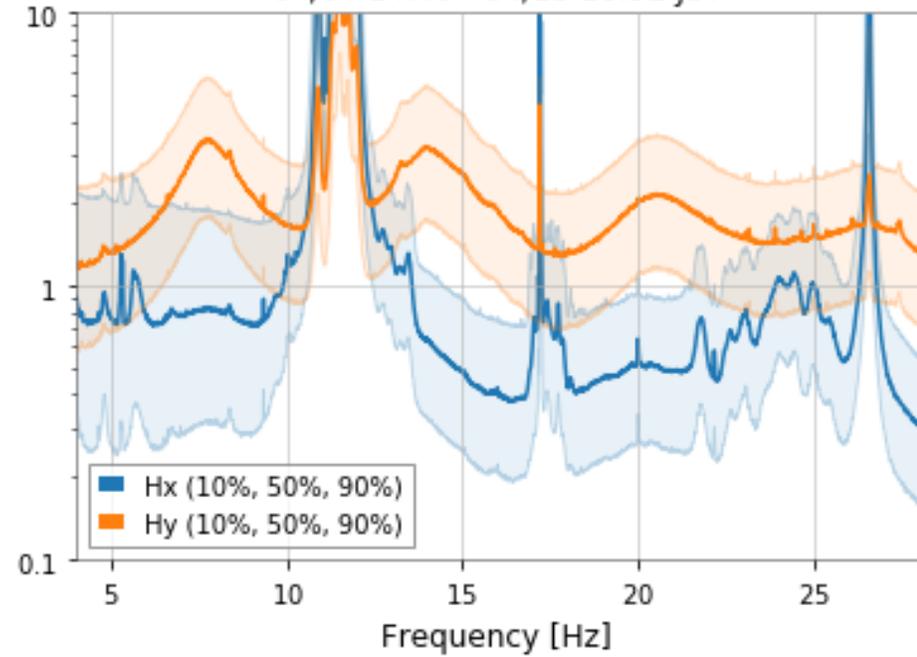
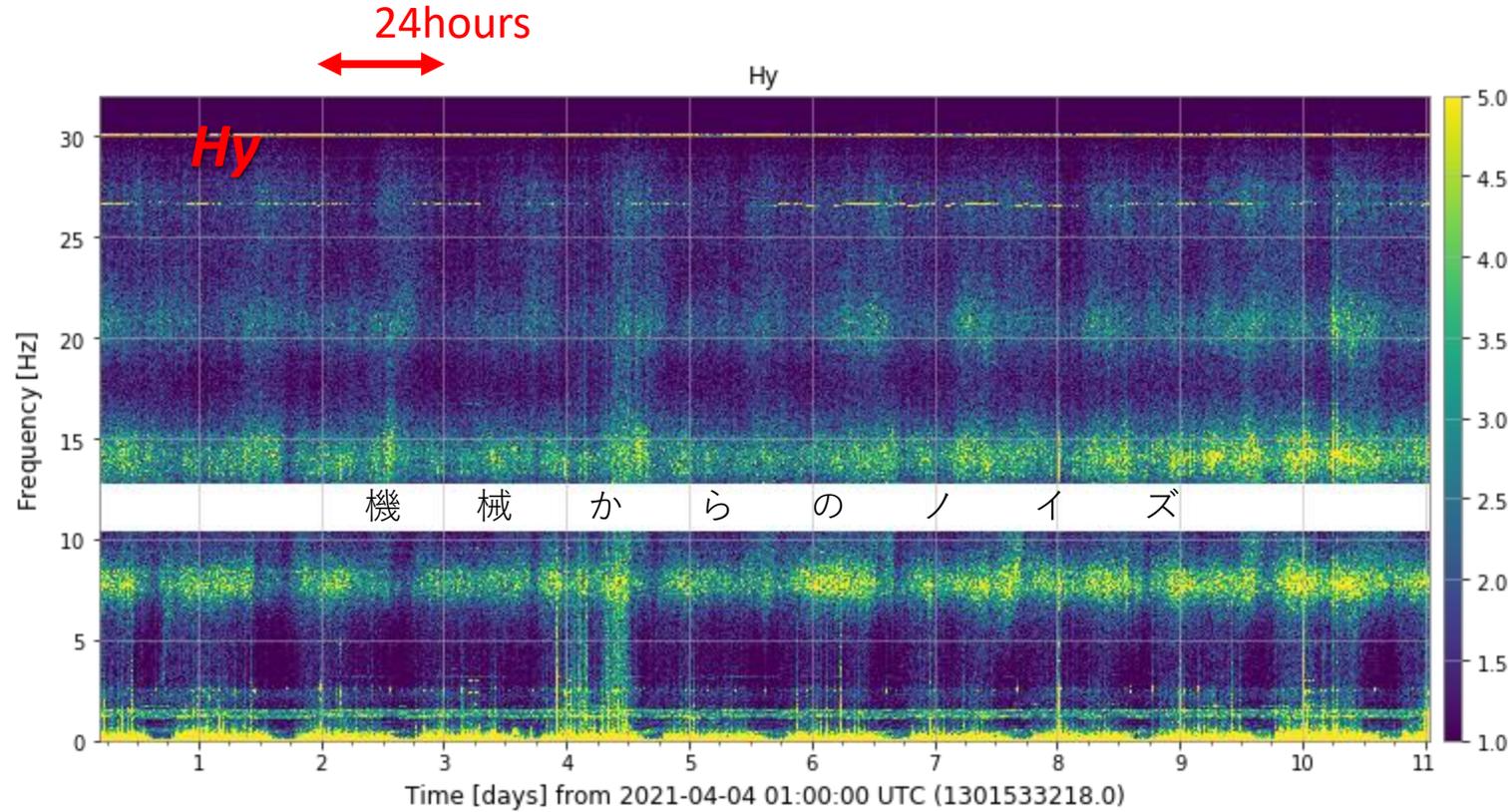
- ✓ 日中は人間活動(車?)のために非常にノイジーだが、夜間は綺麗にシューマン共振が見える
- ✓ 振幅の時間変化は2倍程度
- ✓ モードごとに異なった時間変化をしている

地下データの時間変動

Slope

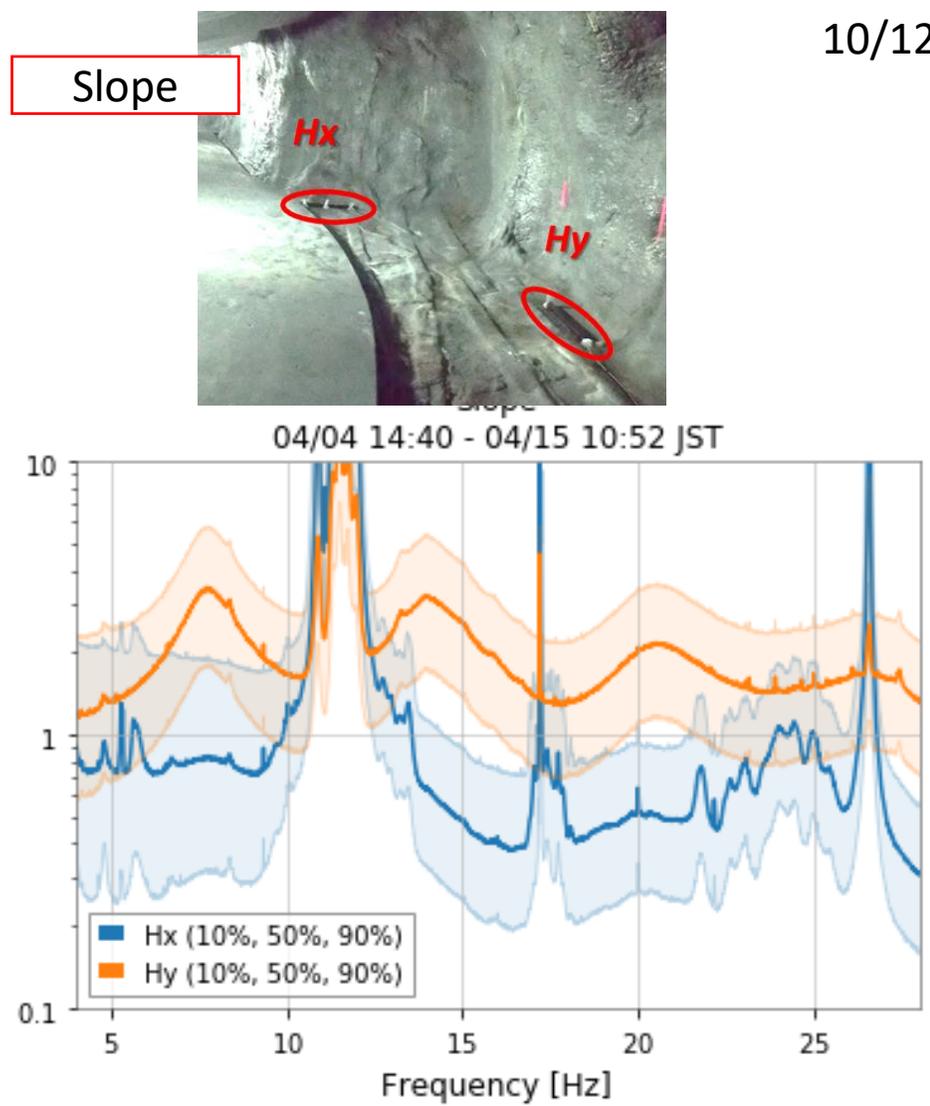
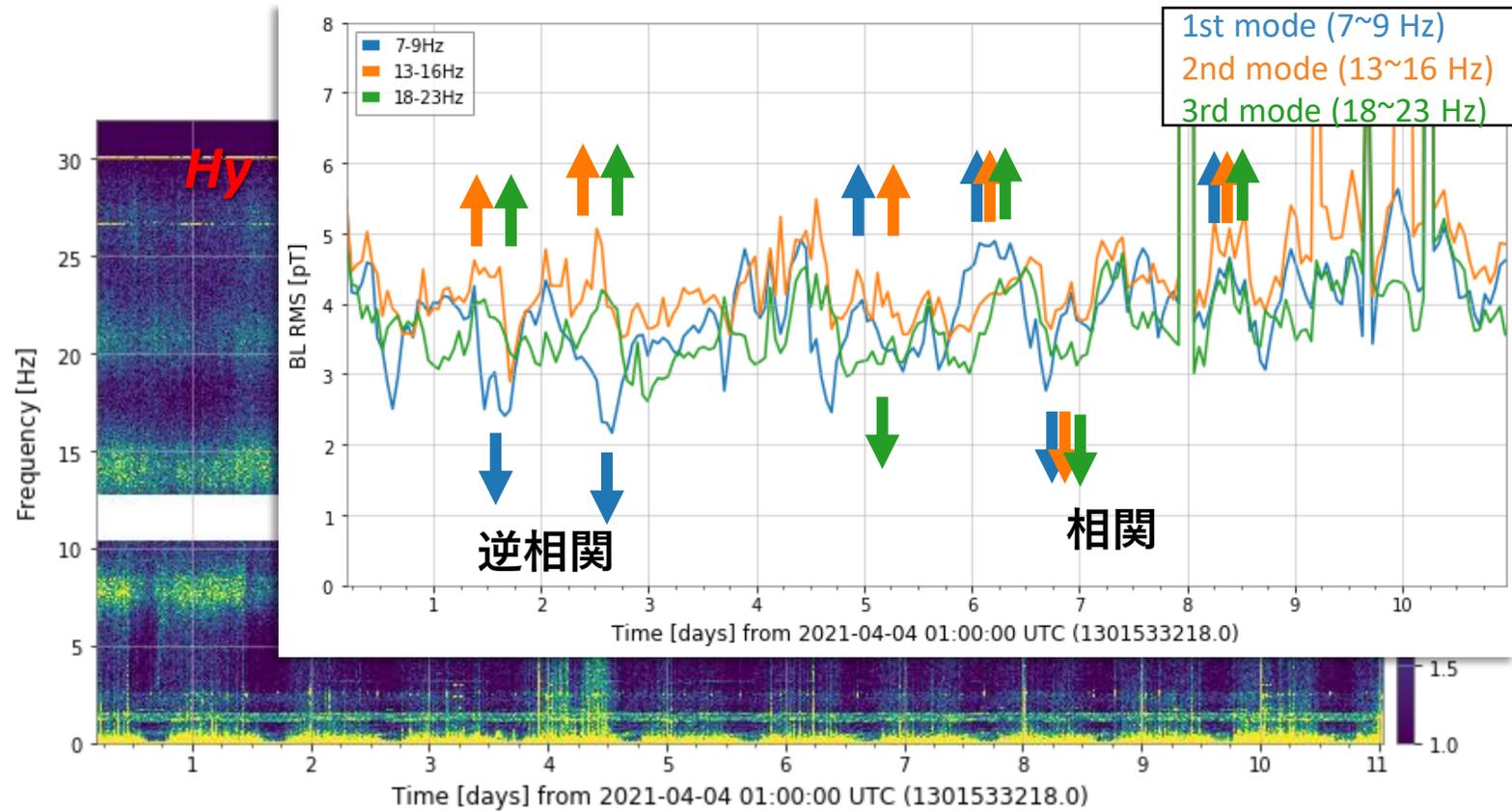


04/04 14:40 - 04/15 10:52 JST



- ✓ 人間通りが少ないので、日夜ともに綺麗にシューマン共振が見える
- ✓ 振幅の時間変化は2倍程度 (地上と同程度)
- ✓ モードごとの時間変化は、時によって正の相関も負の相関もある

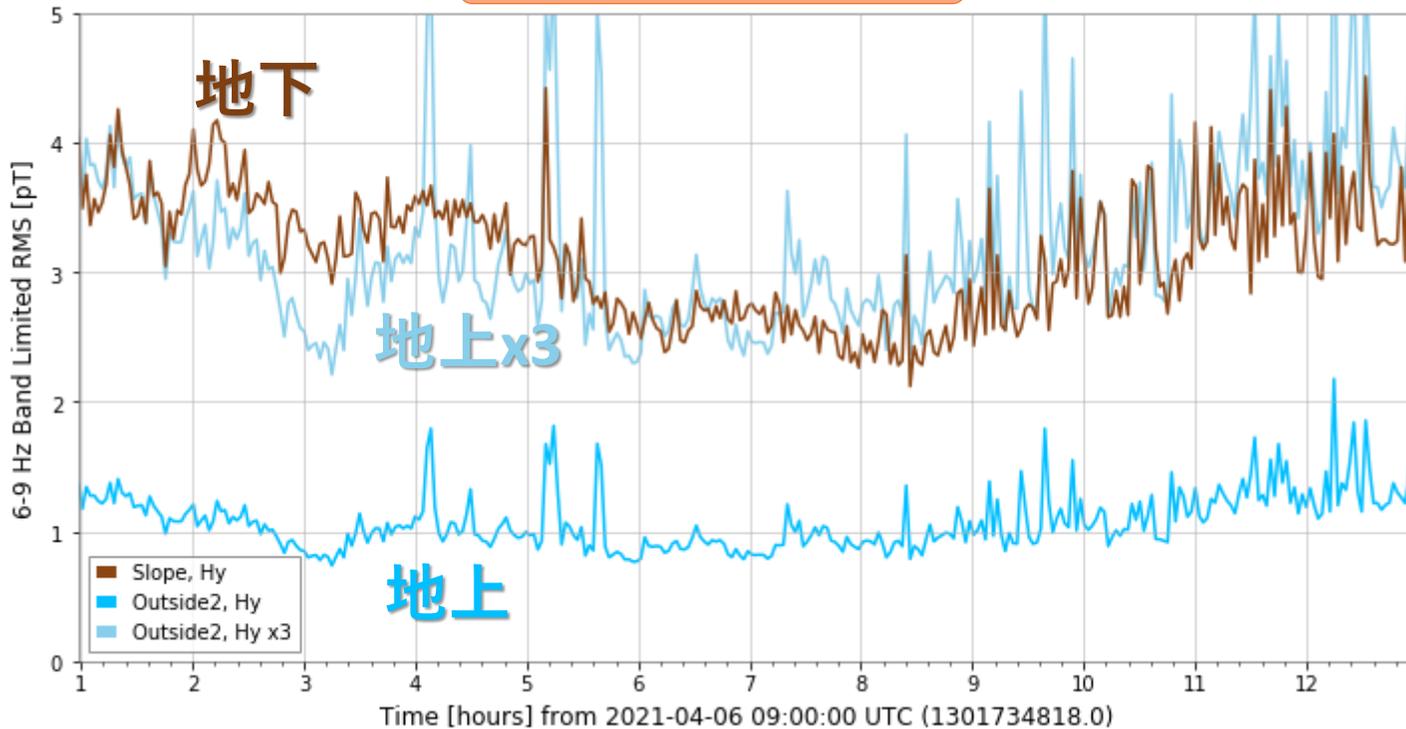
地下データの時間変動



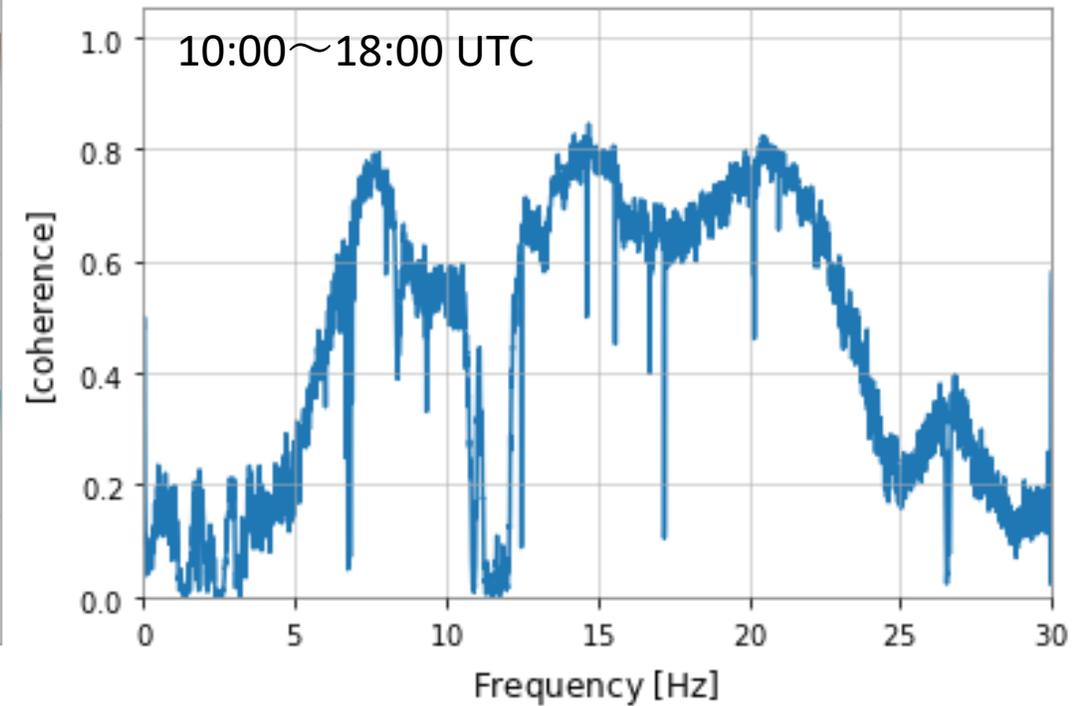
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地上と地下の比較 (Y方向同士)

1次モードの時間変化



Coherence

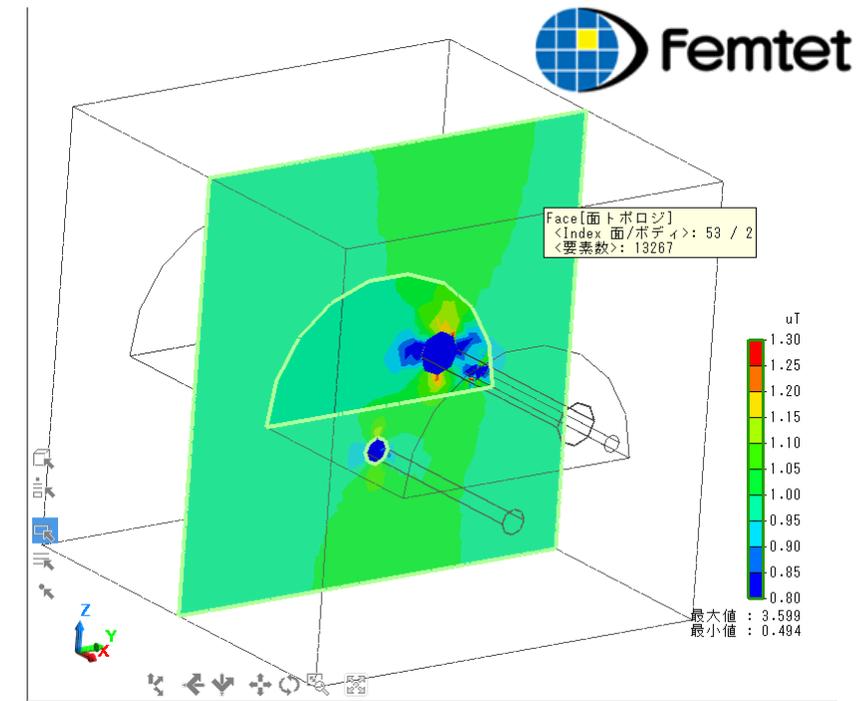
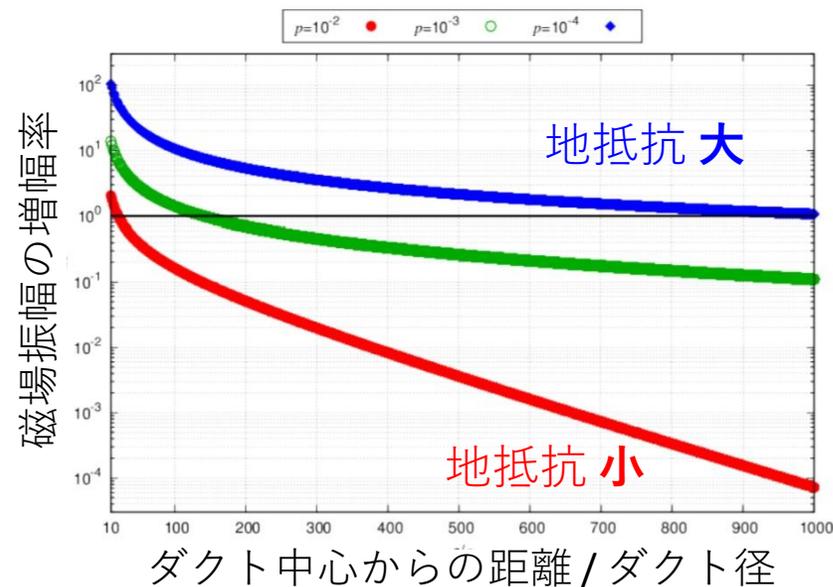
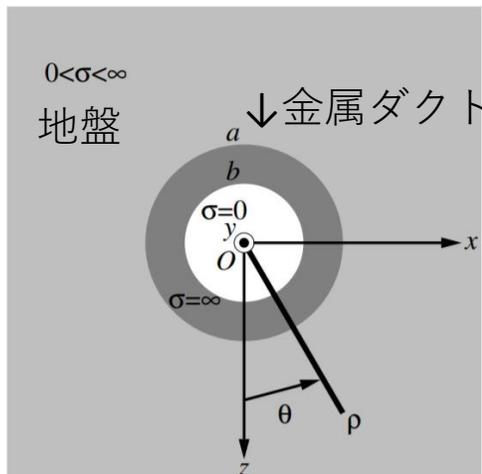


- ✓ シューマン共振磁場の1次モードの大きさは、地下では地上の約3倍
- ✓ 時間変化については、地上と地下でほぼ同様
- ✓ コヒーレンスは良い
- ✓ 磁場ベクトルの方向も地上と地下で概ね一致していた (発表時間の都合で詳細略)

まとめと議論

- ✓ 大型低温重力波望遠鏡KAGRAでのシューマン共振磁場の常時観測にむけた予備調査を行った
- ✓ センサー購入・測定などに際し、地熱技術開発株式会社の長谷様・小泉様にお世話になりました
- ✓ 地下における磁場スペクトル構造は地盤の表皮効果で説明可能
 - 算出された地抵抗値は文献値より小さい。深さ(地表/地下)の違い? 季節(水分量)の違い?
- ✓ 地下のシューマン共振磁場振幅は地上よりも数倍大きい
 - KAGRAのビームダクト(3kmの金属円筒)による影響の可能性が指摘されている
 - 現在、有限要素シミュレーション(Femtet)による検証を進めている

小河勉 (東京大学地震研究所)、2018年 Conductivity Anomaly研究会論文集
http://www.eqh.dpri.kyoto-u.ac.jp/CA/2018/Ogawa_CA2018.pdf



Backup

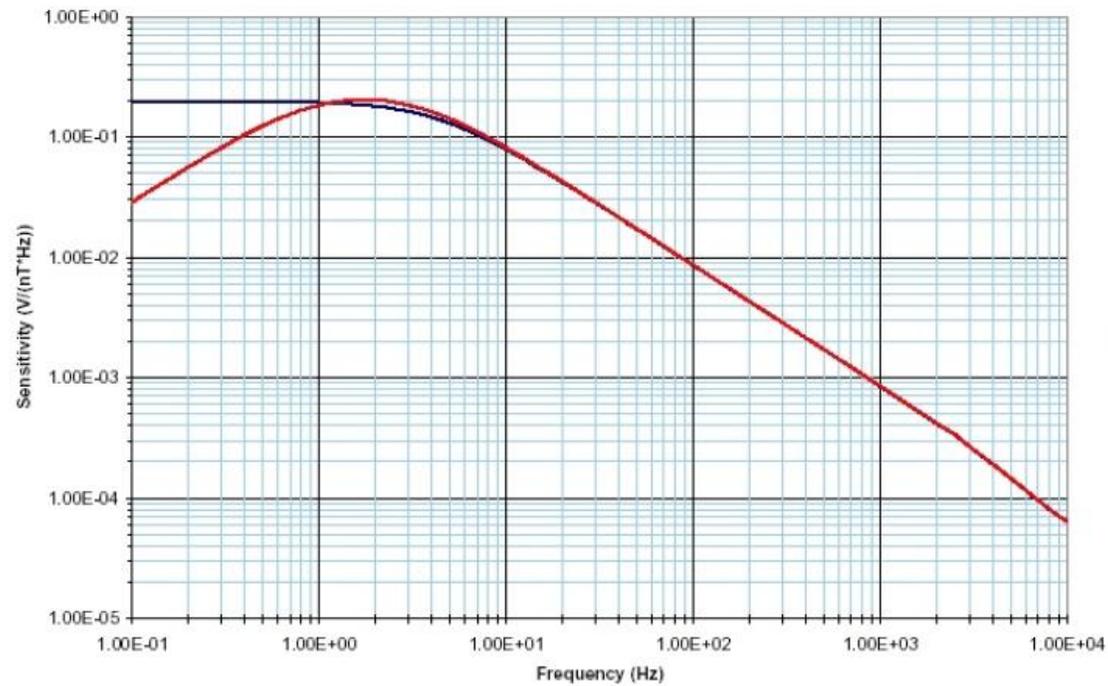
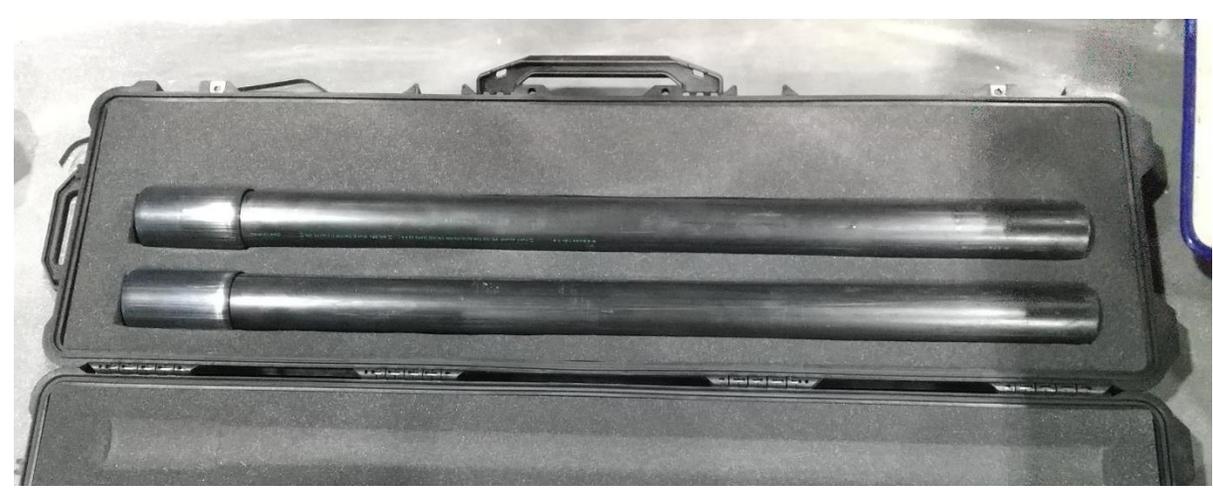
Summary of the activities in KAGRA

#	Date	Sensor / DAQ	purpose	Document
1	2014-12-01 ~ 03	Phoenix AMTC-30 (Rental) Phoenix MTU-5A (Rental)	1 st study (KAGRA solo)	JGW-G1503441 JGW-P1504229 J. Phys.: Conf. Ser. 716 012020 Atsuta's bachelor thesis
2	2016-07-21 ~ 22	Metronix MFS-06 (Rental) Metronix MFS-07e (Rental) Metronix ADU-07e (Rental)	LVK joint measurement Test of Wiener filter	JGW-G1605374 JGW-G1605417 JGW-T1605421 JGW-G1605420 JGW-G1605544 JGW-G1706129 Phys. Rev. D 97, 102007
3	2021-03-31 ~ 04-15	Metronix MFS-06e Metronix ADU-08 (Rental)	Test of the purchased sensors Search for the best location	JGW-G2112749 JGW-G2112764 JGW-G2112777
4	future (O4-)	Metronix MFS-06e KAGRA DGS	Ordinarily monitoring for GW observation	

✂ Washimi was not attend #1 & #2.

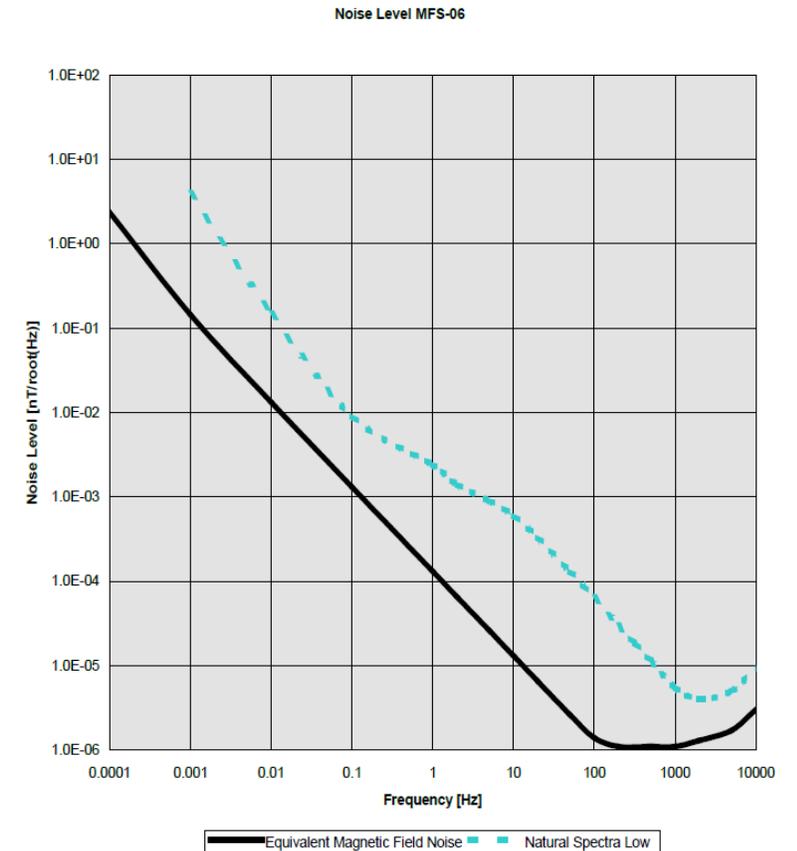
Magnet meter : MFS-06e

- 1-axis magnetometer (Metronix geophysics)
- Sensitive to the Schumann resonance
 - Used in Virgo
- We have purchased 4 ones.
- Tested with ADU-08 (rental)



Sensitivity

— Chopper On
— Chopper off



— Equivalent Magnetic Field Noise — Natural Spectra Low

Calibration @ Outside of the tunnel

Use the function of ADU-08

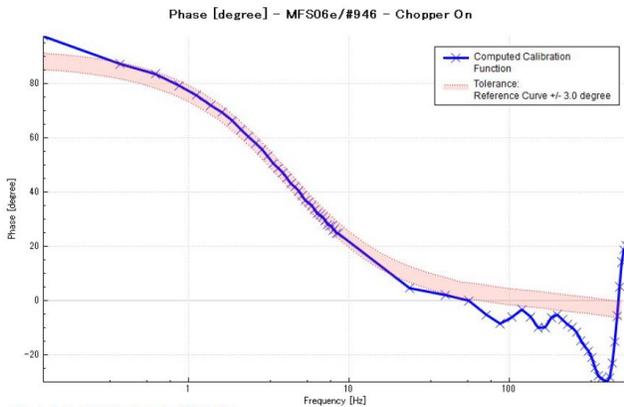
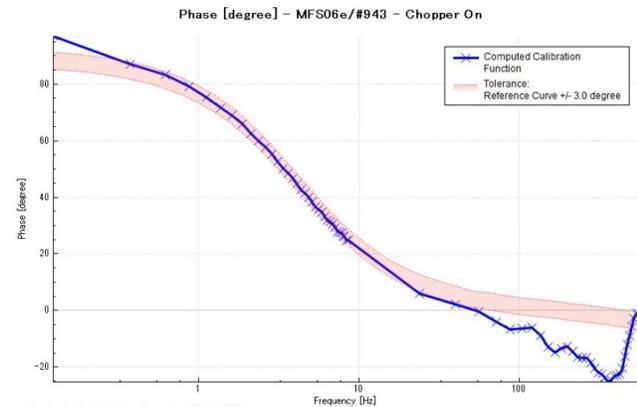
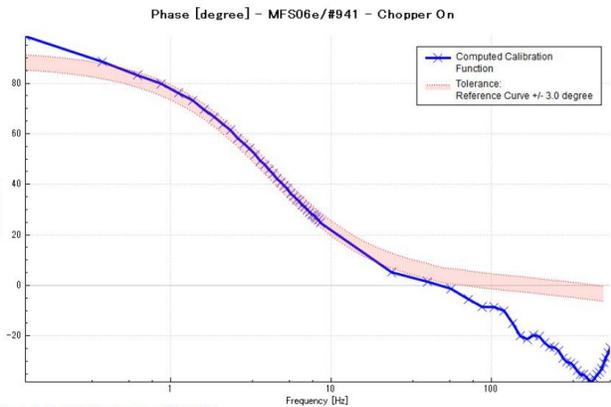
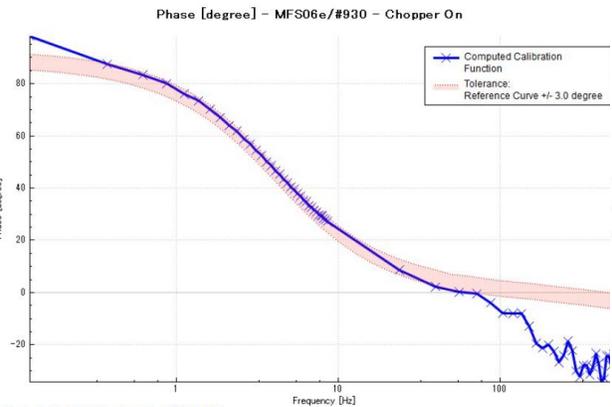
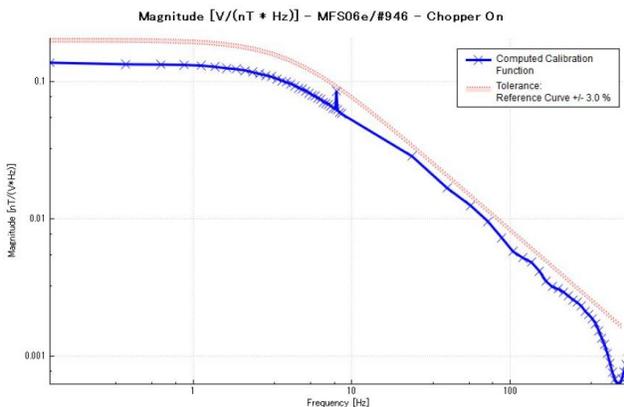
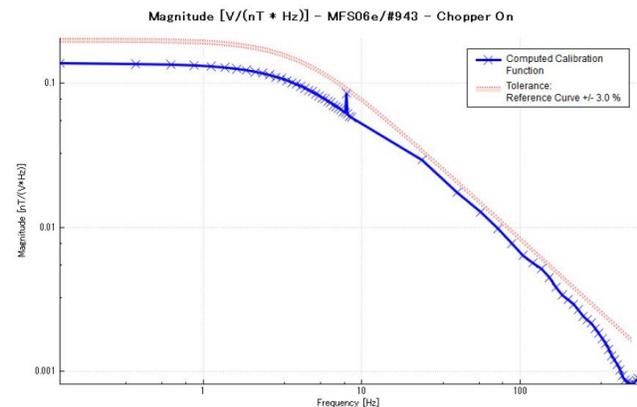
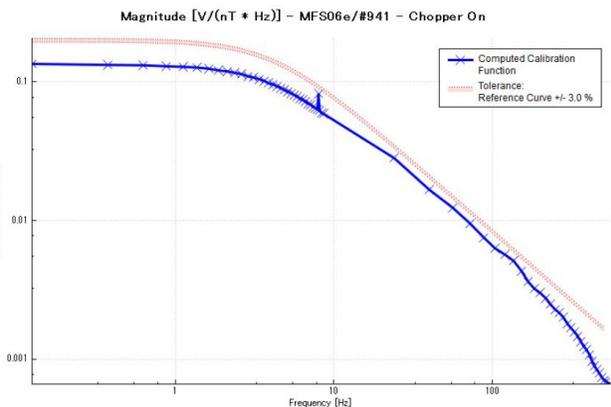
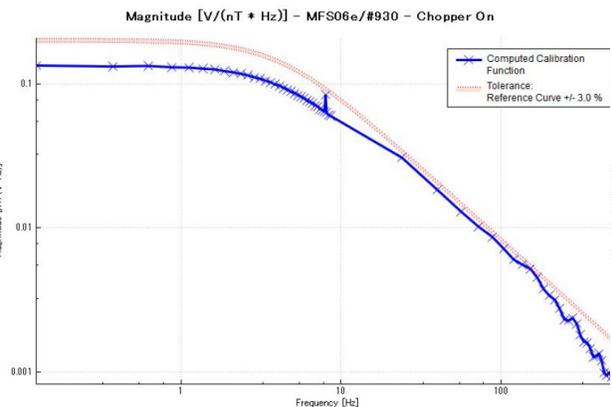


#0930

#0941

#0943

#0946



Transfer Function (nT -> V)

https://www.geo-metronix.de/metronix_manuals/en/mfs-06e/mfs-06e.html

a) CHOPPER ON

$$F_{Sensor} = \frac{V_{output}}{H} = 0.8 \frac{V}{nT} \cdot \frac{P_1}{1+P_1} \cdot \frac{1}{1+P_2} \cdot \frac{1}{1+P_4}$$

or normalized as we use it in our calibration files:

$$F_{on}(f) = \frac{V_{output}}{H \text{ Hz}} = 0.8 \frac{V}{nT} \cdot \frac{P_1}{1+P_1} \cdot \frac{1}{1+P_2} \cdot \frac{1}{1+P_4} / f$$

b) CHOPPER OFF

adds a term $P_3 = i \frac{f}{0.72Hz}$

$$F_{Sensor} = \frac{V_{output}}{H} = 0.8 \frac{V}{nT} \cdot \frac{P_1}{1+P_1} \cdot \frac{1}{1+P_2} \cdot \frac{P_3}{1+P_3} \cdot \frac{1}{1+P_4}$$

or normalized as we use it in our calibration files:

$$F_{off}(f) = \frac{V_{output}}{H \text{ Hz}} = 0.8 \frac{V}{nT} \cdot \frac{P_1}{1+P_1} \cdot \frac{1}{1+P_2} \cdot \frac{P_3}{1+P_3} \cdot \frac{1}{1+P_4} / f$$

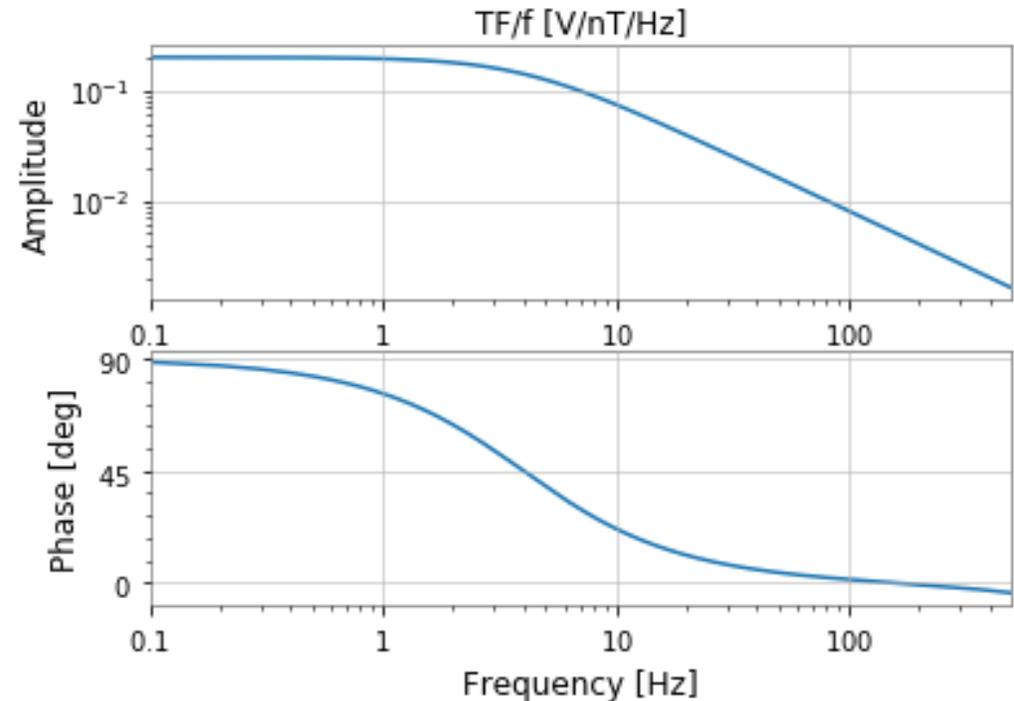
with

$$P_1 = i \cdot \frac{f}{4Hz}, P_2 = i \cdot \frac{f}{8192Hz}, P_3 = i \cdot \frac{f}{0.72Hz}, P_4 = i \cdot \frac{f}{28300Hz}$$

```
f = np.arange(start=0.1, stop=500, step=0.1, dtype='float')
P1 = 1j * f / 4.
P2 = 1j * f / 8192.
P4 = 1j * f / 28300.

TF = FrequencySeries(0.8*P1/(1+P1)/(1+P2)/(1+P4), frequencies=f)
```

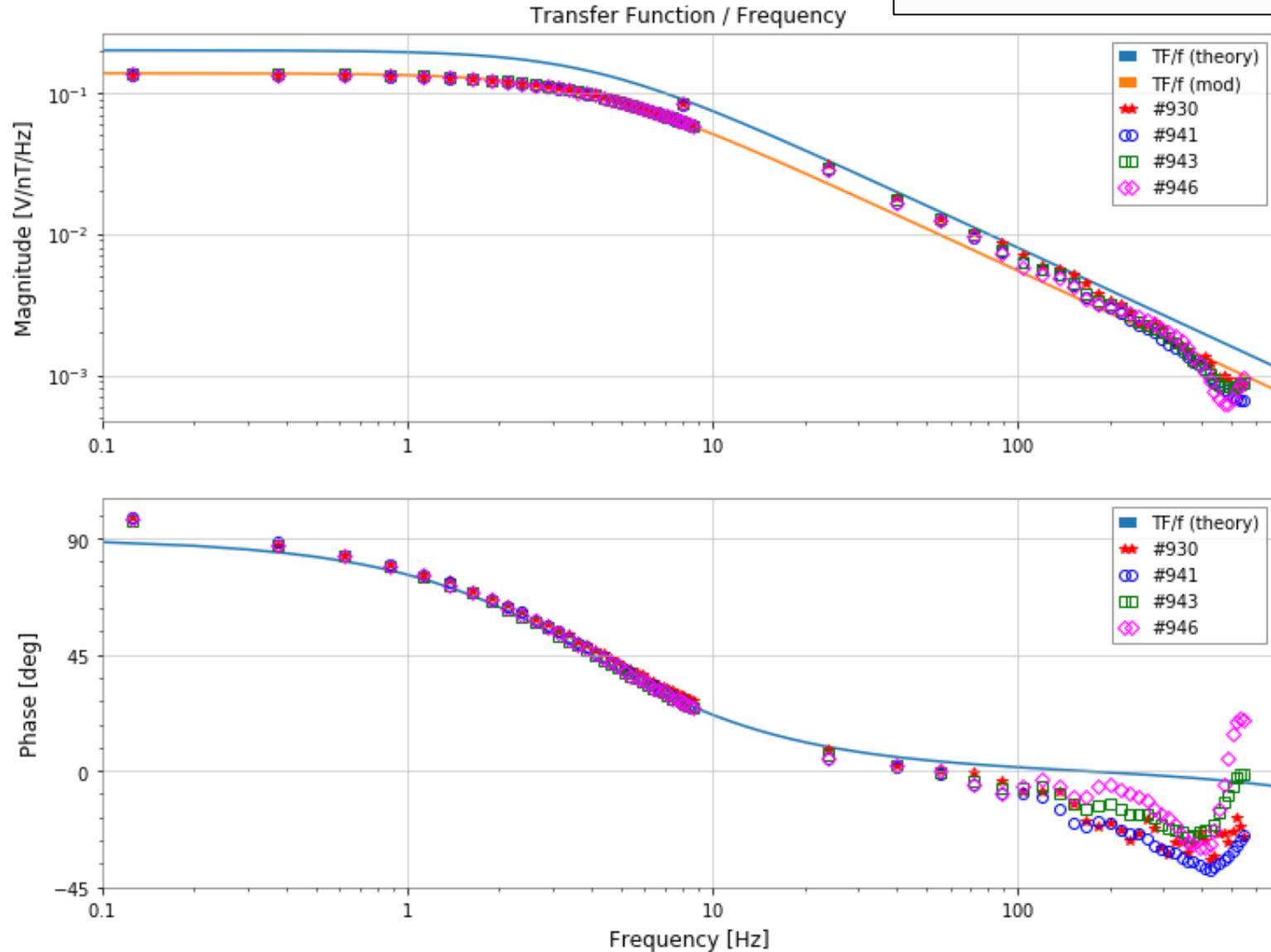
```
plot = BodePlot(TF/f, dB=False)
plot.maxes.set_title('TF/f [V/nT/Hz]')
plot.show()
```



Calibration for TF

a) CHOPPER ON

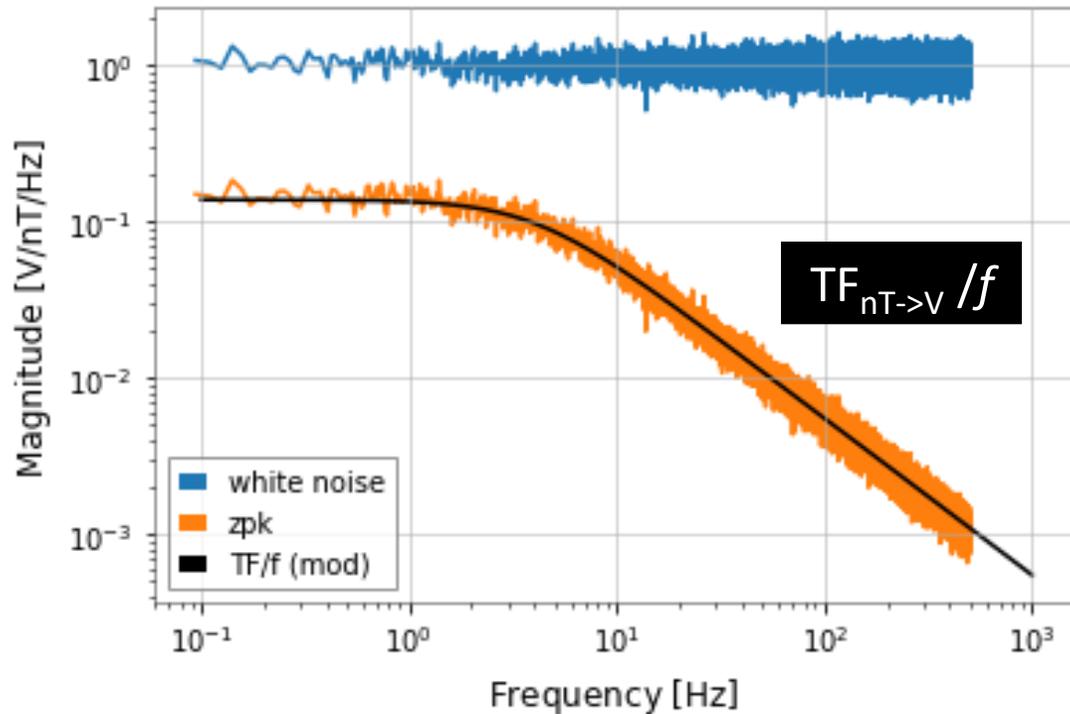
$$F_{Sensor} = \frac{V_{output}}{H} = 0.55 \cdot \frac{V}{nT} \cdot \frac{P_1}{1+P_1} \cdot \frac{1}{1+P_2} \cdot \frac{1}{1+P_4}$$



Filter design

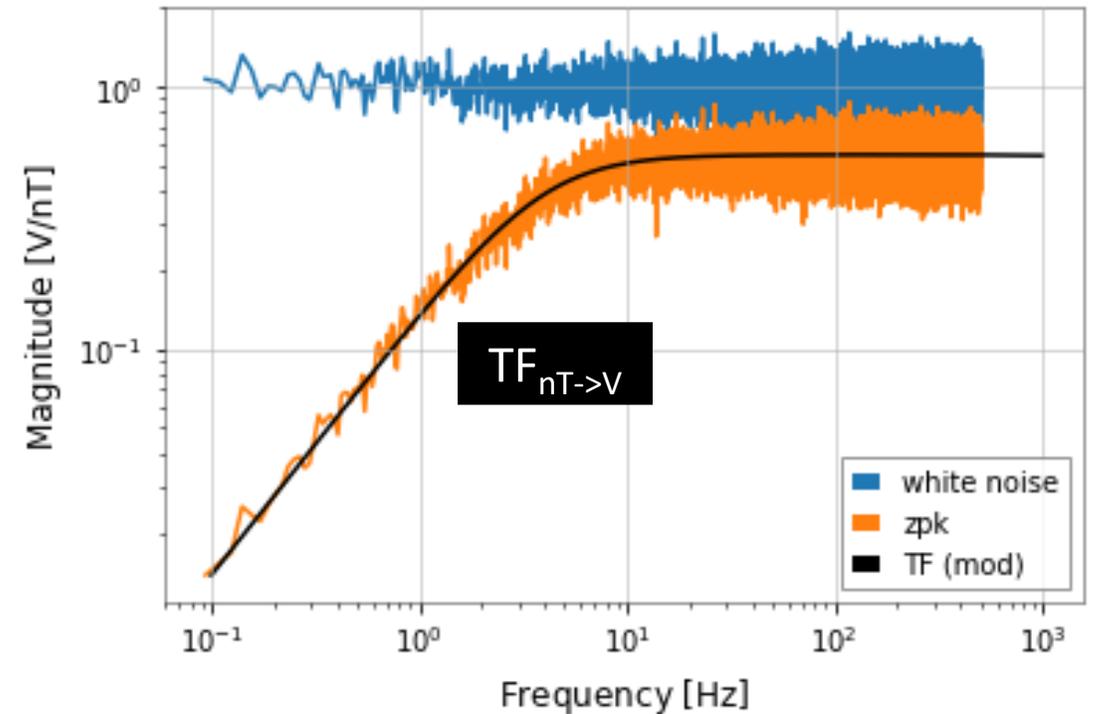
```
asd = TS.asd(64,32,method='median').crop(0.1,500)
plot = asd.plot(xscale='log', yscale='log', label='white noise')
ax = plot.gca()

asd_filt = TS.zpk([], [4, 8192], 4*8192*5.5).asd(64,32,method='median').crop(0.1,500)
ax.plot(asd_filt, label='zpk')
ax.plot(TF_mod.abs()/f, label='TF/f (mod)', color='black')
ax.set_ylabel('Magnitude [V/nT/Hz]')
ax.legend()
plot.show()
```



```
plot = asd.plot(xscale='log', yscale='log', label='white noise')
ax = plot.gca()

asd_filt = TS.zpk([0], [4, 8192], 4*8192*5.5/4/1.6).asd(64,32,method='median').crop(0.1,500)
ax.plot(asd_filt, label='zpk')
ax.plot(TF_mod.abs(), label='TF (mod)', color='black')
ax.set_ylabel('Magnitude [V/nT]')
ax.legend()
plot.show()
```

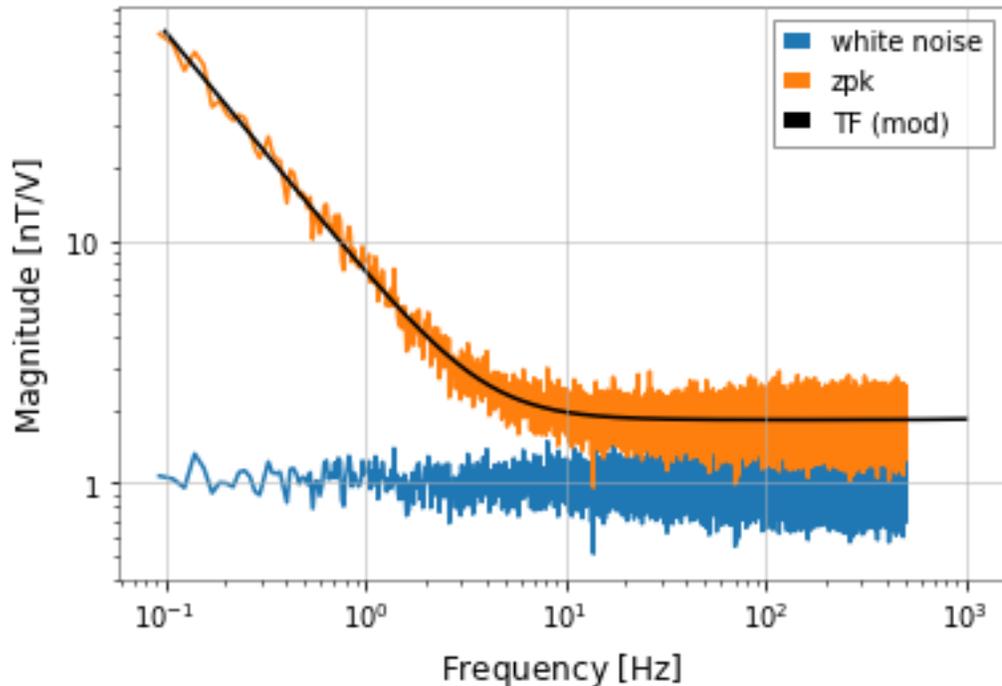


Filter design

```
plot = asd.plot(xscale='log', yscale='log', label='white noise')
ax = plot.gca()

asd_filt = TS.zpk([4],[0],1.8).highpass(1e-2).asd(64,32,method='median').crop(0.1,500)
#asd_filt = TS.zpk([4,8192],[0],1.8).asd(64,32,method='median').crop(0.1,500)

ax.plot(asd_filt , label='zpk')
ax.plot(1/TF_mod.abs(), label='TF (mod)', color='black')
ax.set_ylabel('Magnitude [nT/V]')
ax.legend()
plot.show()
```



逆フィルターが定義できない(零点の数が極の数より多いとエラーになる)ので、無理やり再現

位相が変なことになってるかもしれないが、とりあえず置いておく

```
plot = asd.plot(xscale='log', yscale='log', label='white noise')
ax = plot.gca()

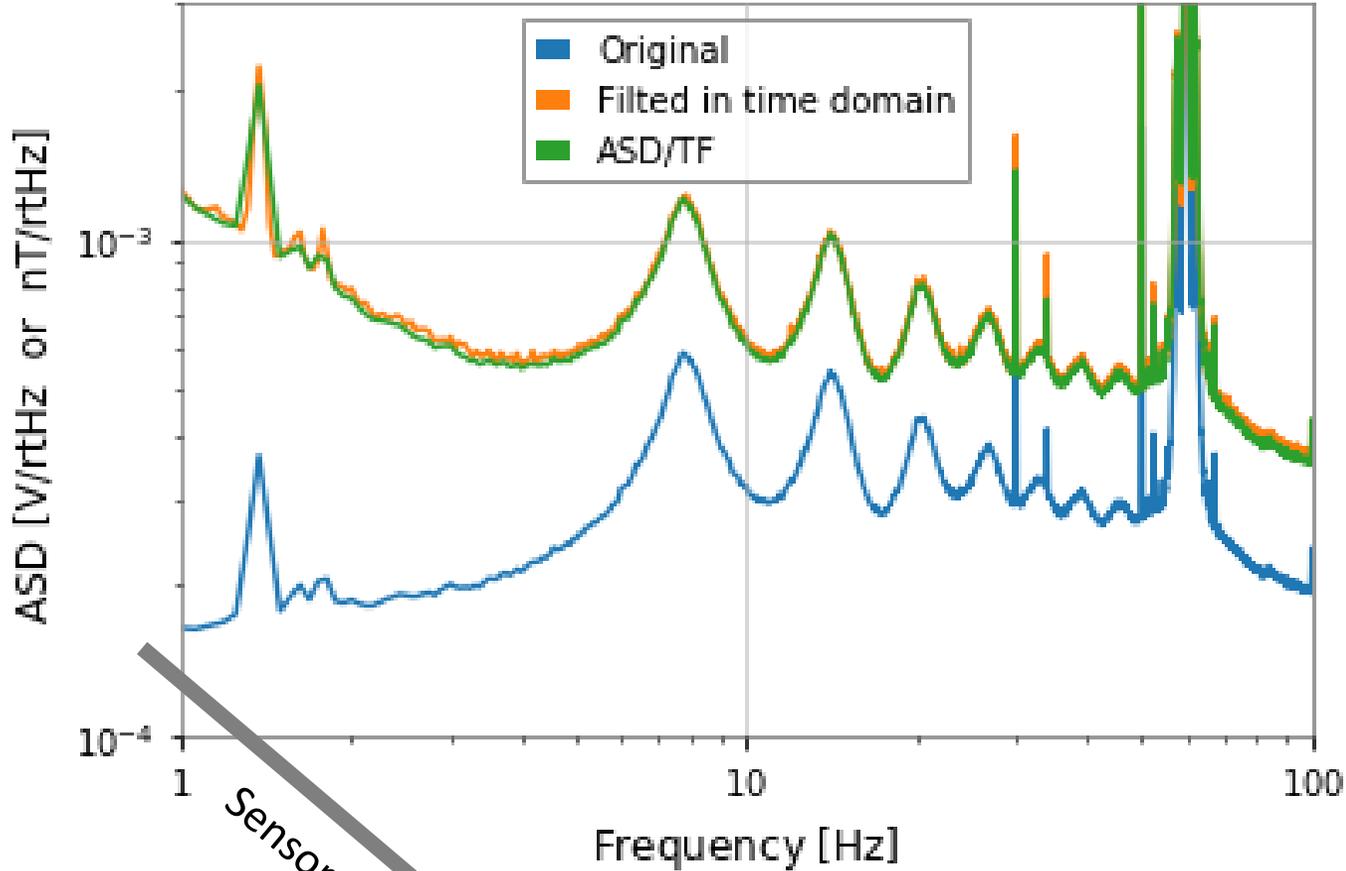
#asd_filt = TS.zpk([4],[0],1.8).highpass(1e-2).asd(64,32,method='median').crop(0.1,500)
asd_filt = TS.zpk([4,8192],[0],1.8).asd(64,32,method='median').crop(0.1,500)

ax.plot(asd_filt , label='zpk')
ax.plot(1/TF_mod.abs(), label='TF (mod)', color='black')
ax.set_ylabel('Magnitude [nT/V]')
ax.legend()
plot.show()
```

```
-----
ValueError                                Traceback (most recent call last)
<ipython-input-141-b1ff1d6f2cab> in <module>()
      3
      4 #asd_filt = TS.zpk([4],[0],1.8).highpass(1e-2).asd(64,32,method='median').crop(0.1,500)
----> 5 asd_filt = TS.zpk([4,8192],[0],1.8).asd(64,32,method='median').crop(0.1,500)
      6
      7 ax.plot(asd_filt , label='zpk')
```

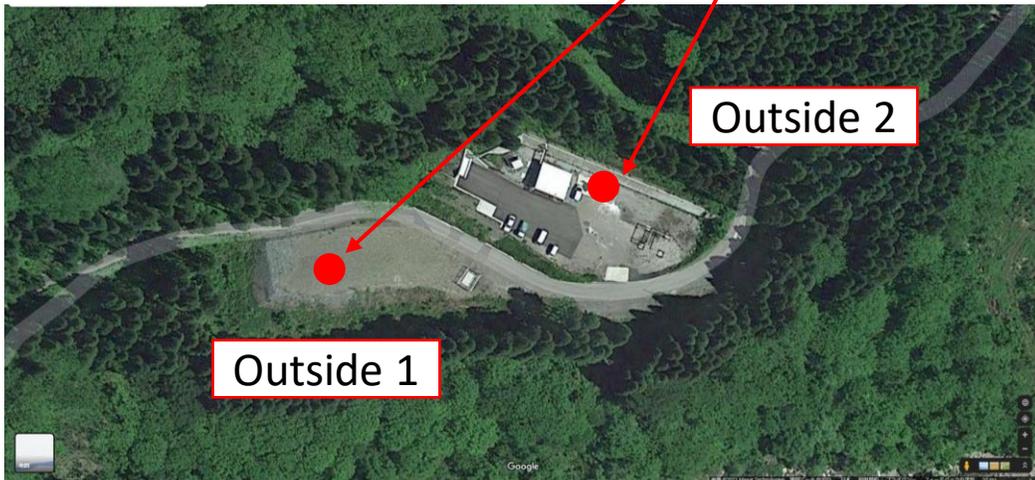
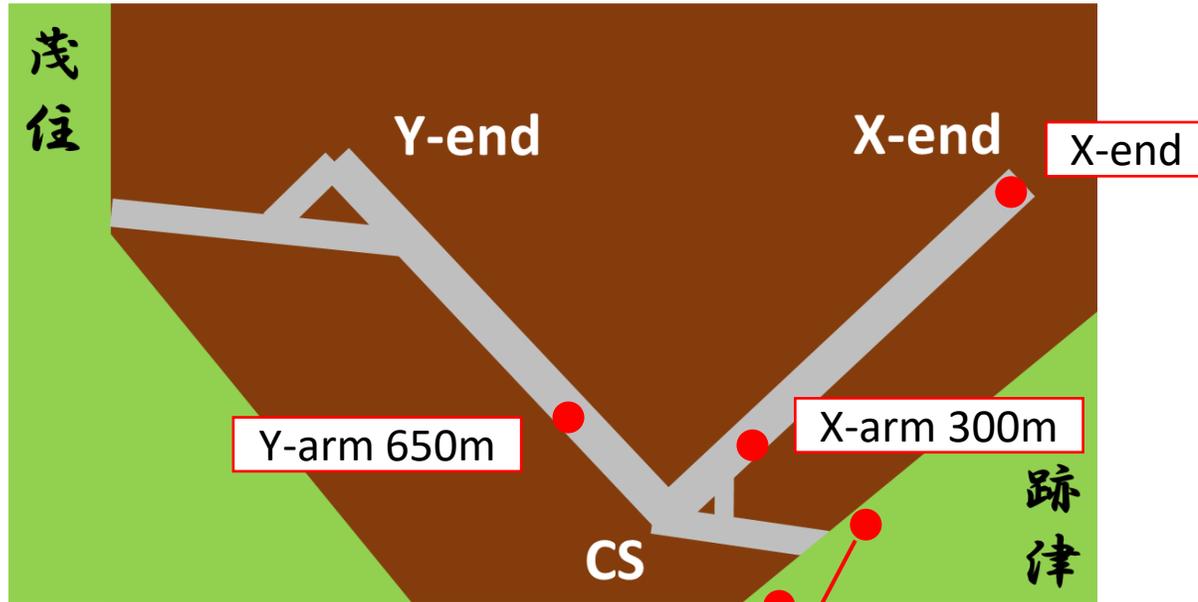
Applied for the data (Outside of the mine, NS)

Outside1, NS
03/31 14:24 - 04/01 09:31 JST

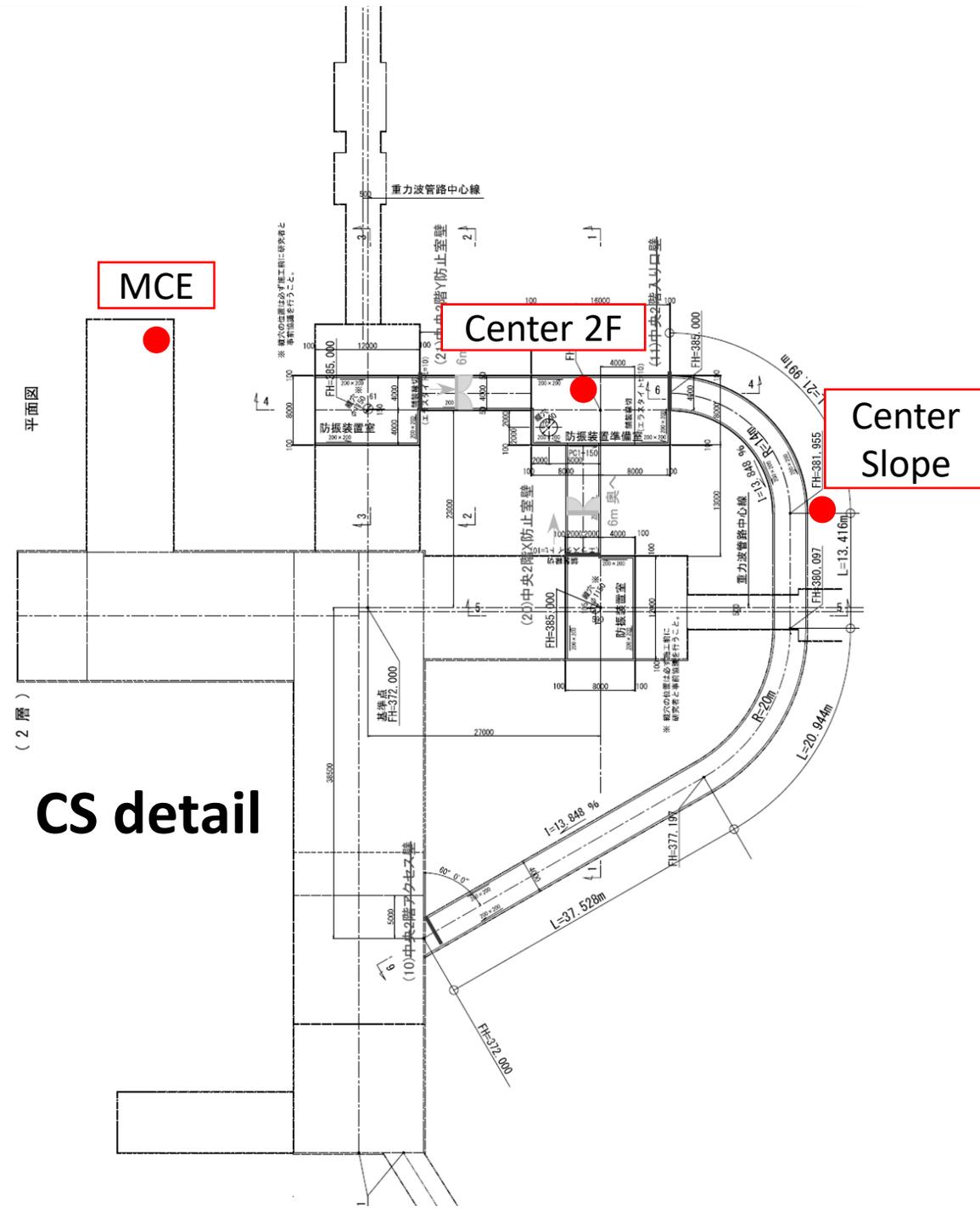


↓ ADC noise level $\sim 1.6 \times 10^{-7}$ V/vHz

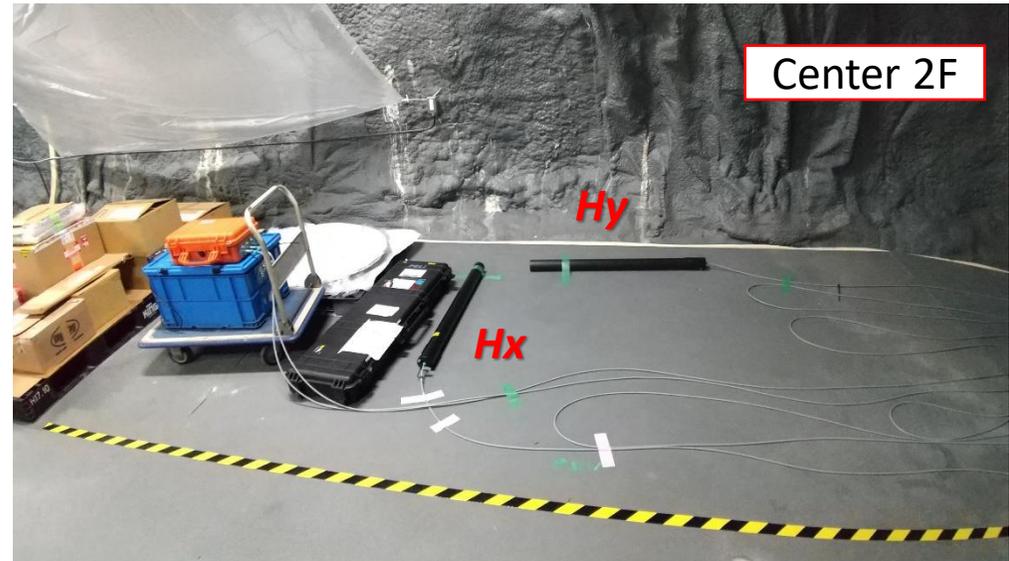
Measurements Location



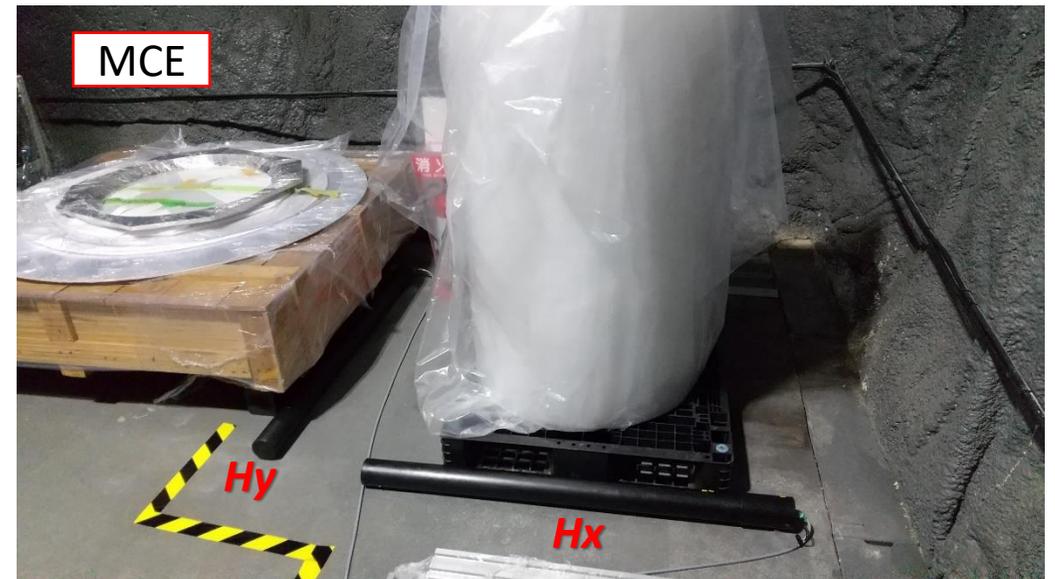
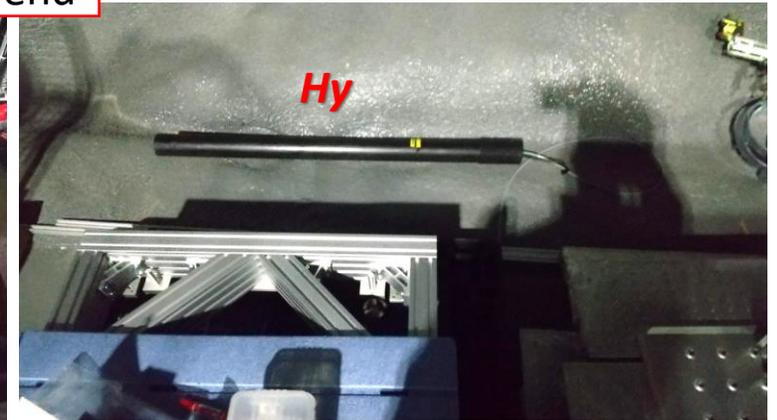
中央エリア構造一般図(4) 縮尺 1:200



Photos



Photos



Absolute value check @ Outside1

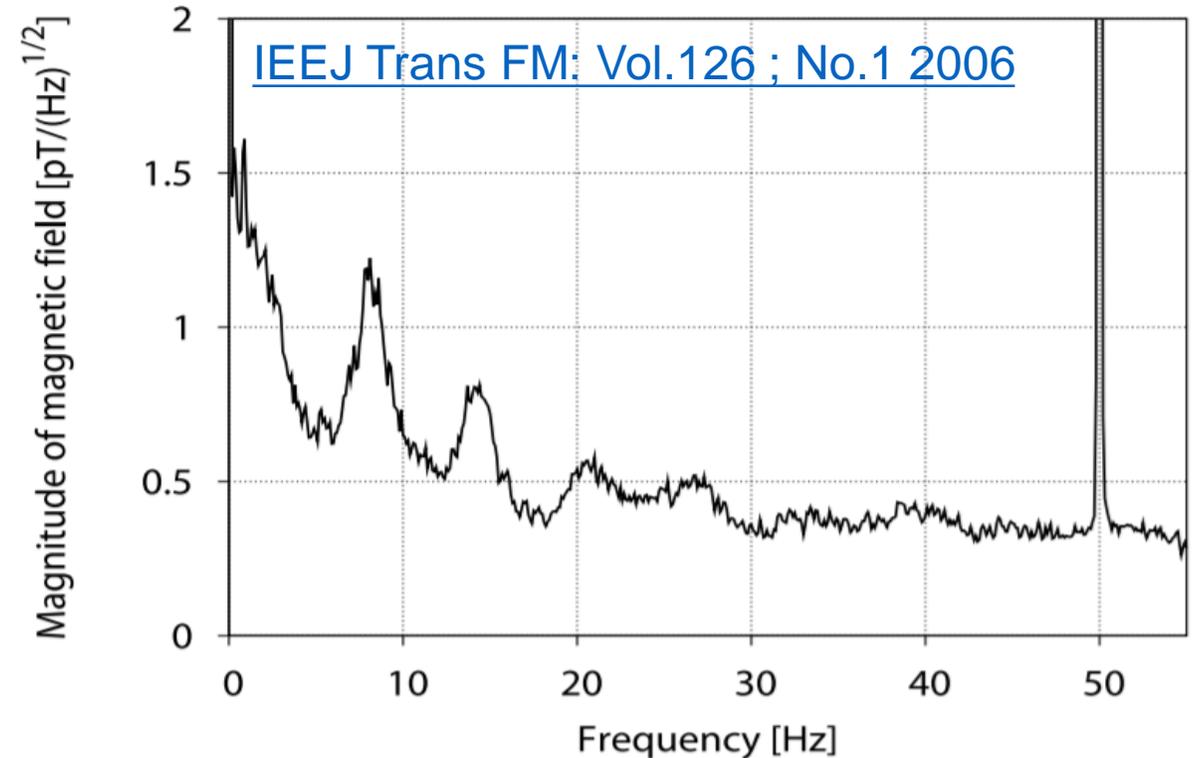
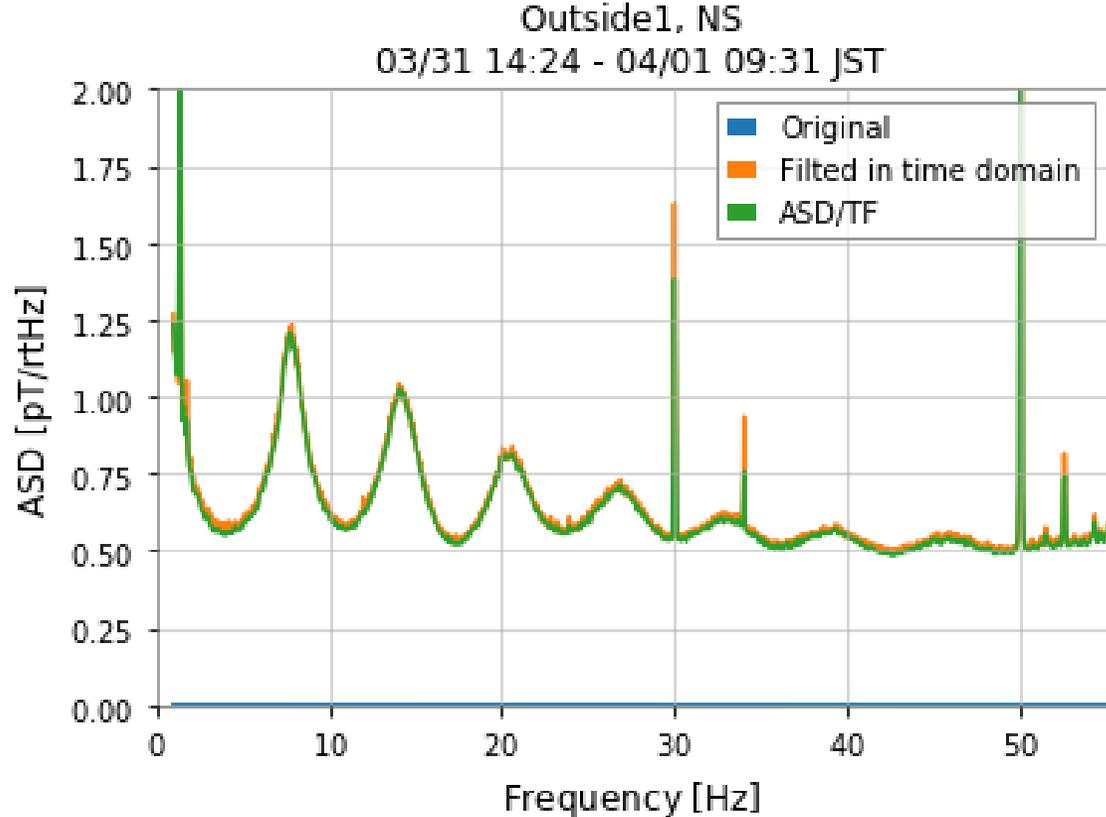
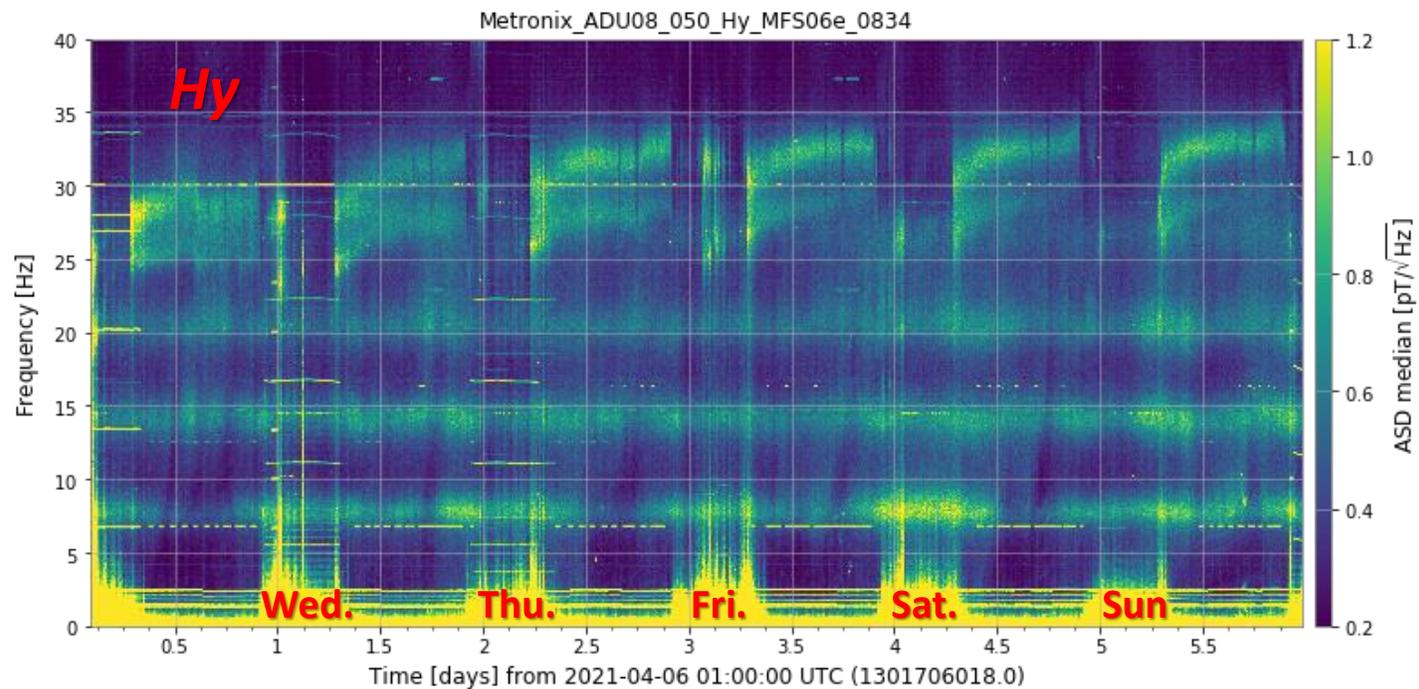
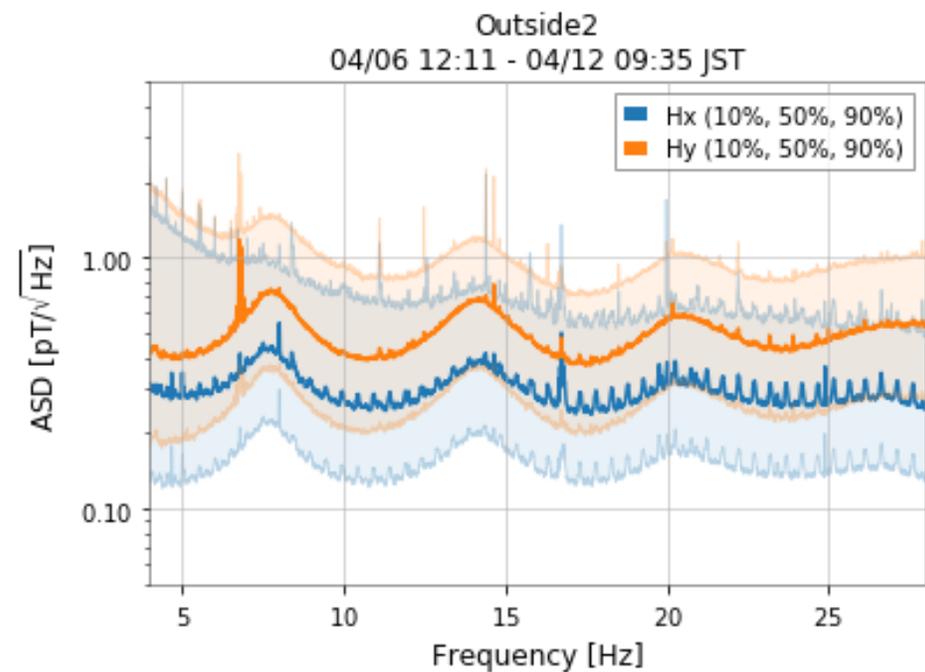
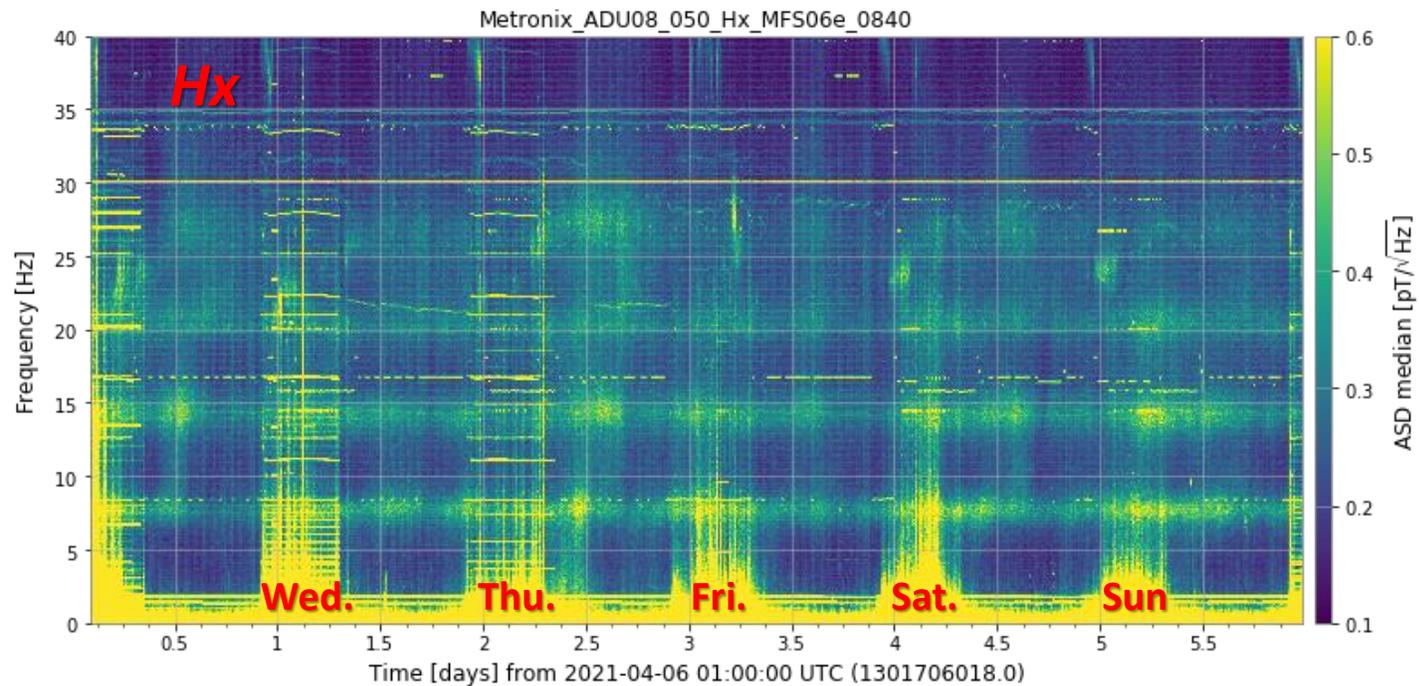
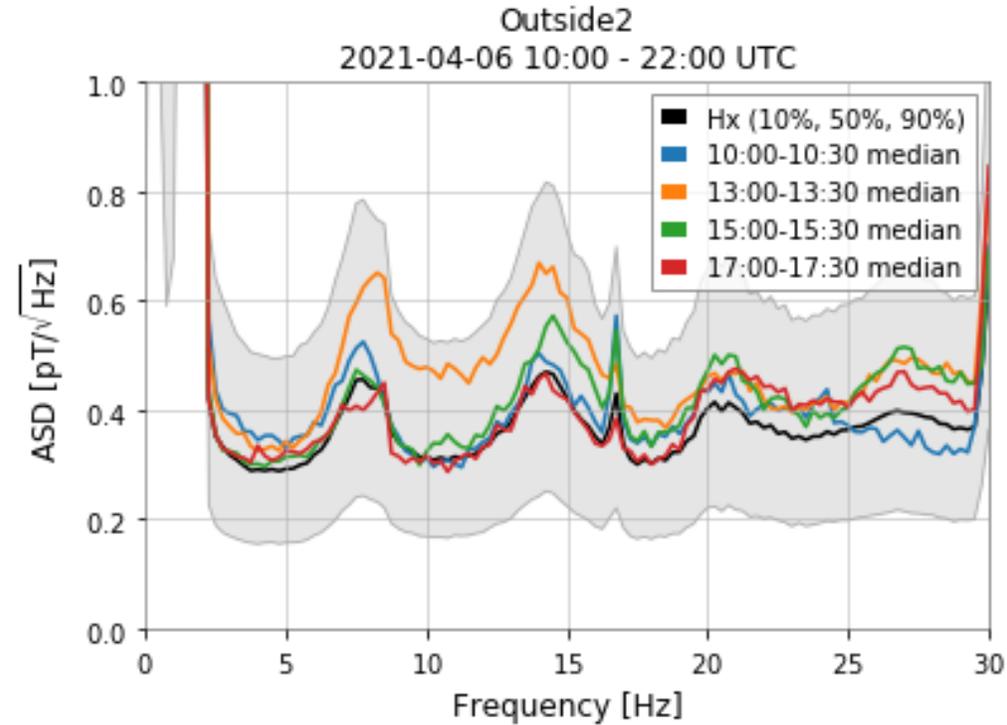
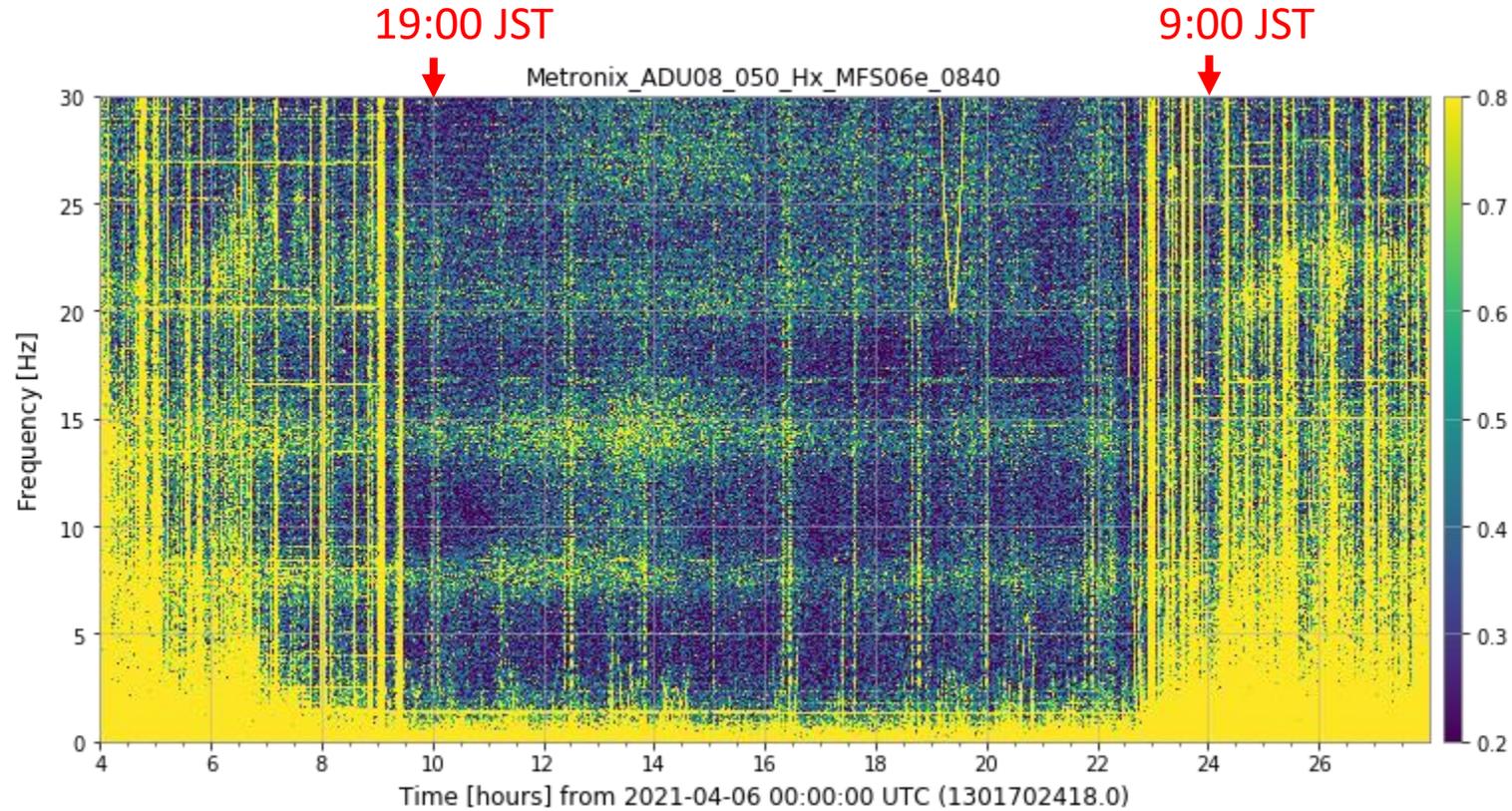


Fig. 1. An example of the spectrum of Schumann resonance: The first resonant peak is observed at about 8 Hz; The data were collected at Moshiri, Hokkaido, Japan (44° 20'N 142° 15'E) at 18:00UT on 15th August 2004. The discrete response at 50 Hz is the noise radiated from the commercial power supply system

Outside2, 6 days



Outside2 (Hx), 24 hour

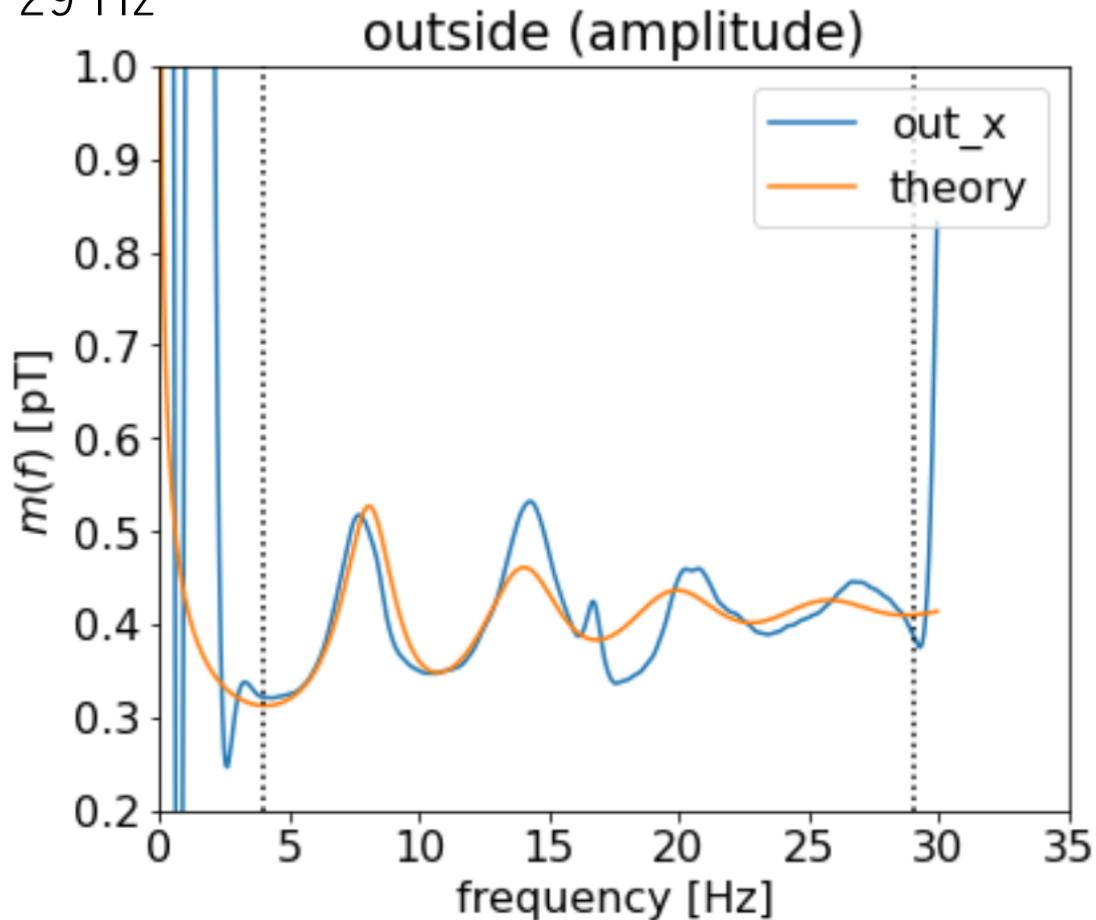


- It's noisy in daytime due to the human activity (cars?).
- Night time is good.
- The amplitude changes about factor 0.5 ~ 2.

Fitting for the “Outside2” data

2021/4/6 10:00:00 - 22:00:00 UTC

Quadratic-butterworth filtered data, 4 – 29 Hz



$$P_{\text{SR}}(f) = P_{\text{B}}(f) \sum_{\ell} \frac{[f'_{\ell}/(2Q)]^2}{(f - f'_{\ell})^2 + [f_{\ell}/(2Q)]^2}$$

$$P_{\text{B}}(f) = A \left(\frac{f}{10 \text{ Hz}} \right)^{-\alpha} \quad (\text{typically } \alpha = 0.88)$$

$$f_{\ell} = \frac{\sqrt{\ell(\ell+1)} c}{2\pi a} \quad f'_{\ell} = s \times f_{\ell}$$

(typically $s=0.78$)

a : Earth radius

Q : Q value (typically ~ 5)

4 free
parameters

best-fitted by

$$\alpha = 0.72$$

$$Q = 4.8$$

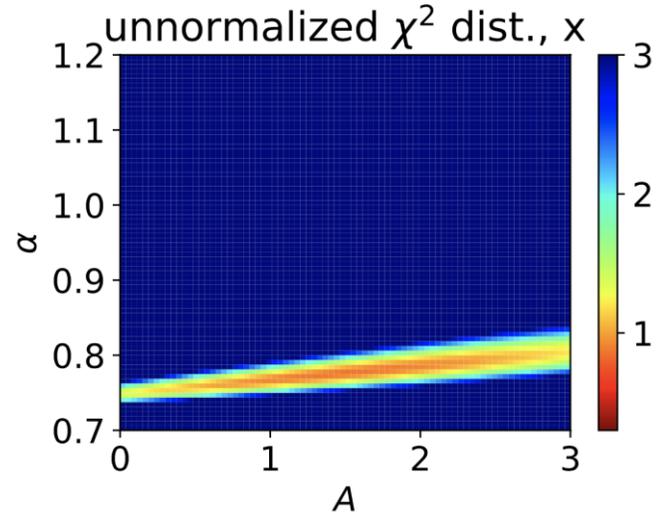
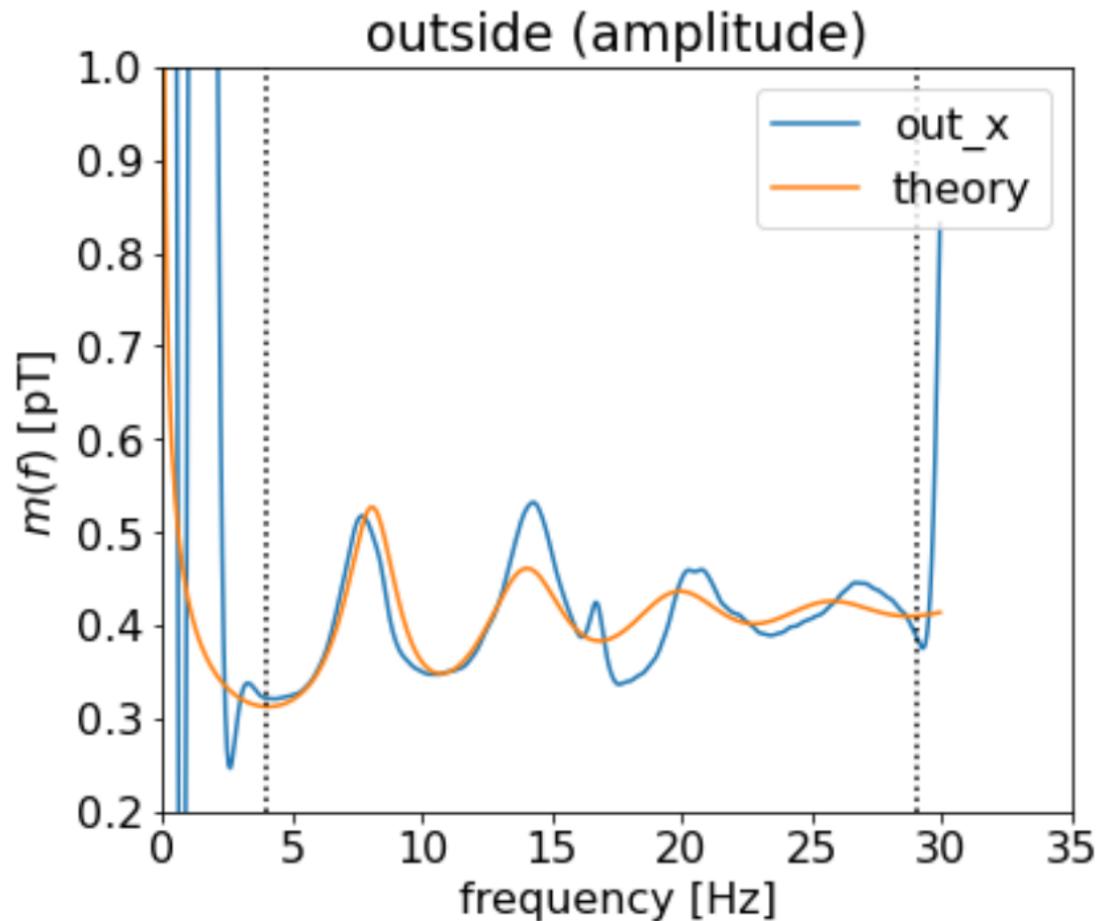
$$s = 0.77$$

$$A = 0.3 \text{ pT}^2/\text{Hz}$$

Fitting for the “Outside2” data

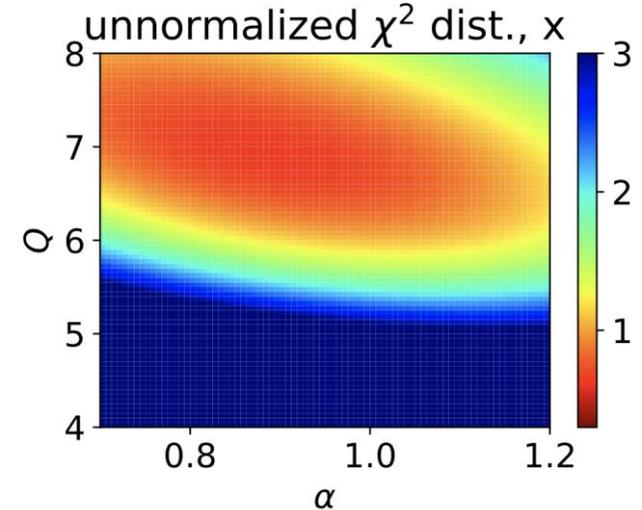
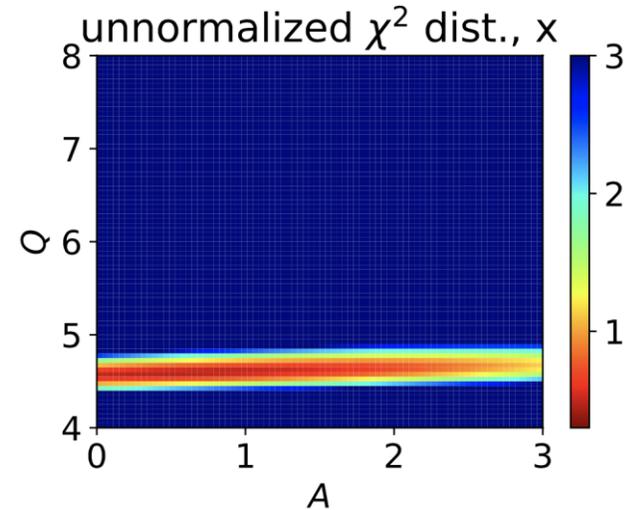
2021/4/6 10:00:00 - 22:00:00 UTC

Quadratic-butterworth filtered data, 4 – 29 Hz



Fixing the other parameters to the best-fitting ones.

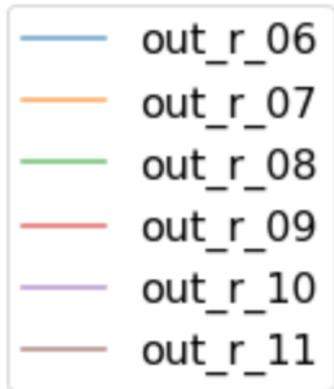
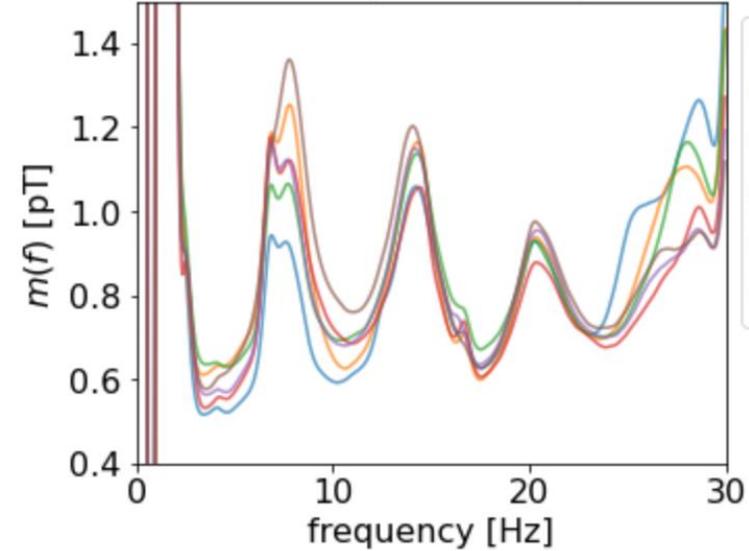
No strong correlation between parameters.



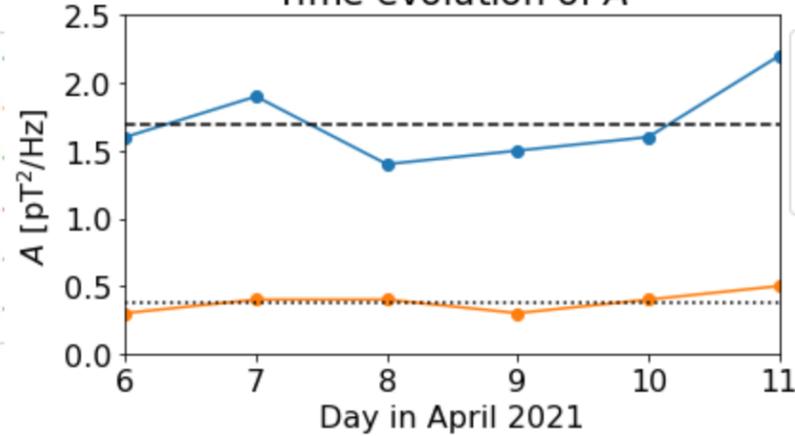
Fitting for the "Outside2" data

Fitting for each nights data

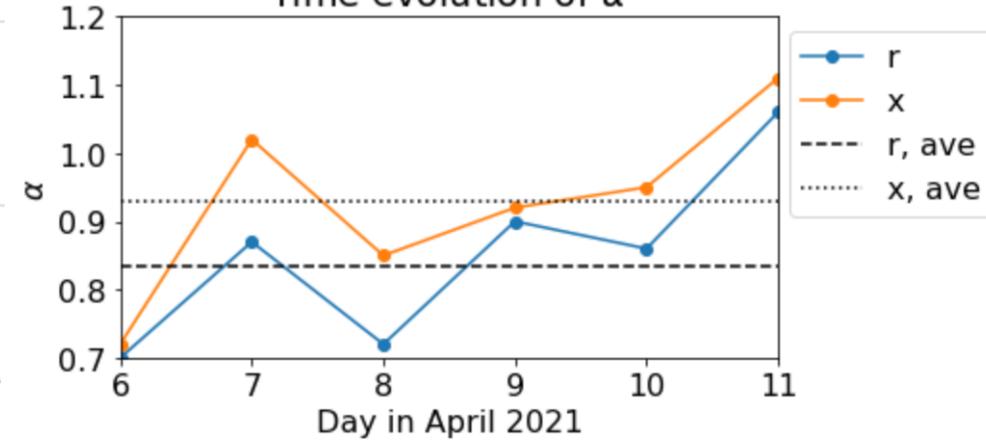
outside (amplitude), Apr 2021



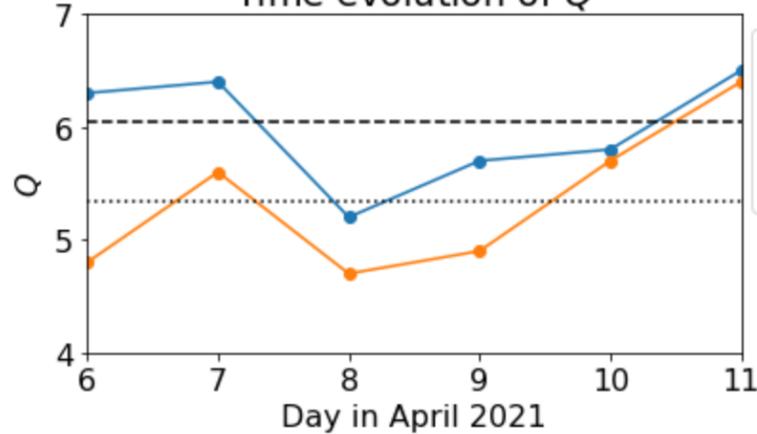
Time evolution of A



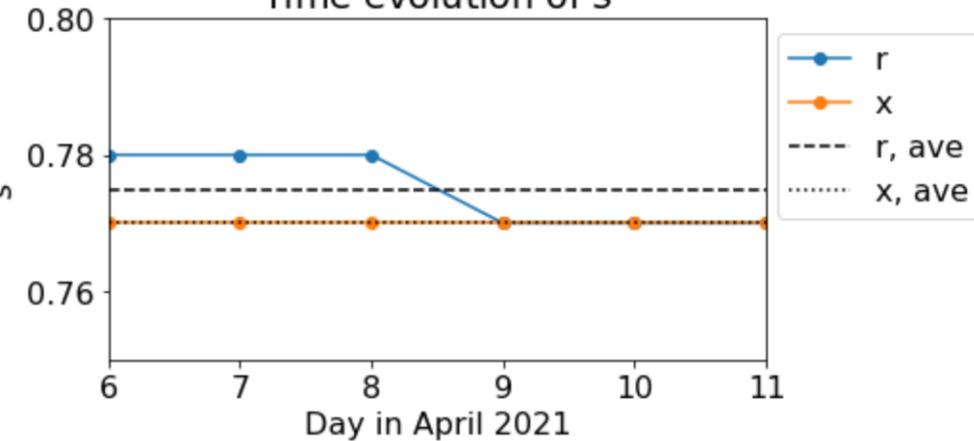
Time evolution of α



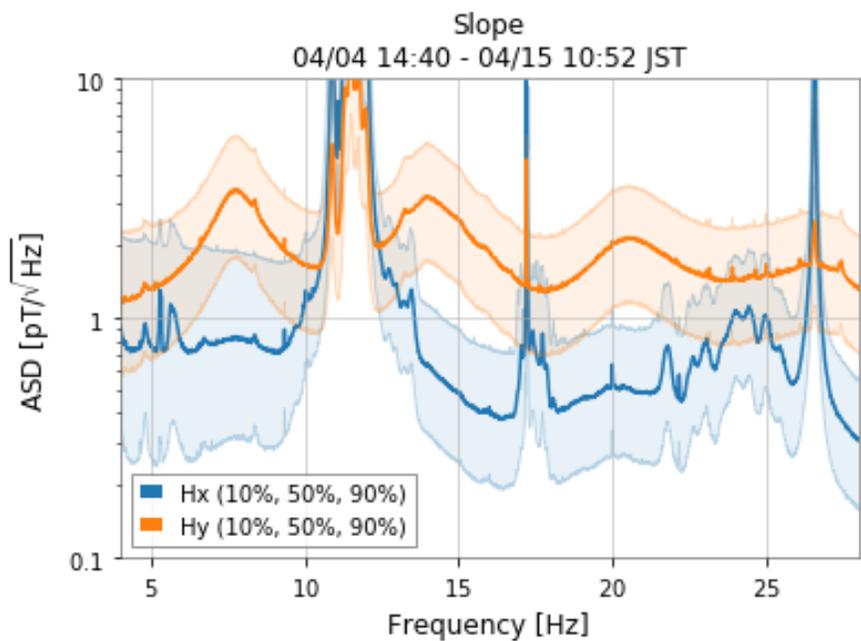
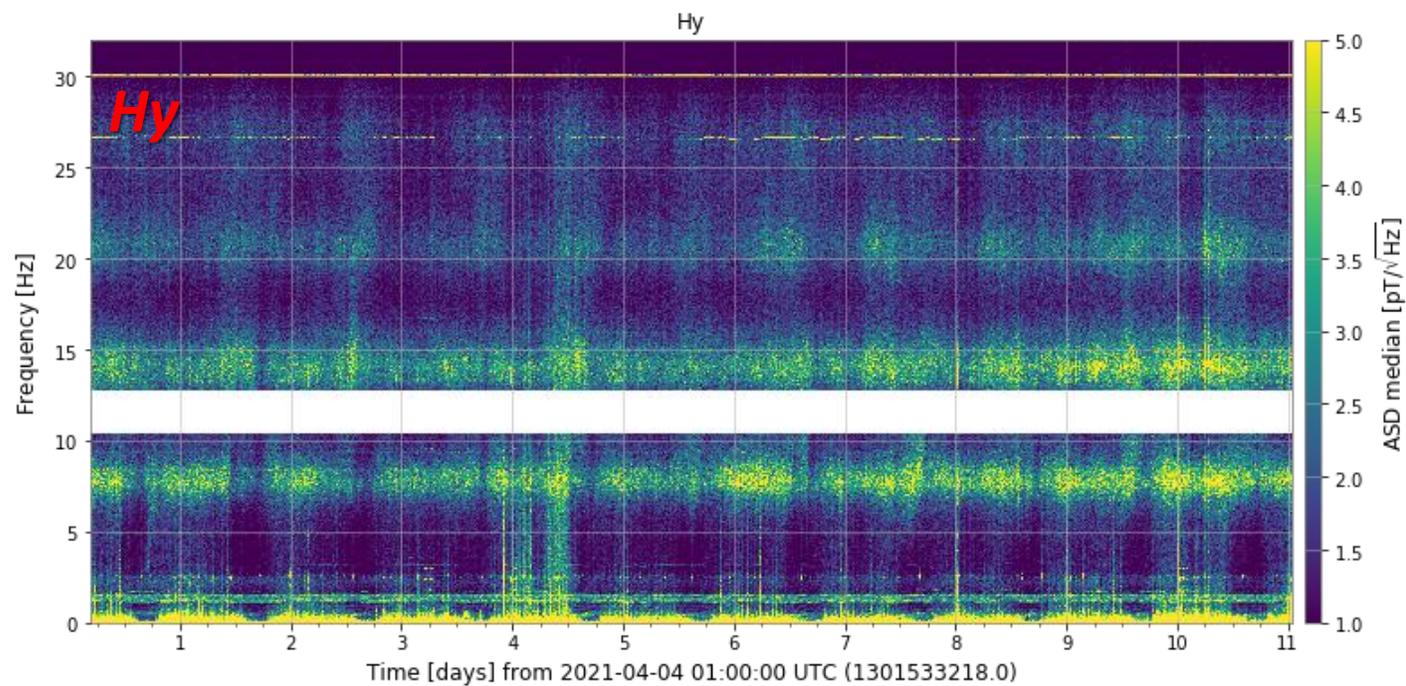
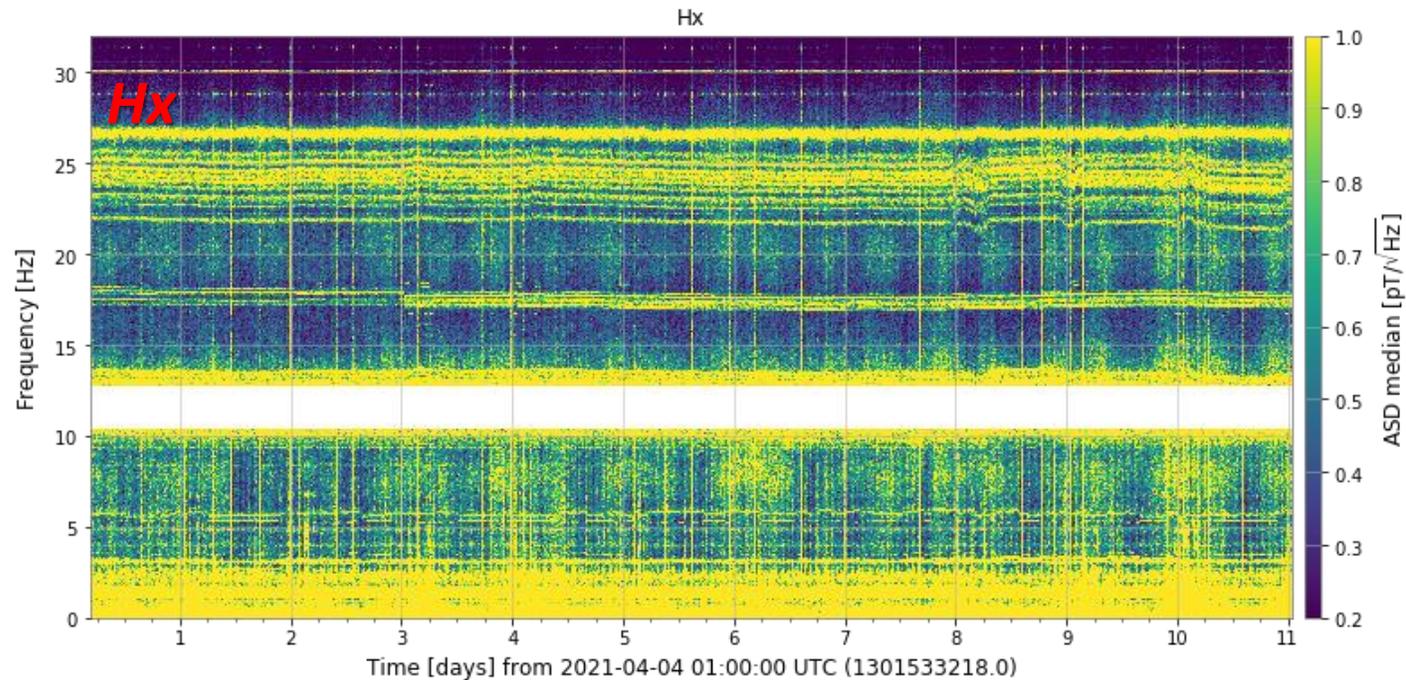
Time evolution of Q



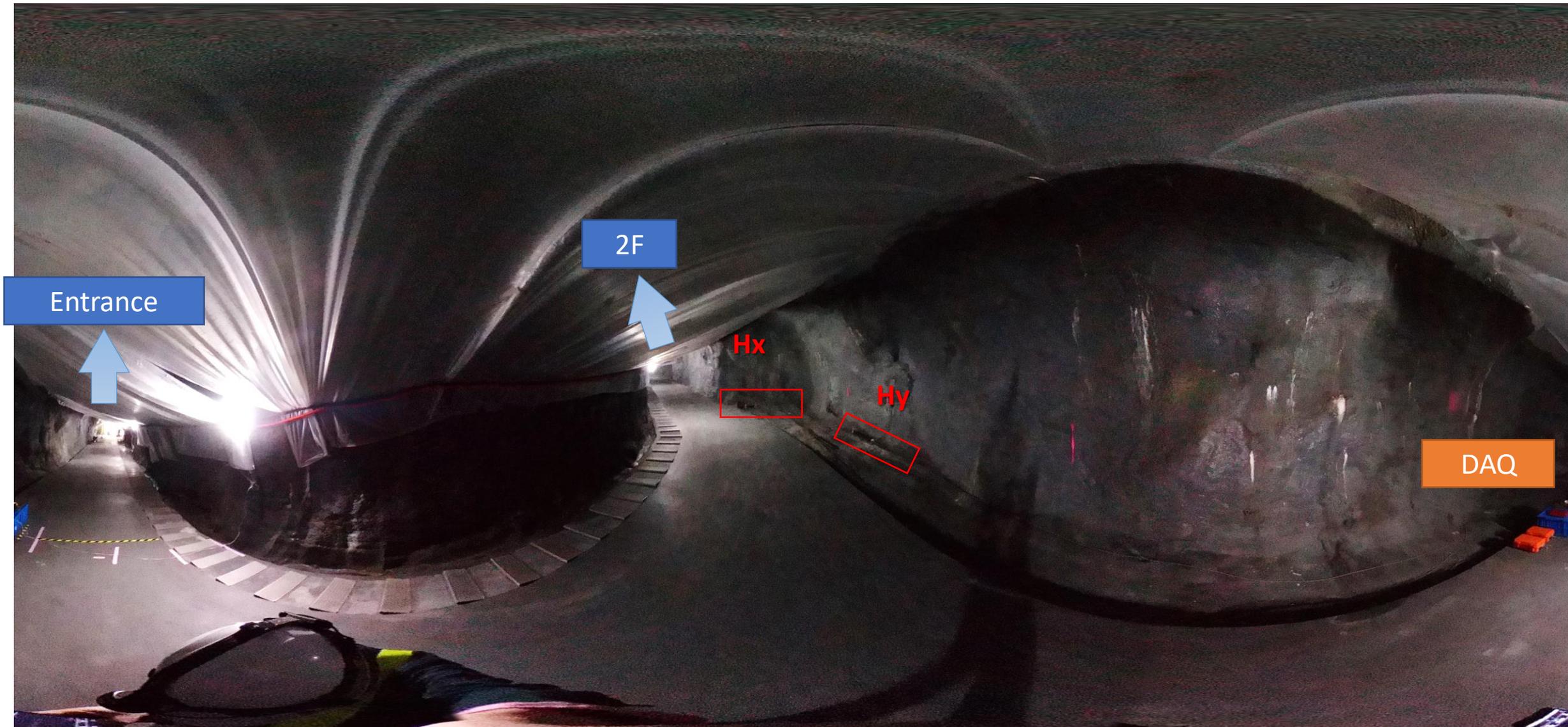
Time evolution of s



Slope, 11 days

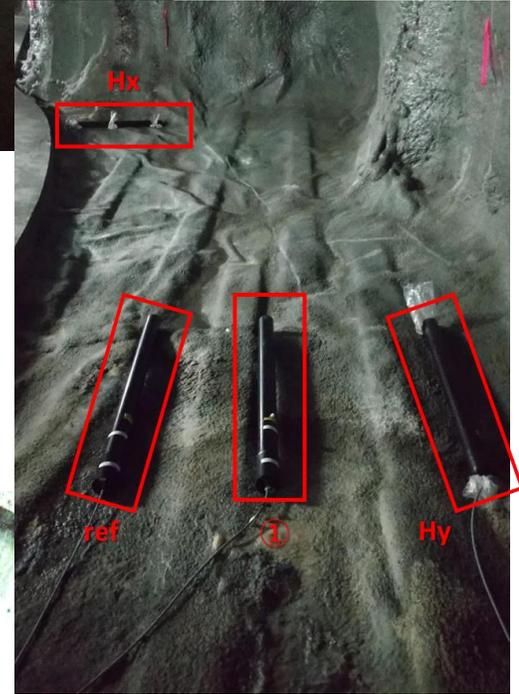
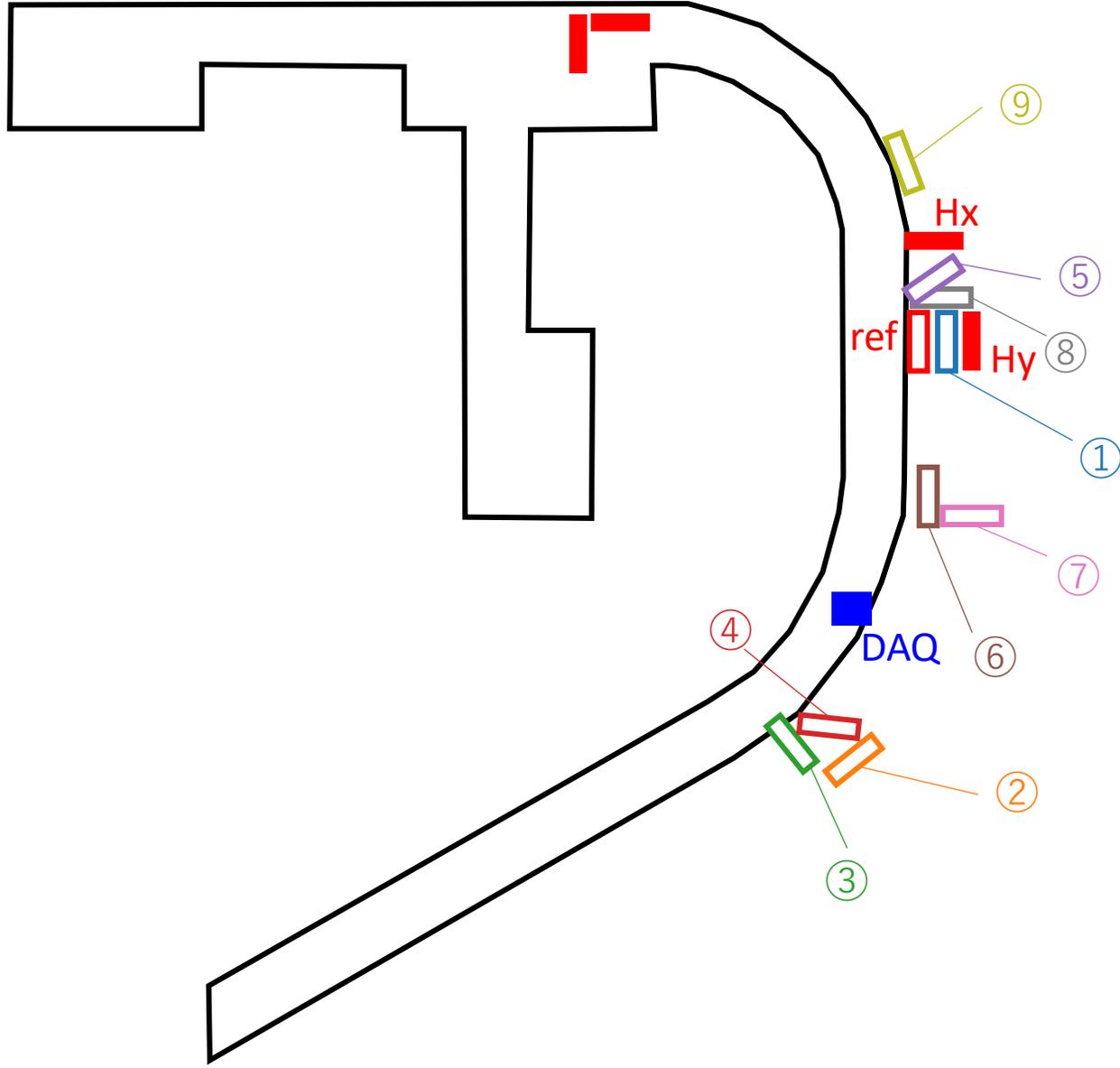


Measurements @ Slope



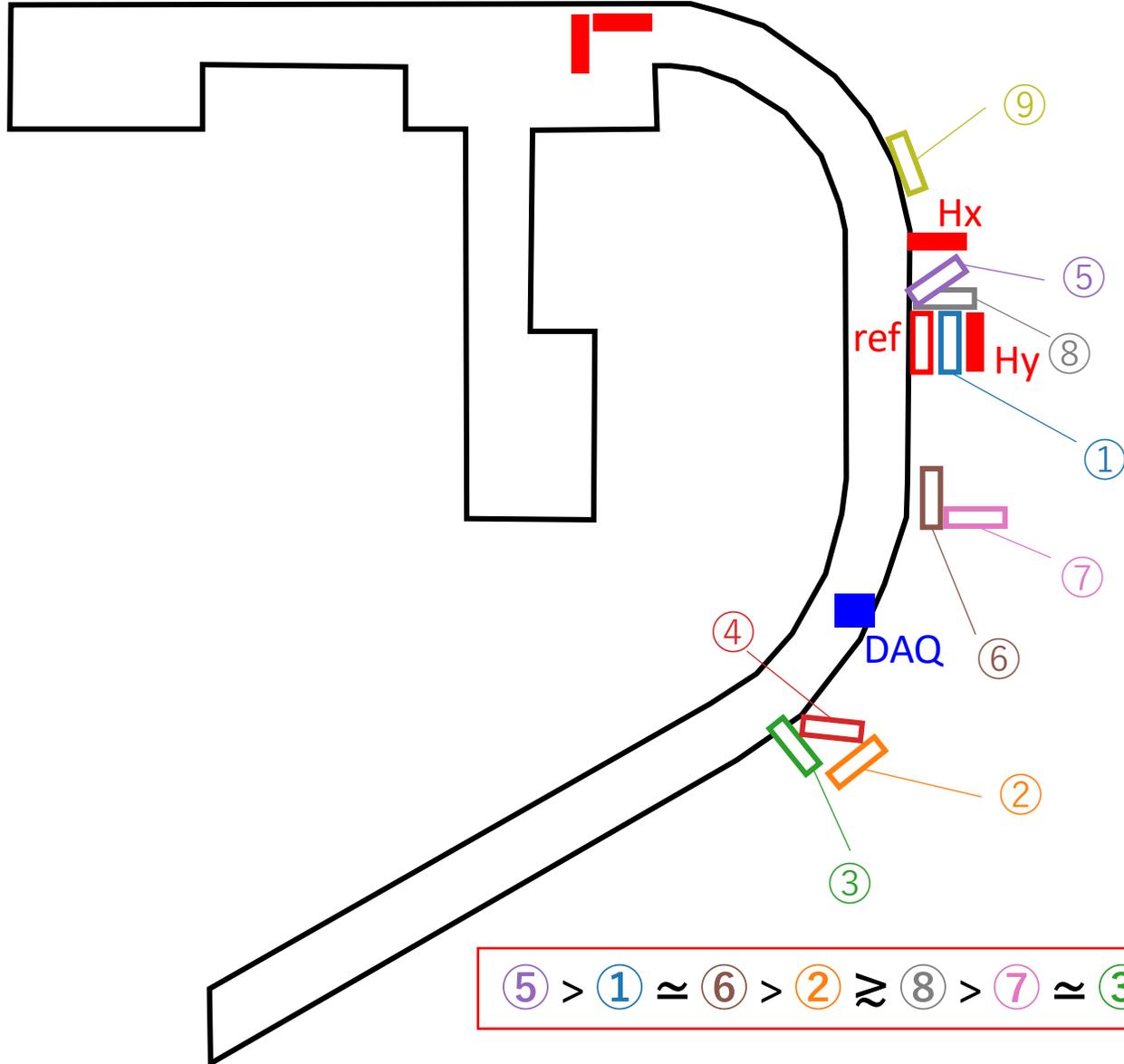
Measurements @ Slope

"Center2F"

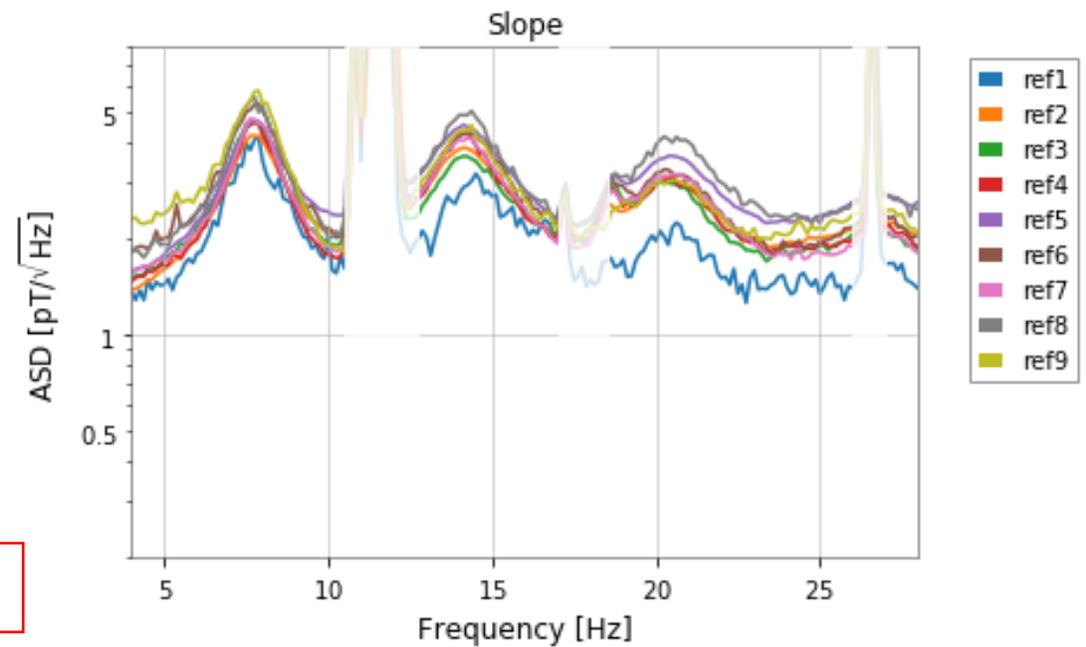
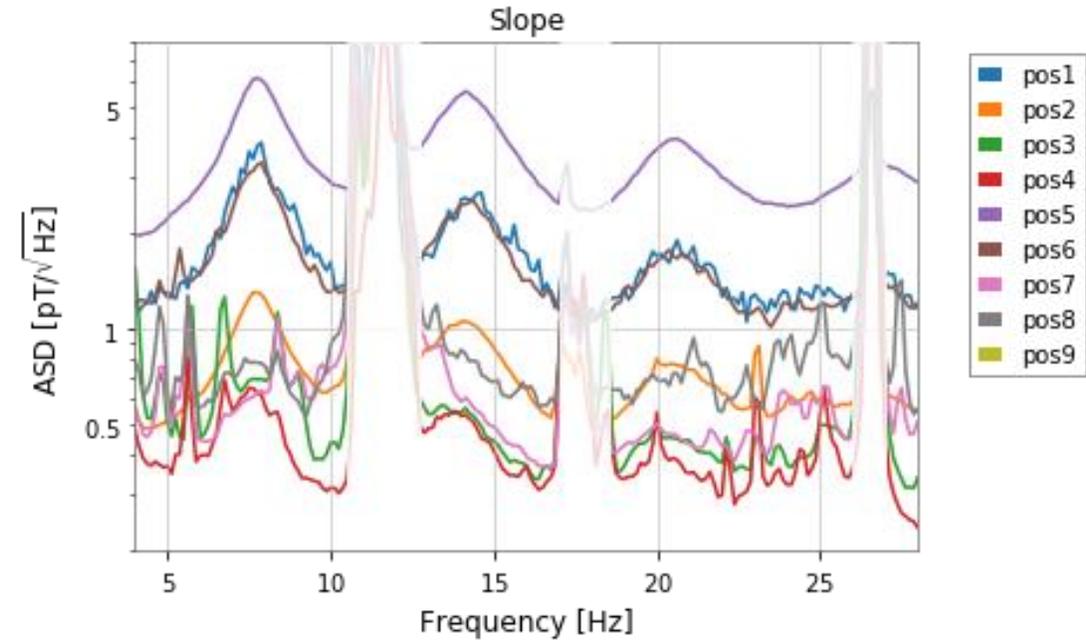


Measurements @ Slope

“Center2F”

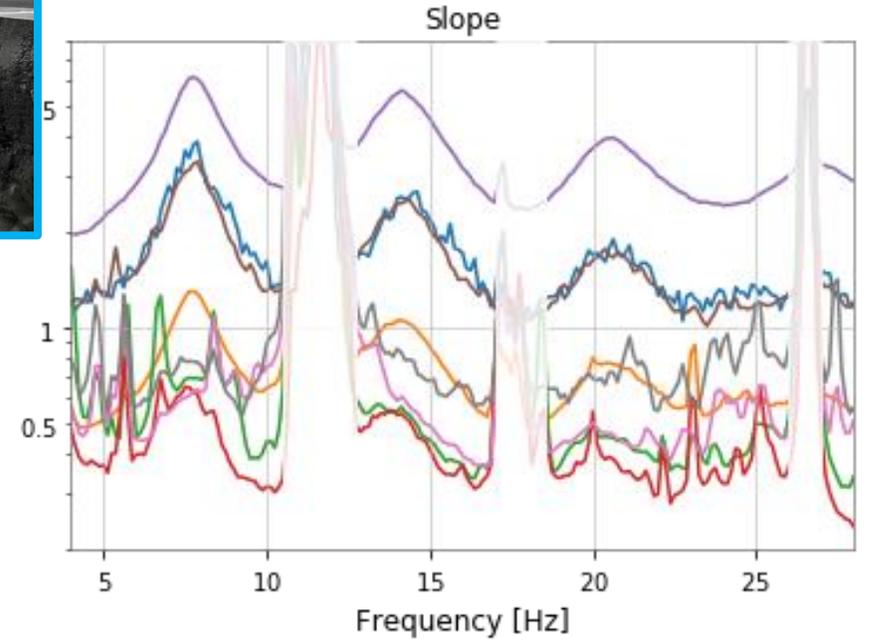
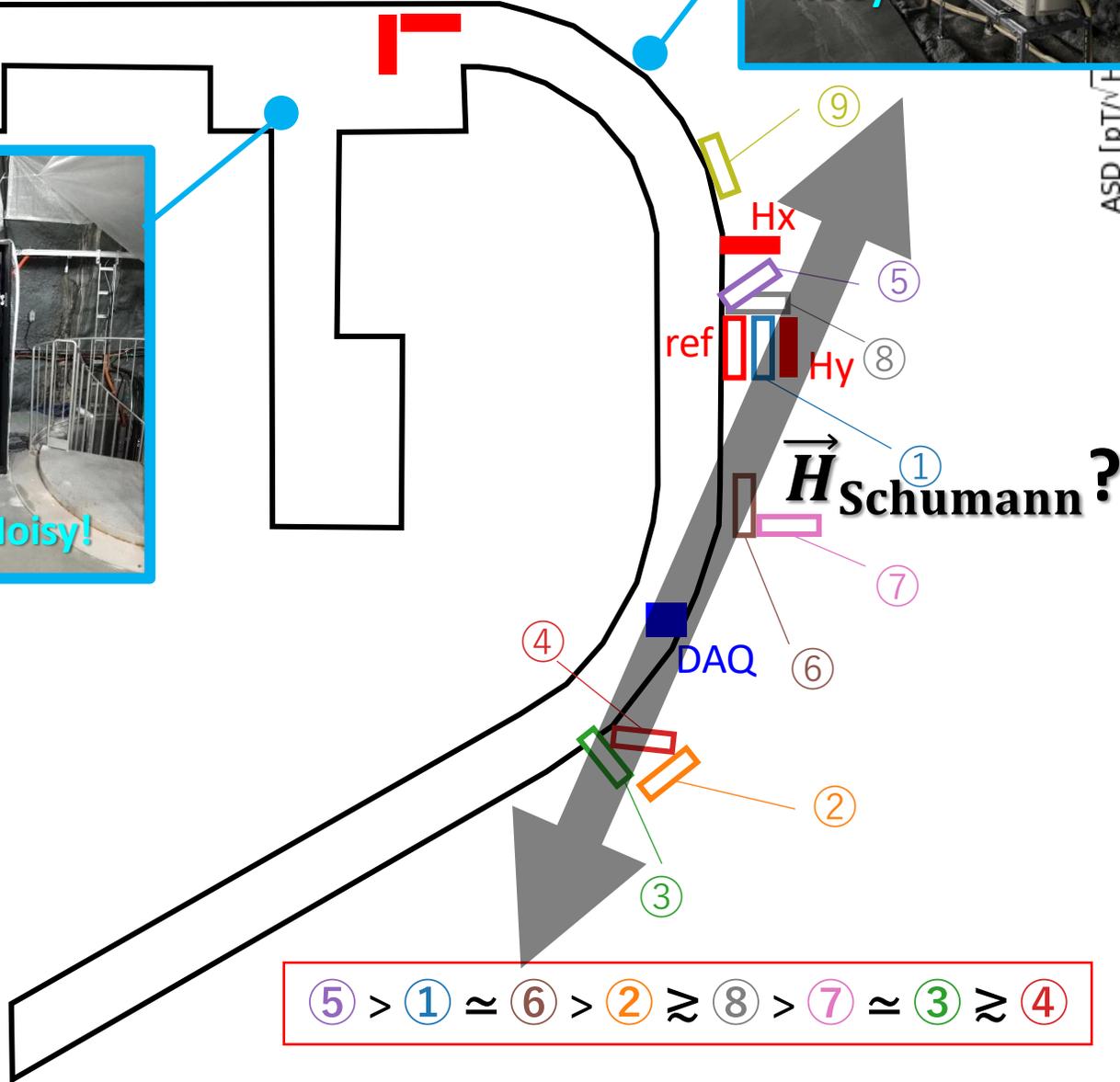


$$\textcircled{5} > \textcircled{1} \approx \textcircled{6} > \textcircled{2} \approx \textcircled{8} > \textcircled{7} \approx \textcircled{3} \approx \textcircled{4}$$



Measurements @ Slo

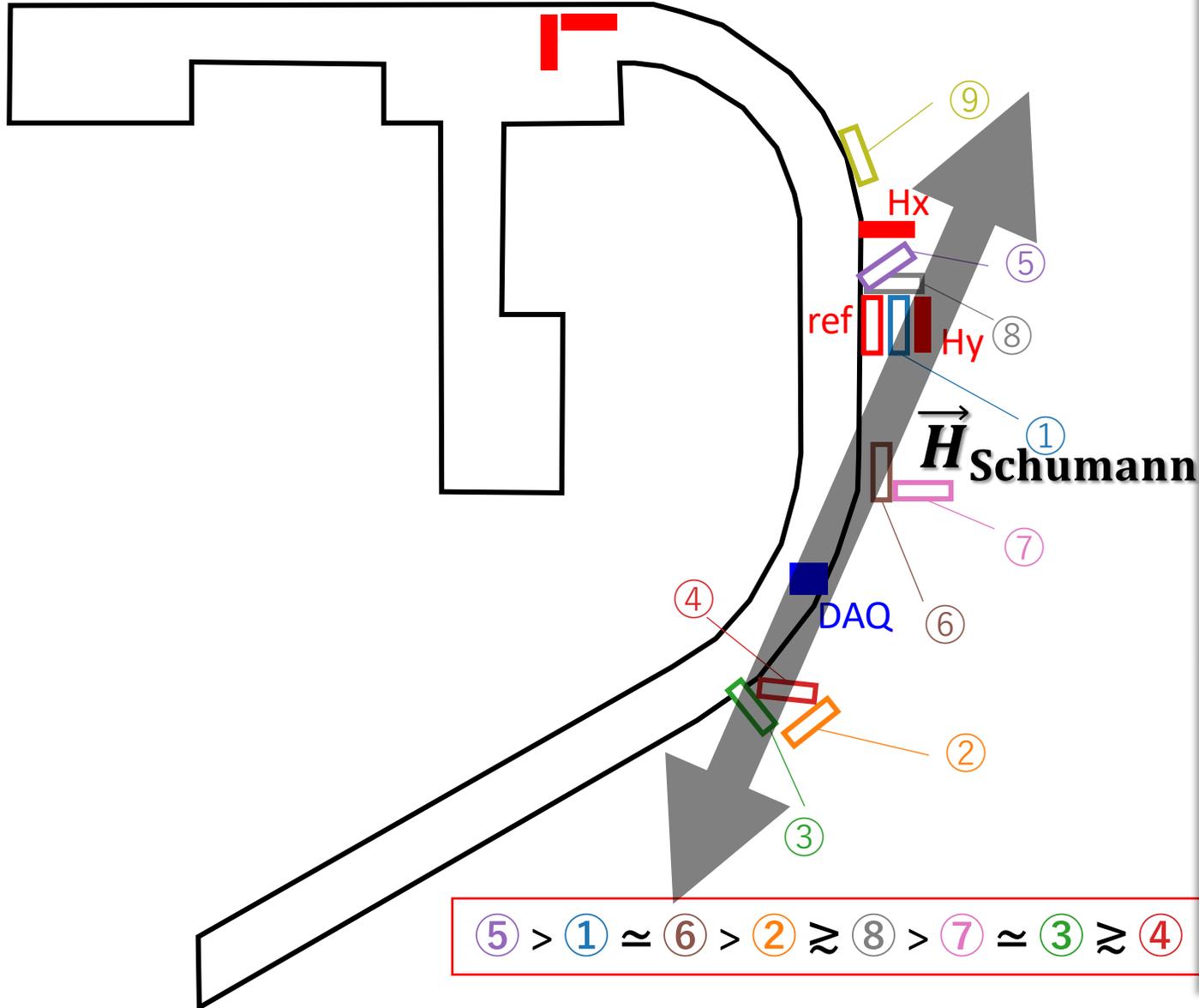
"Center2F"



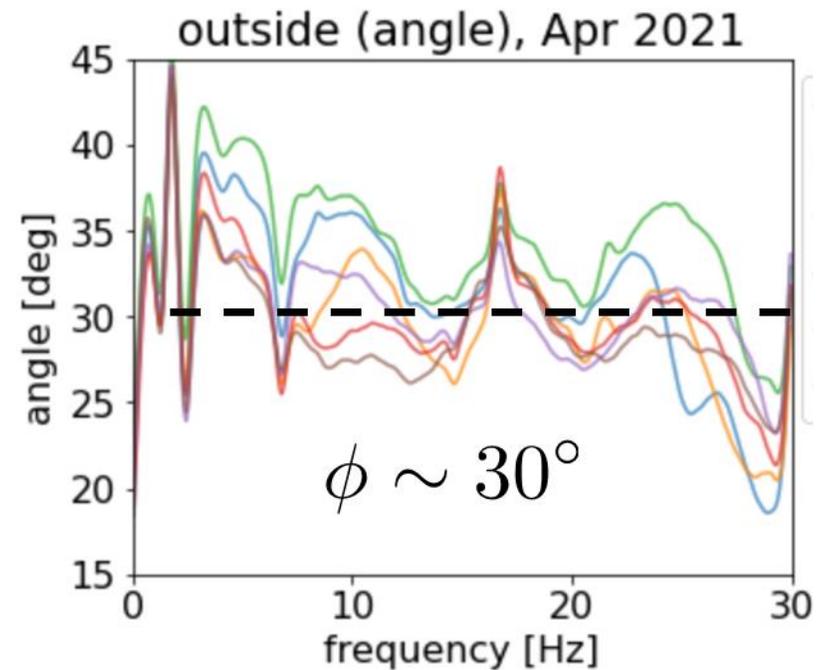
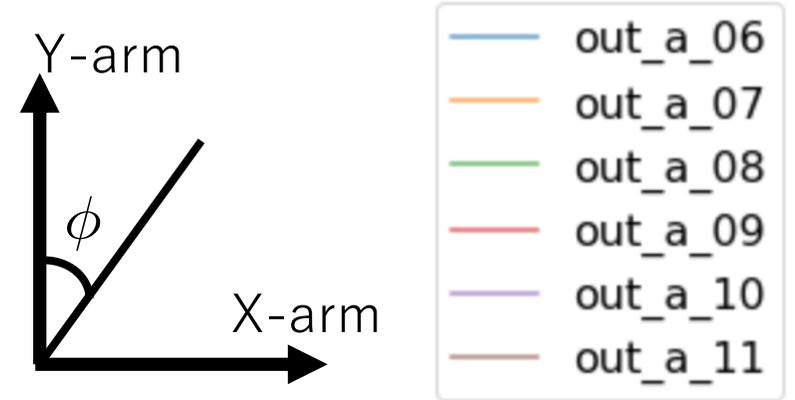
- pos1
- pos2
- pos3
- pos4
- pos5
- pos6
- pos7
- pos8
- pos9

Measurements @ Slope

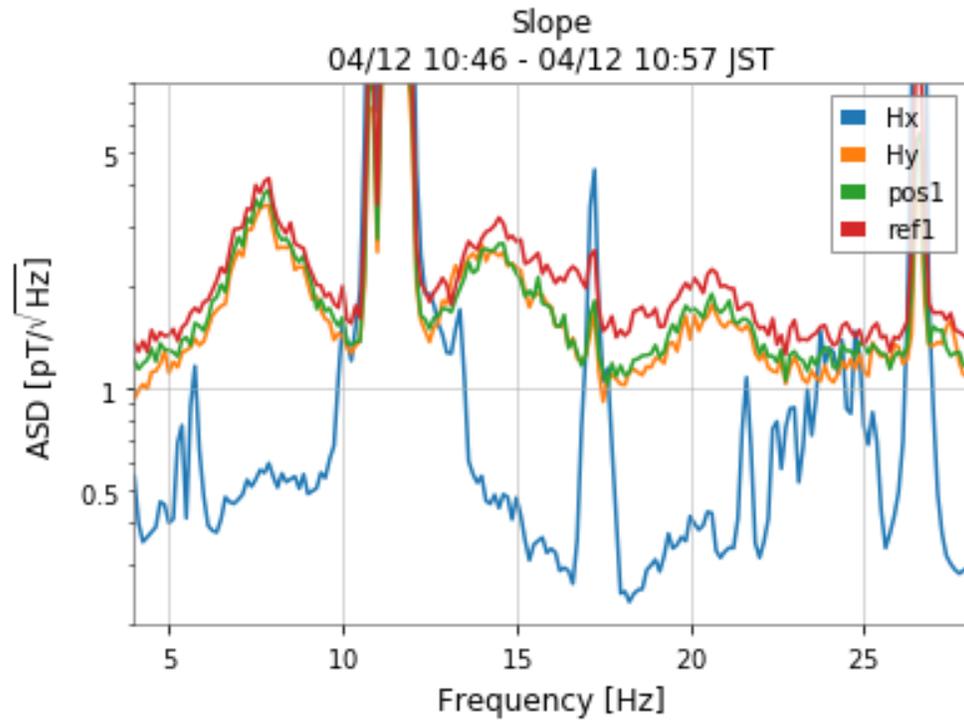
“Center2F”



Compared with “Outside2” data, the direction is about consistent.



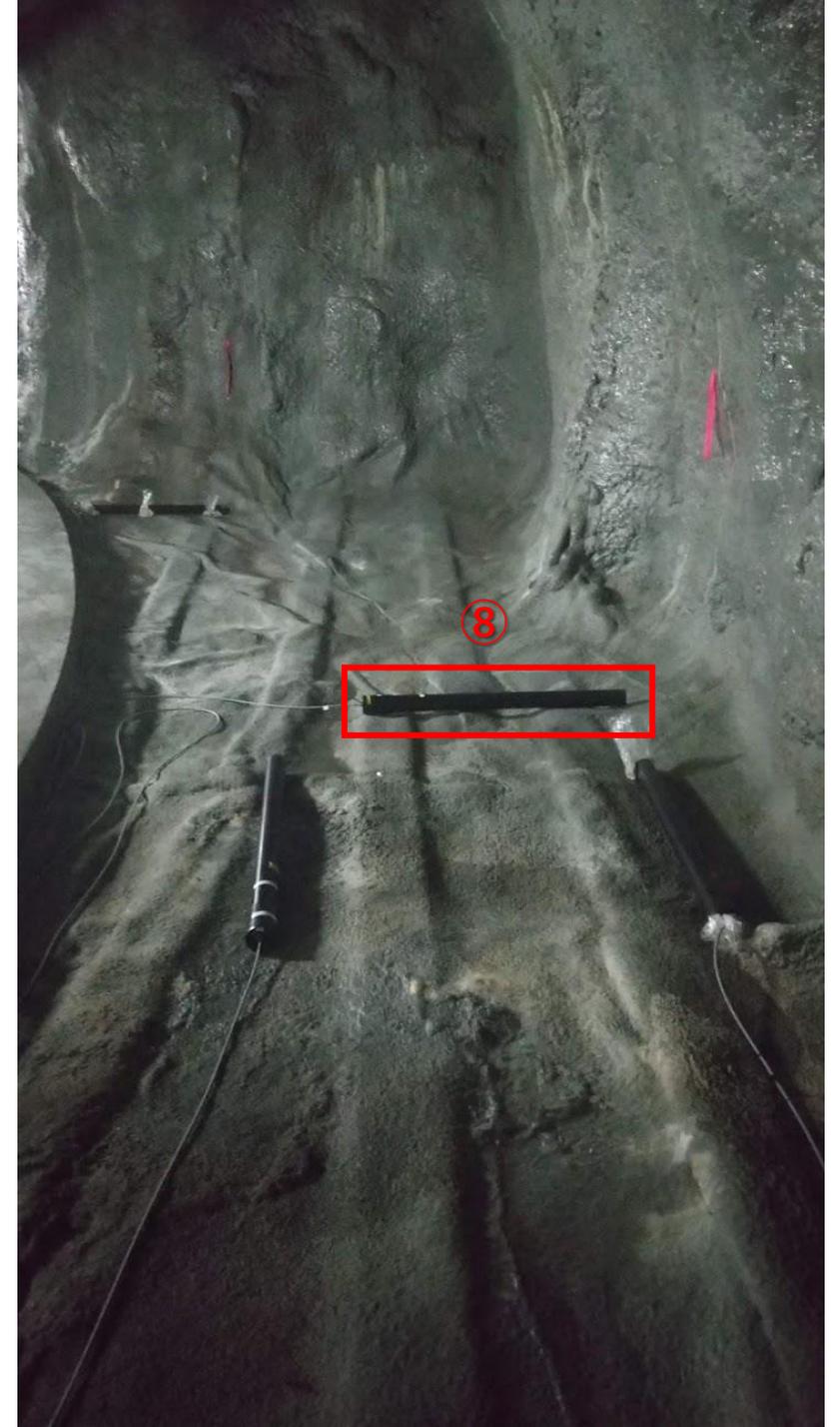
Measurements @ Slope



Measurements @ Slope



Measurements @ Slope



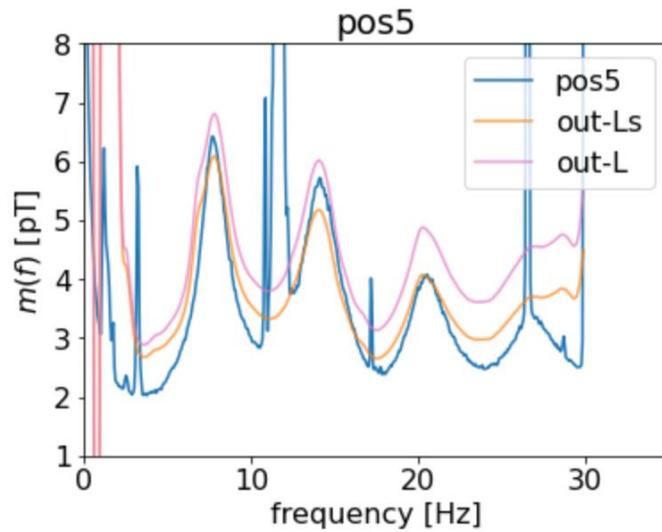
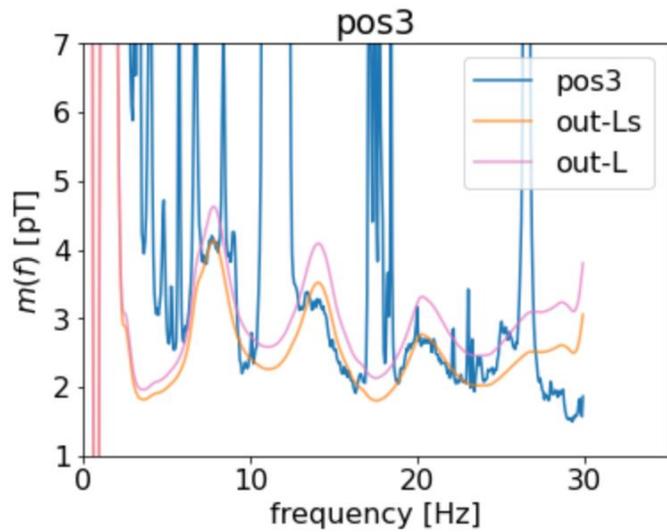
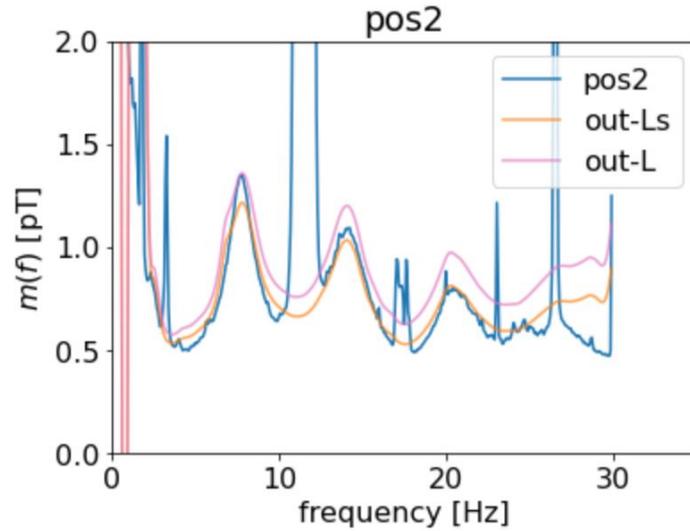
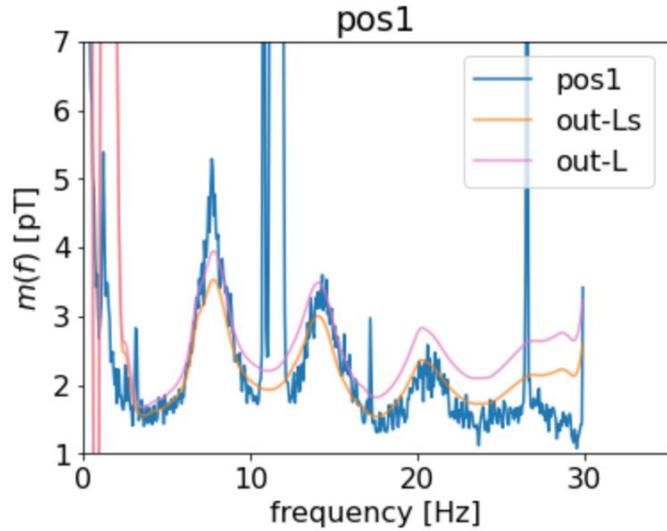
Measurements @ Slope



Measurements @ Slope



Fitting for the Slope data



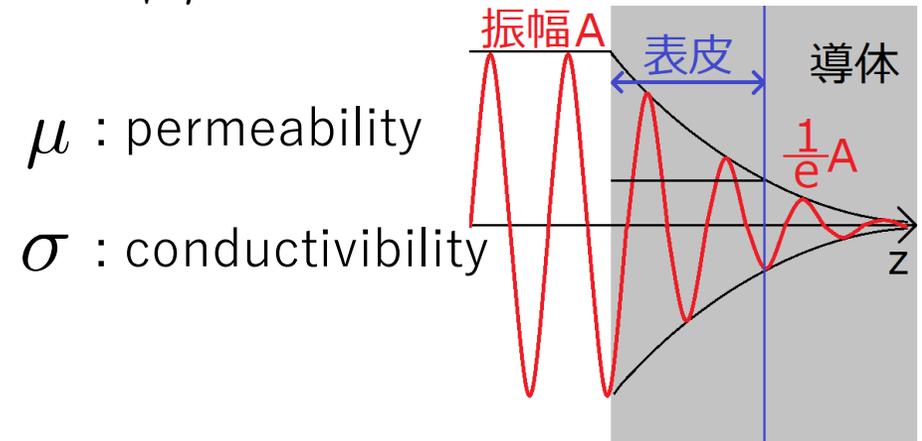
Blue : Data

Pink : Scaled "Outside2" Fitting result

Orange : Pink \times Skin effect

$$H(z, t) = H_0 e^{-z/\delta} \cos(z/\delta - \omega t)$$

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} \quad : \text{skin depth}$$



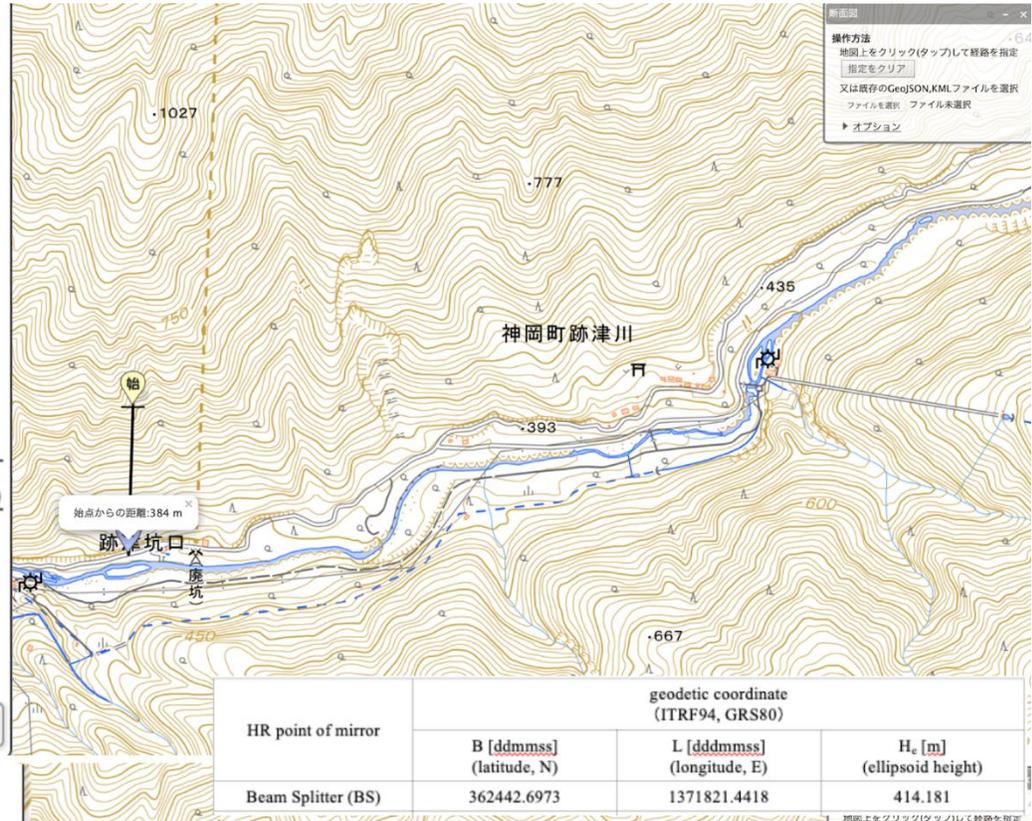
μ : permeability

σ : conductivity

From the data at position 2,

$$\sqrt{\pi\mu\sigma}z = 0.045 \text{ Hz}^{-1/2}$$

Electrical resistivity of the ground



From $\sqrt{\pi\mu\sigma}z = 0.045 \text{ Hz}^{-1/2}$

assuming $z = 160, 200, 275 \text{ m}$,

electrical resistivity is

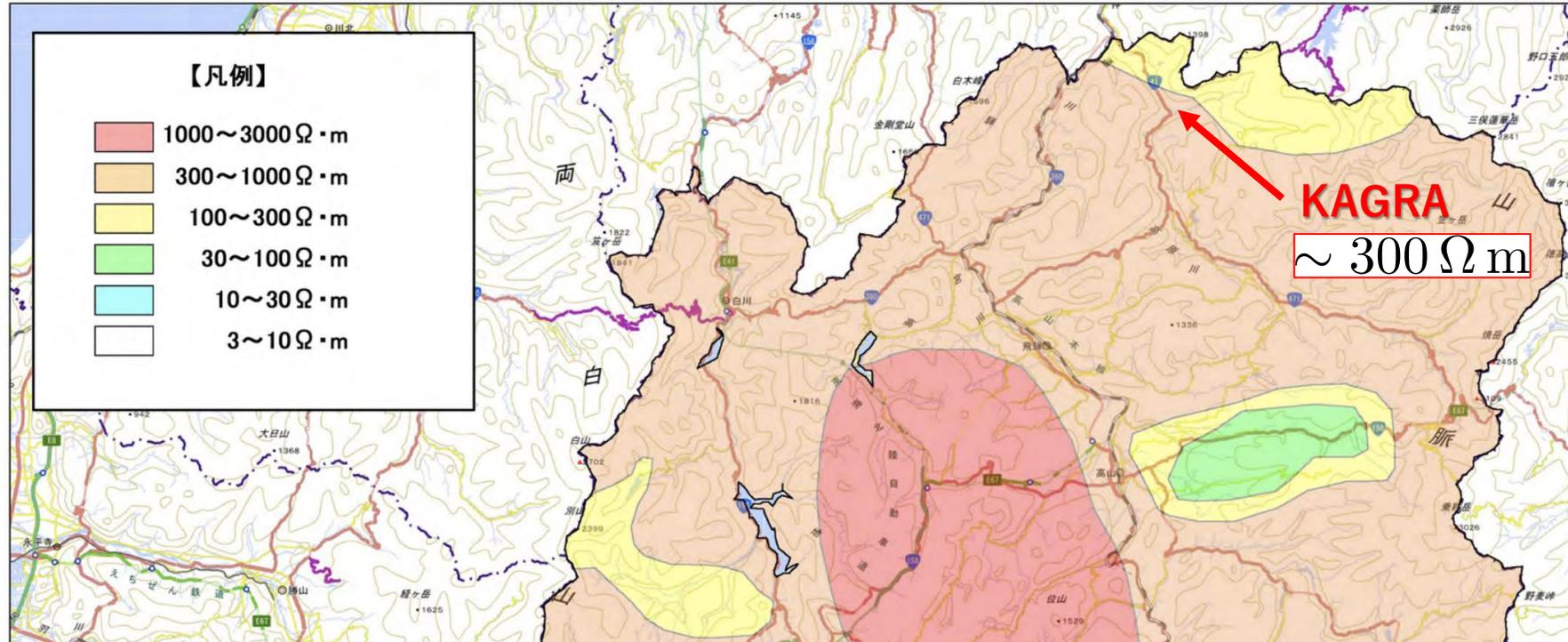
$$\mu = 4\pi \times 10^{-7} \text{ N A}^{-2}$$

$$\rho = 1/\sigma = 50, 78, 150 \Omega \text{ m} \quad \text{for Ikenoyama mountain}$$

Electrical resistivity of the ground

地理院地図
GSI Maps

Hokuden website: <https://hokuden-earth.co.jp/resistivity/>

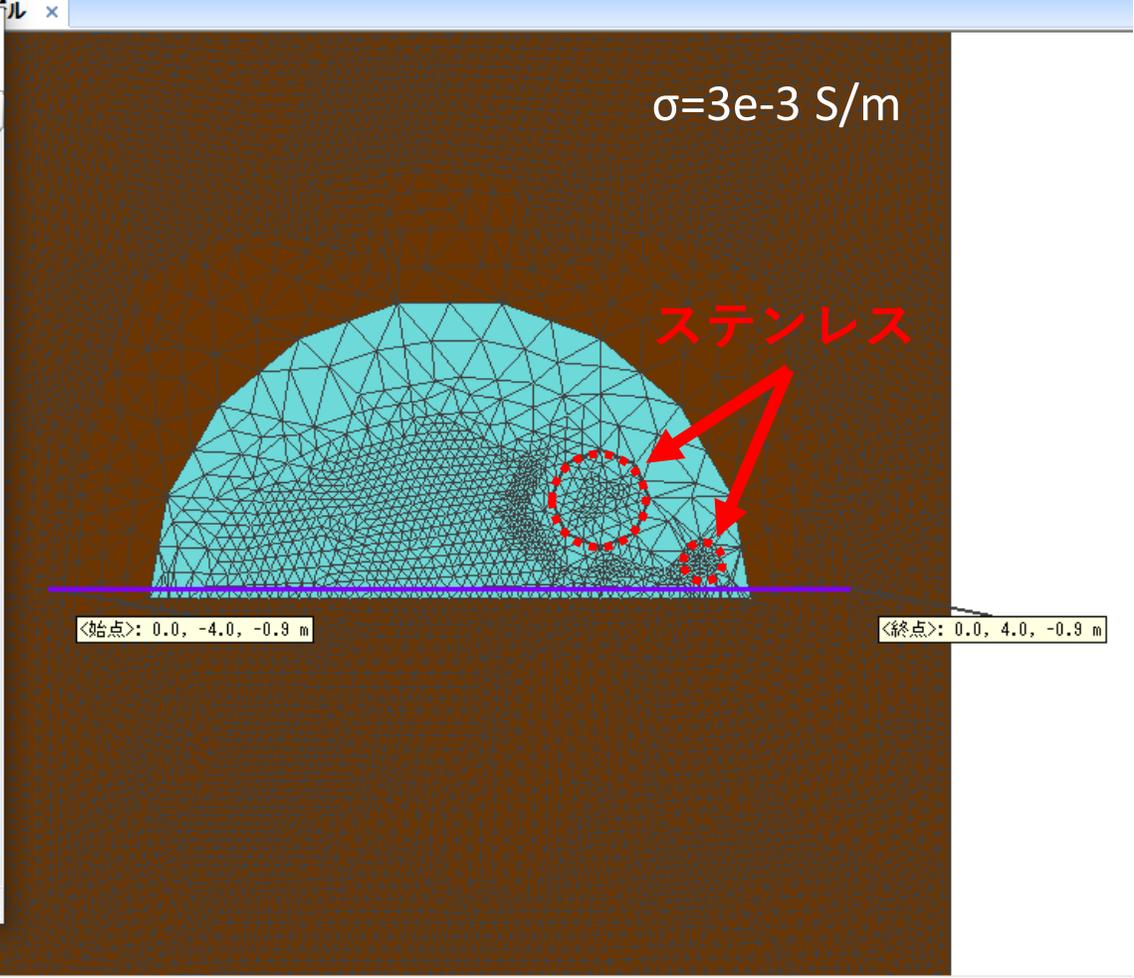
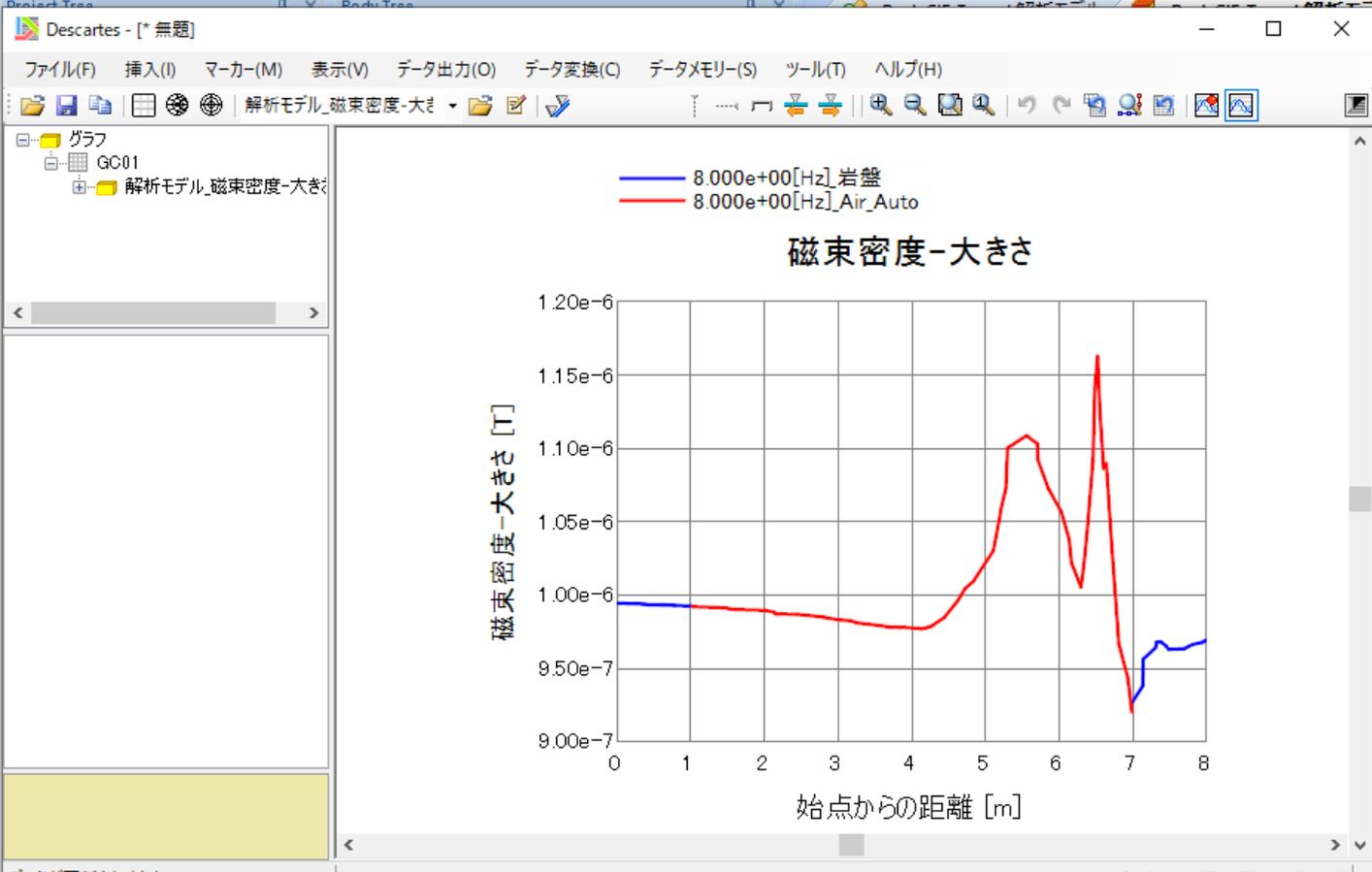


Why our measurements show the smaller value?

- Our measurement is not on the surface of the mountain, but inside the mountain, where water content would be larger.
- Ikenoyama mountain may be a special place, guessed from its name.
- To derive the value of the resistivity, we use the measurement data at only one place (~ a day). Better to use data at several different places.

解析結果 表示 モデル ツール ウィンドウ

磁場解析 0: 8.000e+00[Hz] 変位 面選択
 磁束密度[T] ベクトルXYZ 要素ベクトル 磁束線 最大最小
 0° Linear 表面ベクトル メッシュ 断面 描画設定
 表示内容 視点変更 視点操作 表示 結果表示 結果抽出 解析



複数座標 始点・終点入替

分割設定

自動(要素境界点)

分割数 10

間隔 1.7320508075

モード範囲

開始 0: 8.000e+00[Hz]

終了 0: 8.000e+00[Hz]

04:06:34 ソルブ:02:26:00)