Investigations for the Schumann Resonances Amplification in KAGRA

2023-05-10 XIII ET Symposium

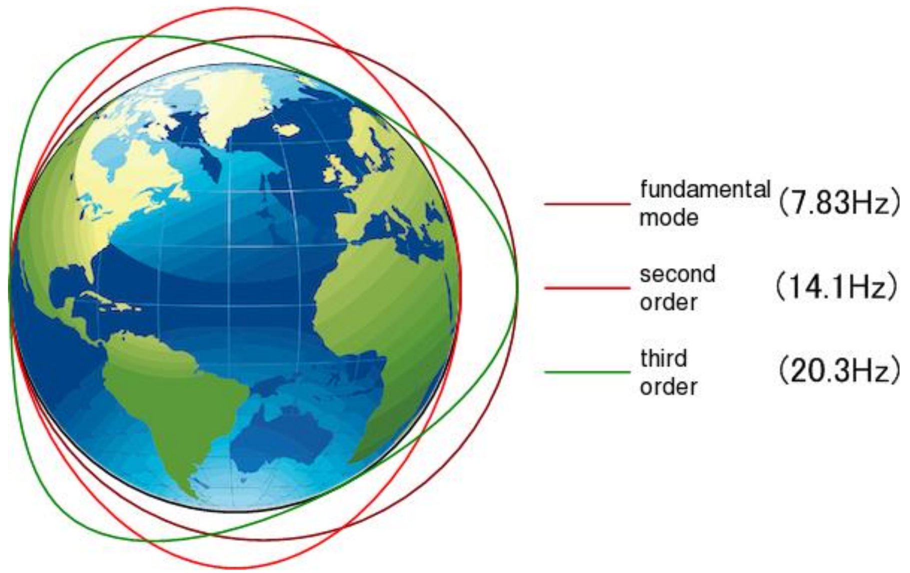
Tatsuki Washimi (NAOJ)

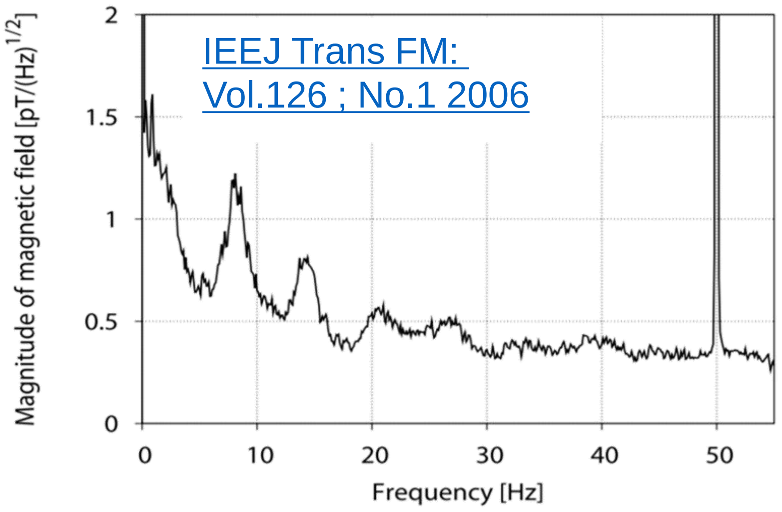
Isamu Fukunaga (OMU)

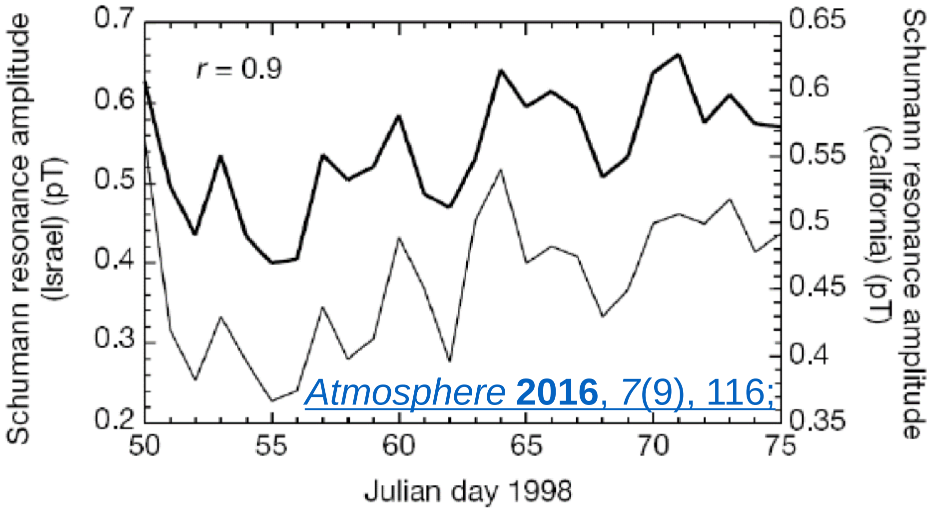
Schumann resonance

Resonance of the Earth electromagnetic field (ELF)

- Excited by lightnings, solar wind, *etc*.
- $f_n = \frac{c}{2\pi R_\oplus}\sqrt{n(n+1)} = 7.8\ \mathrm{Hz},\ 14.1\ \mathrm{Hz},\ 20.3\ \mathrm{Hz}, \ldots$
- Amplitude $\sim 1\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$
- Coherent in the Earth -> It can fake a Stochastic GW signal
  - *e.g.*, Meyers *et al.* PRD 102, 102005 (2020)





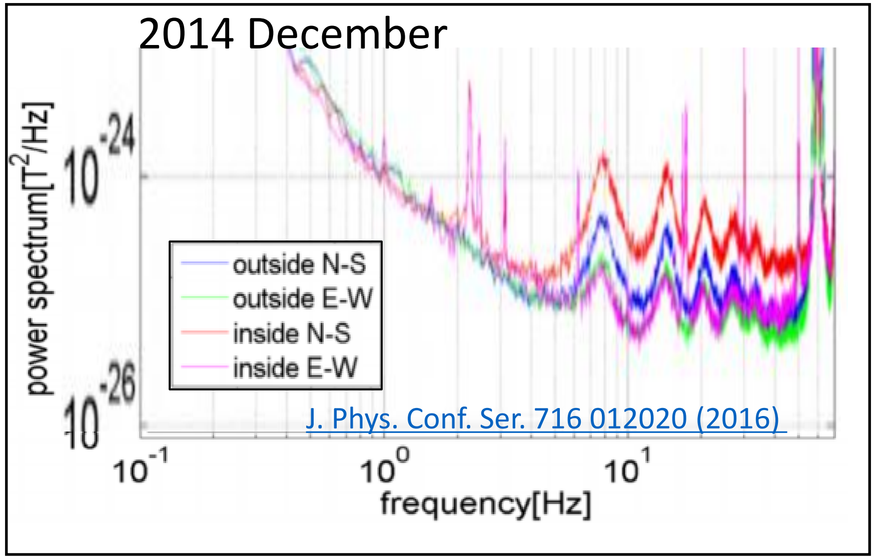


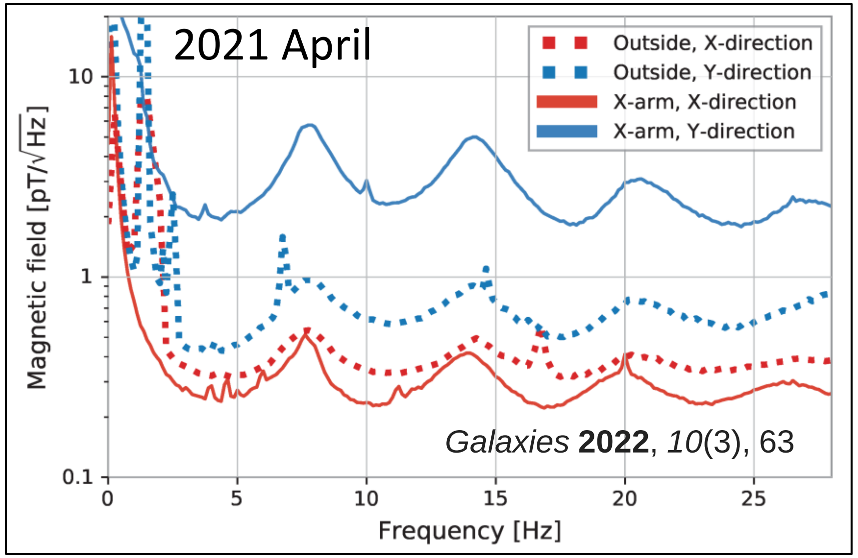
Amplification of the Schumann Resonance

In the underground of the KAGRA site, the Schumann resonance is observed to be larger than the outside.

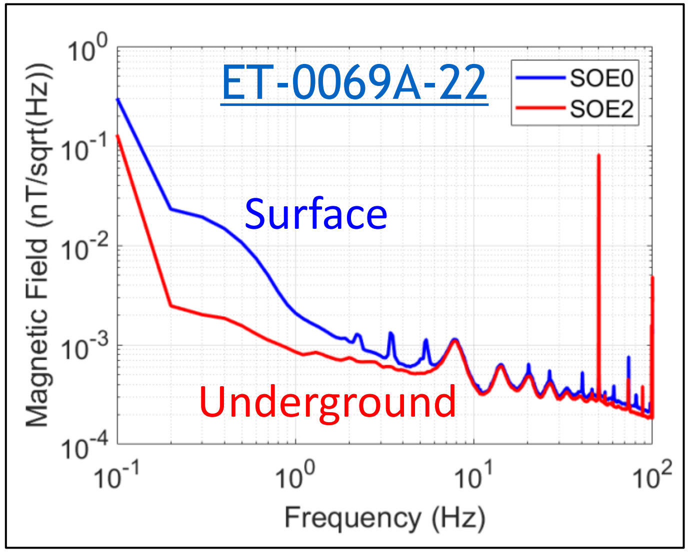
- for the N-S direction (2014) / Y-direction in the X-arm tunnel (2021)
- Not due to the miss-calibration of the sensors
- Such amplification is not observed in Sos Enattos (Sardegna)

KAGRA





Sos Enattos



Theoretical model

One hypothesis is the effect of the vacuum tube (metal).

- T. Ogawa (ERI, UTokyo), proceedings of the Conductivity Anomaly (2018), written in Japanese
  http://www.eqh.dpri.kyoto-u.ac.jp/CA/2018/Ogawa_CA2018.pdf
- Solve the Maxwell eq. with the boundary condition of $E_y = 0$ on the vacuum tube surface.
- Only for the outside of the tube. (Impossible to extrapolate to the inside)

$b_\rho = B_\rho / B_{x0},\ R = \rho/a、\ p = \lambda a$

$$b_\rho(R,\theta) = -\frac{ie^{-\pi i/4}}{pR}\sum_{k=1}^{\infty} k\alpha_k(pR)\sin k\theta,$$

$$b_\theta(R,\theta) = -\frac{i}{2}\sum_{k=0}^{\infty}\left(a_{k+1}(pR) - \frac{a_k(p)}{A_k(p)}A_{k+1}(pR)\right)\cos k\theta + \frac{i}{2}\sum_{k=1}^{\infty}\left(a_{k-1}(pR) - \frac{a_k(p)}{A_k(p)}A_{k-1}(pR)\right)\cos k\theta,$$

$$a_k(pR) = 2(-i)^k(\mathrm{ber}_k(pR) - i\,\mathrm{bei}_k(pR)),$$

$$A_k(pR) = 2(-i)^k(\mathrm{ker}_k(pR) - i\,\mathrm{kei}_k(pR)),$$

$$\alpha_k(pR) = a_k(pR) - \frac{a_k(p)}{A_k(p)}A_k(pR)$$

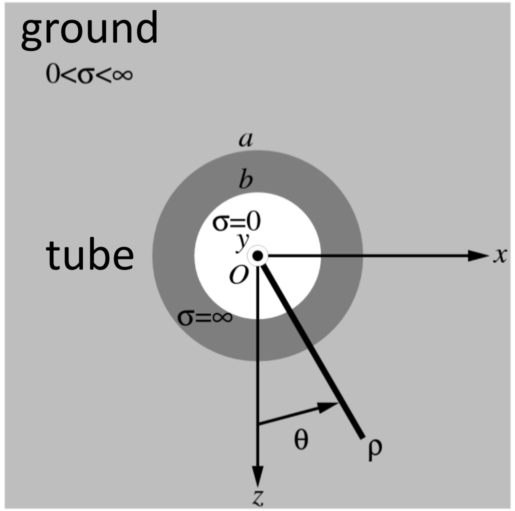


Figure1 Schematic view of the 2-D section of the space considerd in the present study, and the definition of the Cartesian coordinate system (x, y, z).

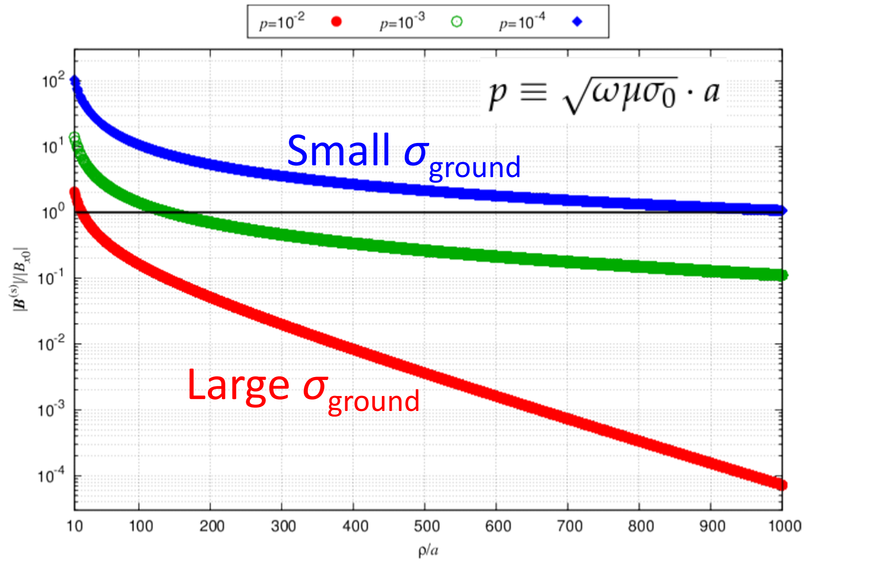
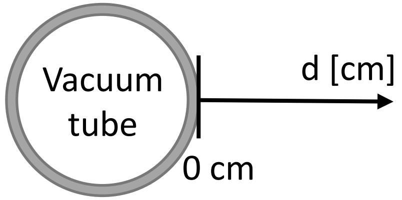


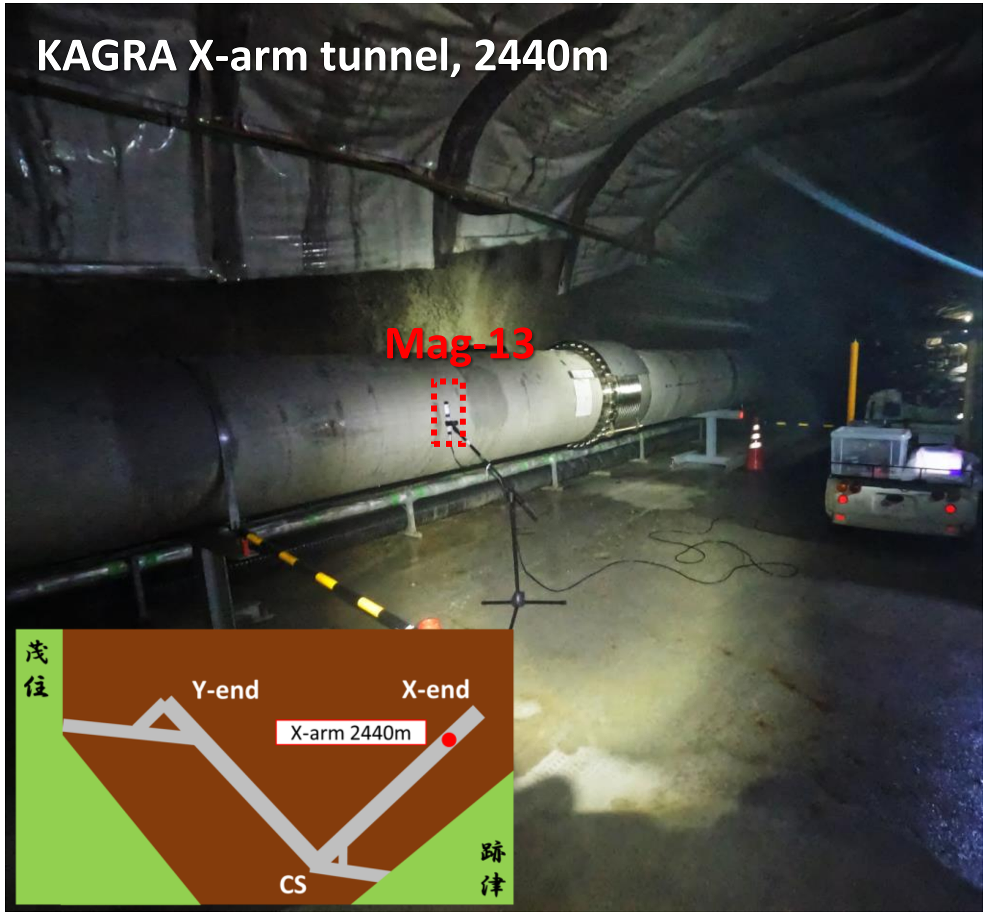
Figure2 Absolute value of the secondary magnetic flux density relative to the absolute value of the primary magnetic flux density at $z/a = 0$ as functions of ρ/a. $p = 10^{-2}$ (red solid circles), 10^{-3} (green open circles), and 10^{-4} (blue diamonds).

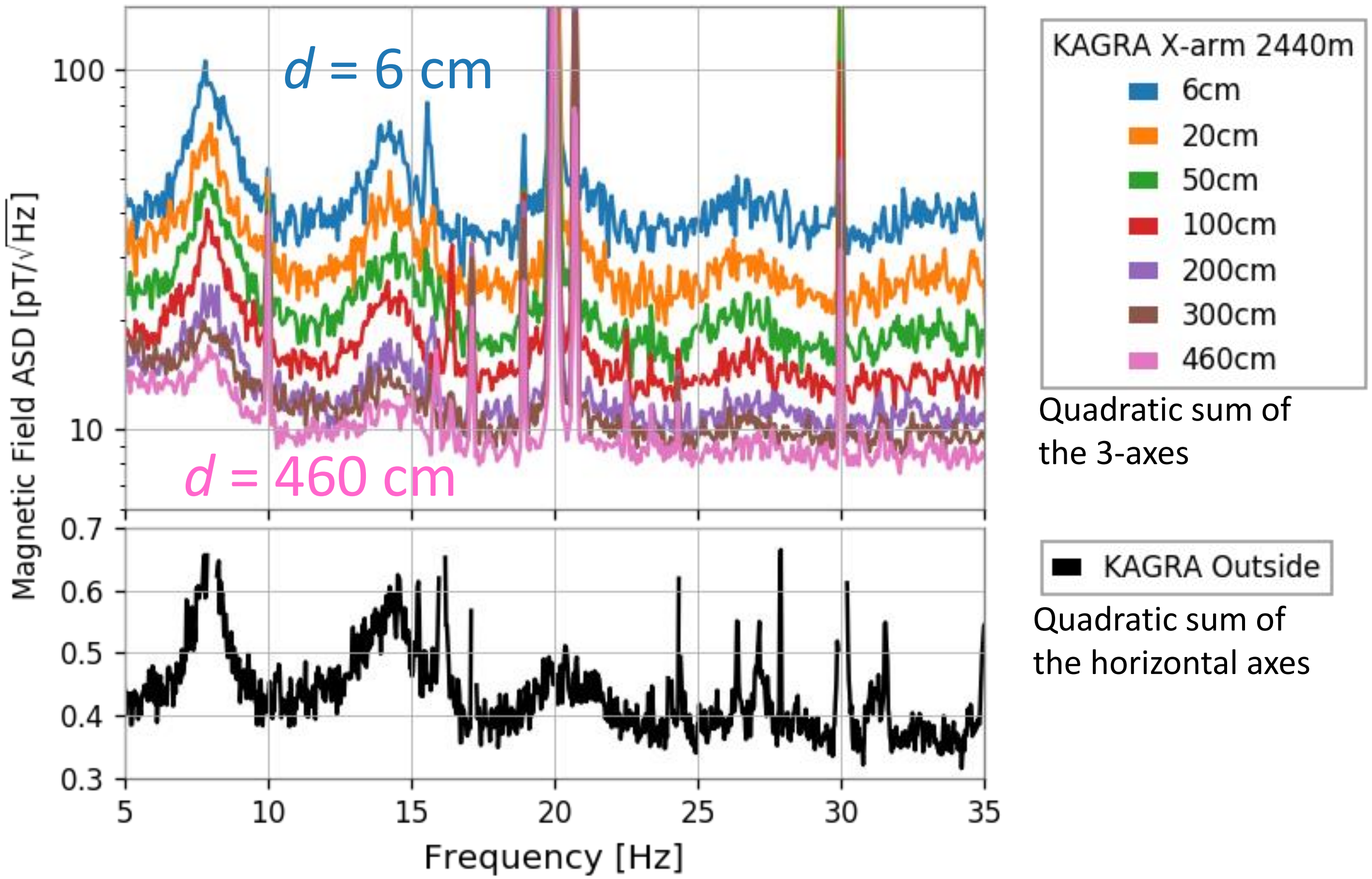
Measurements: Distance from the tube

We measured the magnetic field near the vacuum tube.

- Amplified Schuman resonance was observed.
- Amplification gain was larger near the vacuum tube. (Max ~ 140 times!)



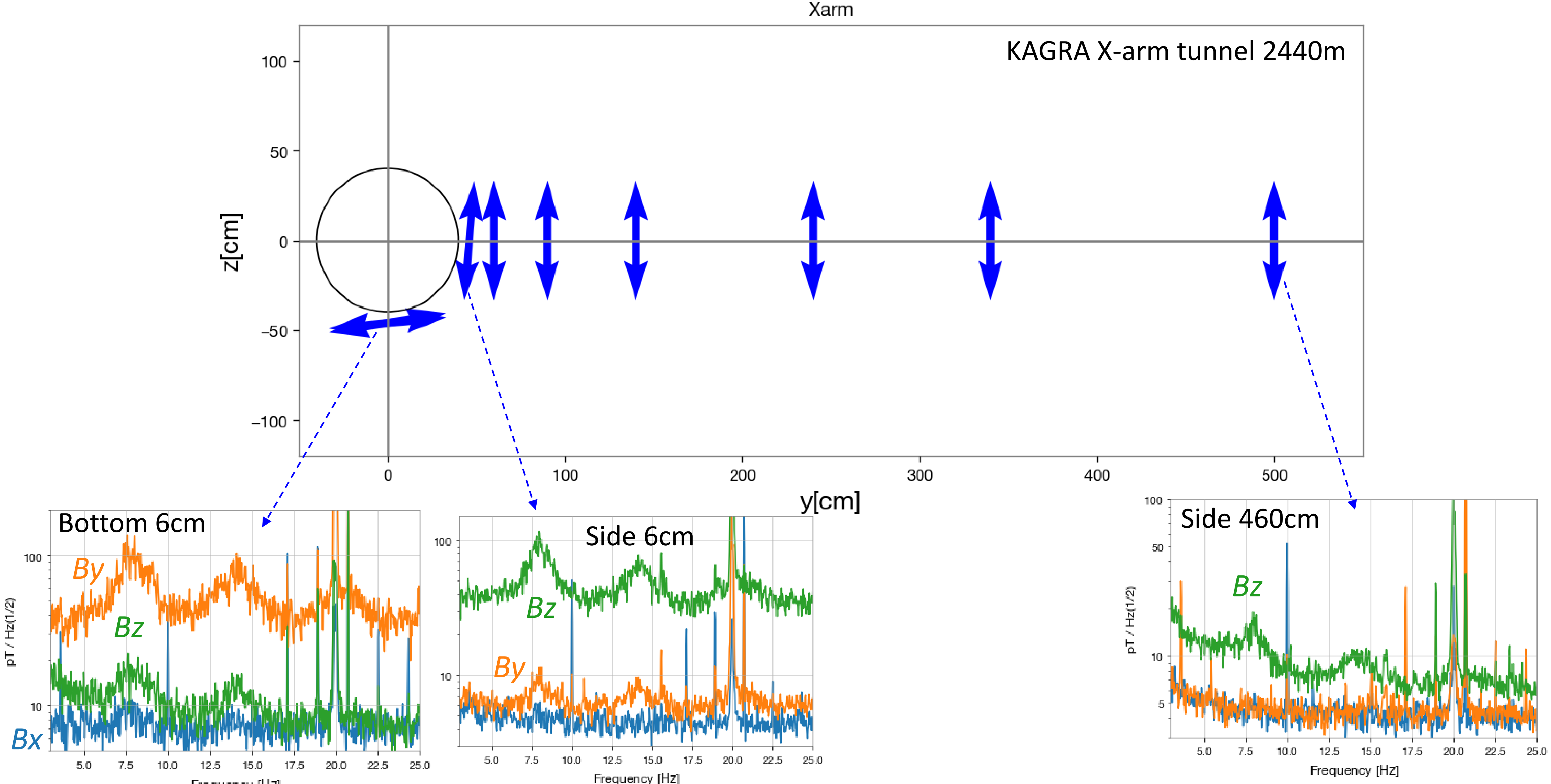




Quadratic sum of the 3-axes

Quadratic sum of the horizontal axes

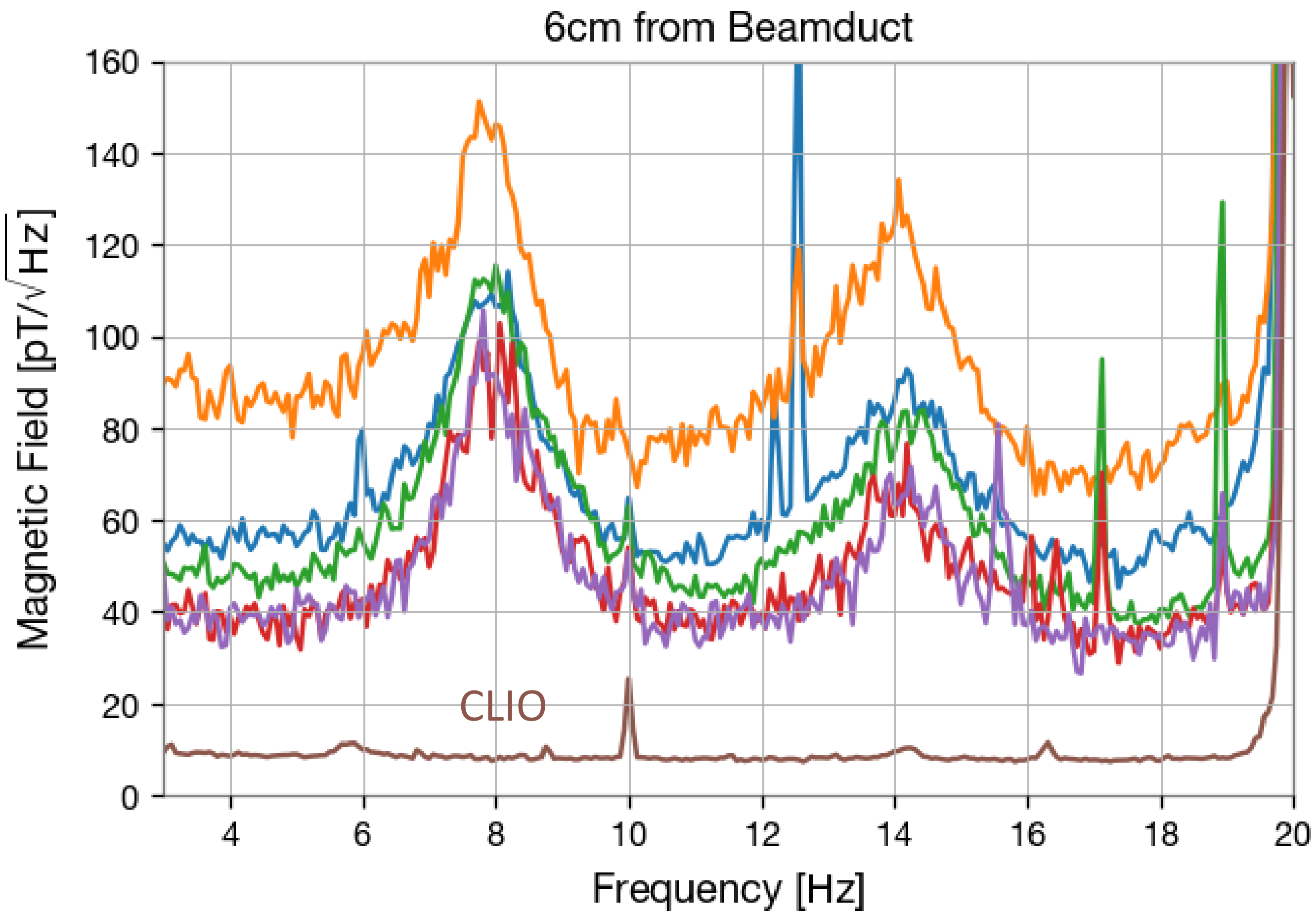
Measurements: Direction of the vector

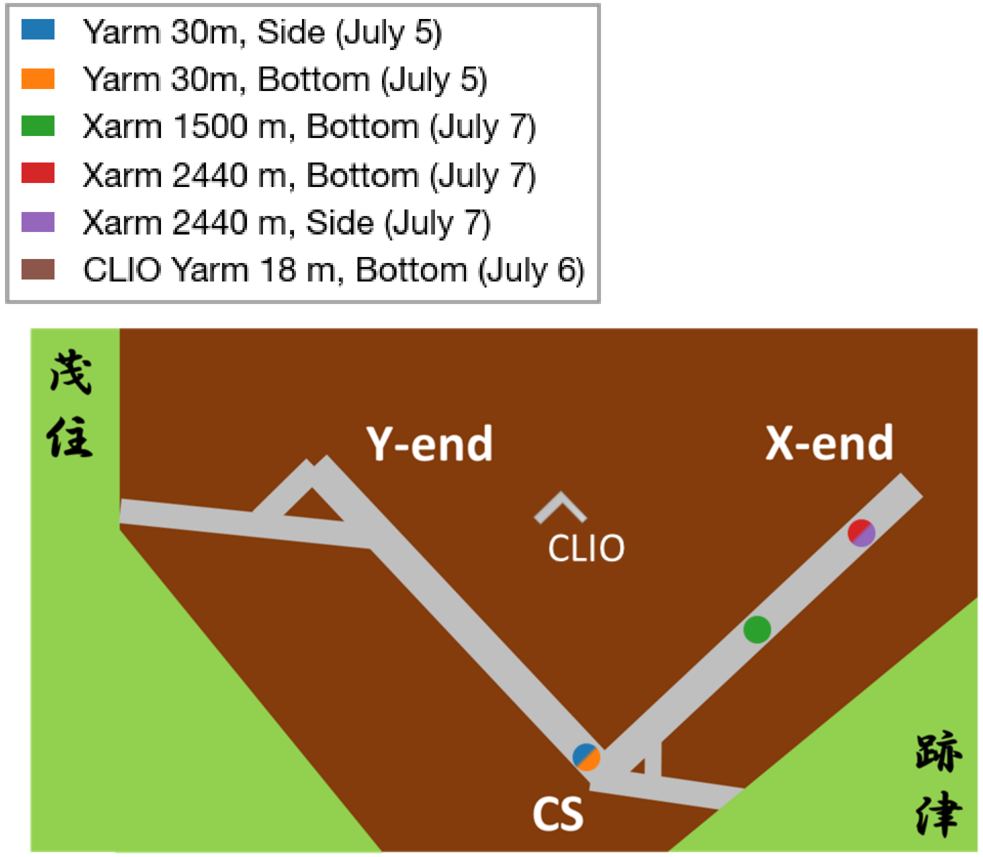


Measurements: Many Locations

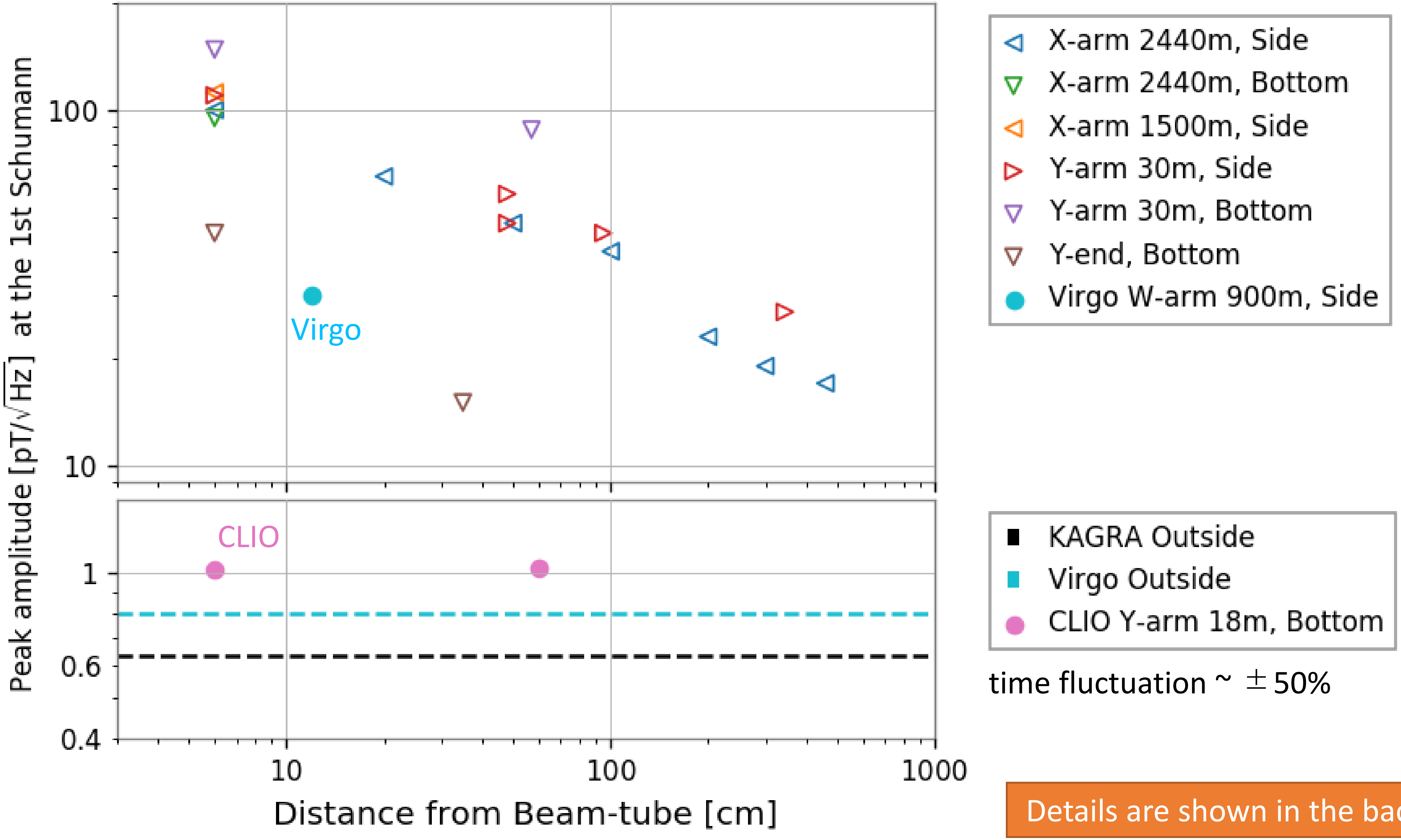
We performed the same measurements at many locations.

- Amplification gain was not so much changed depending on the location.
    - Smaller at the end station. (See backup pages)
- At the CLIO site, amplification of the Schuman resonance was not observed. (See backup pages)





Summary of the 1st mode peak

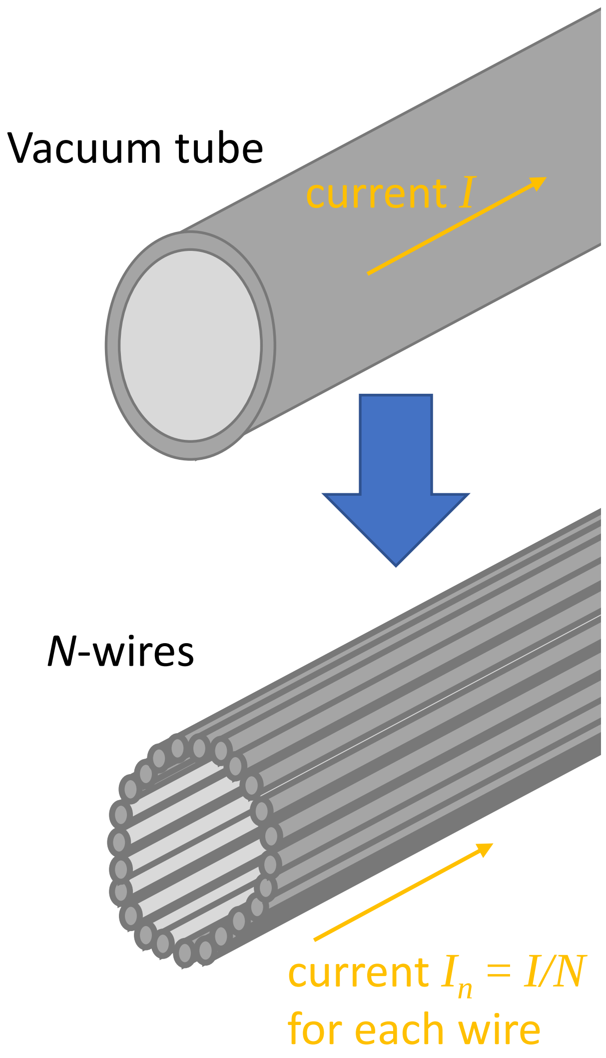


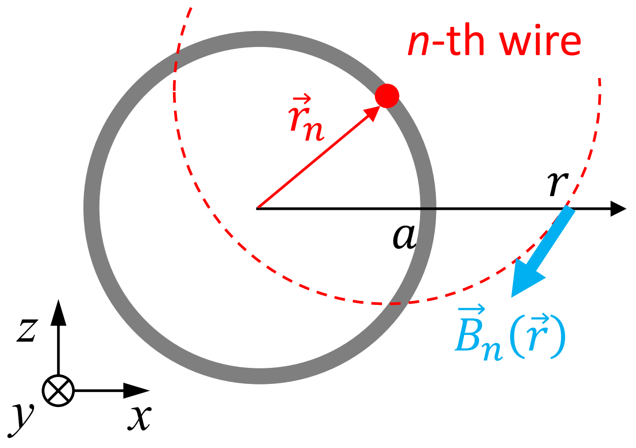
time fluctuation ~ ±50%

Details are shown in the backup pages

Magnetic field induced by the vacuum tube

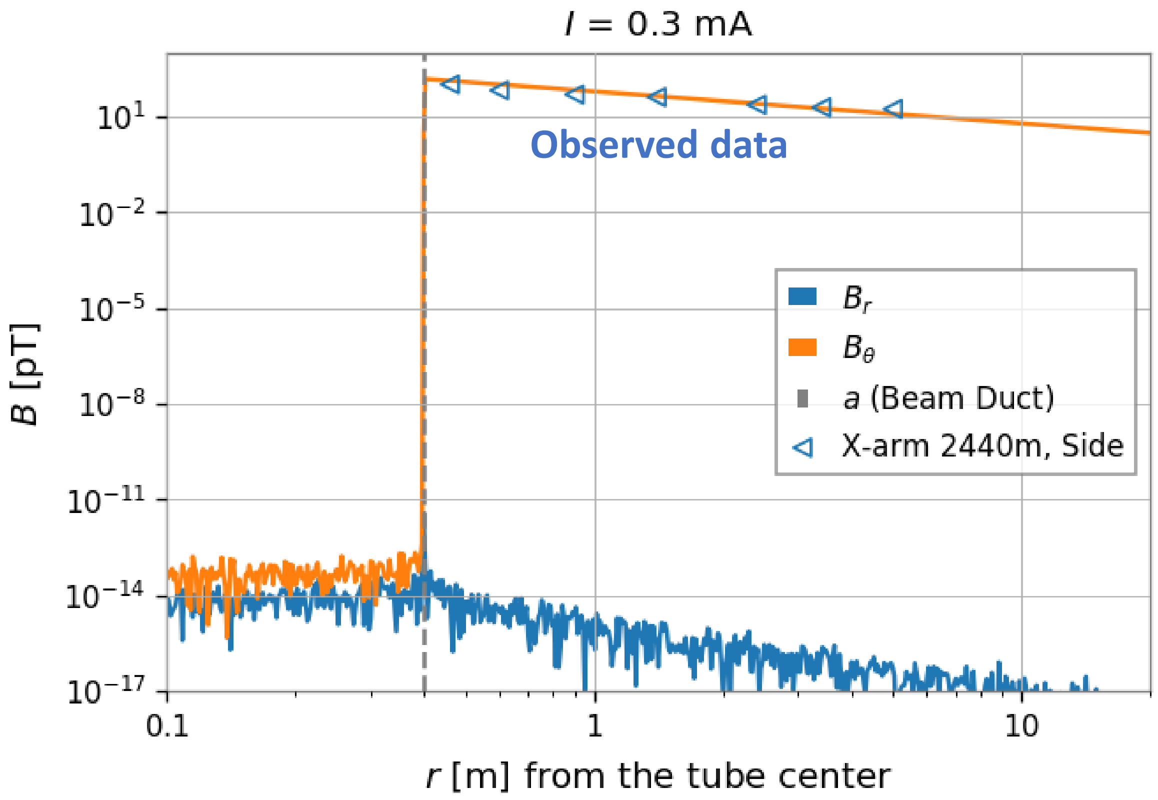
Split the vacuum tube into many wires and integrate the induced magnetic field vectors.





$$\vec{B}_n(\vec{r}) = \frac{\mu_0 \vec{I}_n \times (\vec{r} - \vec{r}_n)}{2\pi |\vec{r} - \vec{r}_n|^2}$$

$$\vec{B}(\vec{r}) = \sum_{n=1}^{N} \vec{B}_n(\vec{r})$$



- Outside of the tube : $B_\theta \sim r^{-1}$
- Inside of the tube : No magnetic field

consistent with the numerical error

Conclusion

- Amplification of the Schumann resonance observed in the KAGRA underground site is caused by the 3-km vacuum tube.
  - It is also observed at the Virgo site.
  - It was not confirmed at the CLIO site (Kamioka underground, 100m arms).
  - It is not a characteristic of the underground environment.

We will write a paper

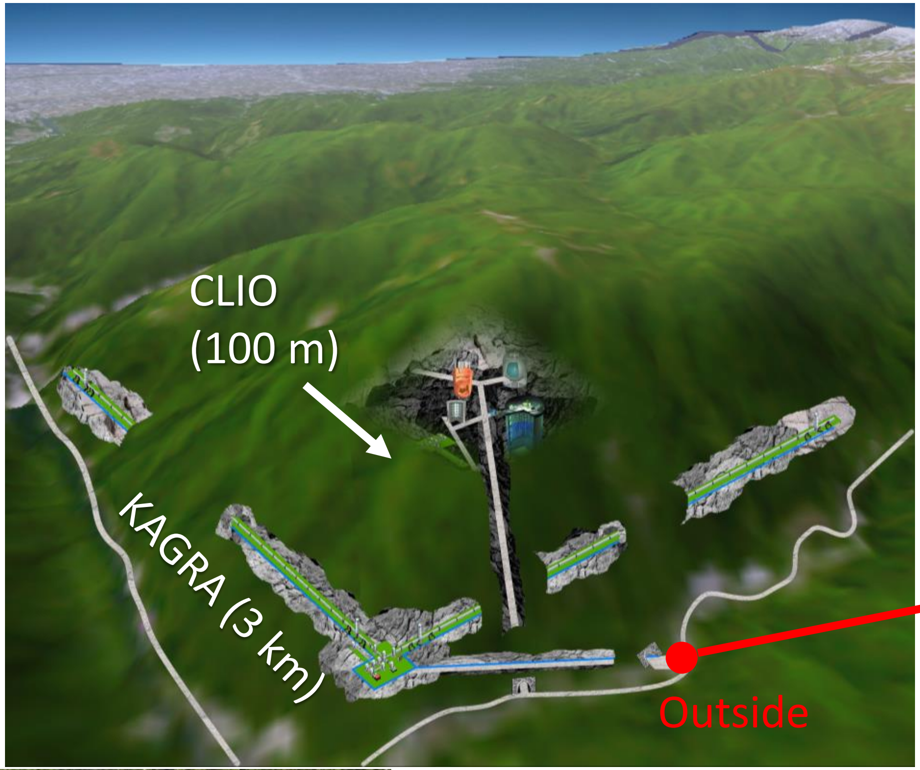
- Calculation for the magnetic field induced by the vacuum tube:
  - Almost consistent with the KAGRA data (with tuning the current).
  - No magnetic field inside of the tube.

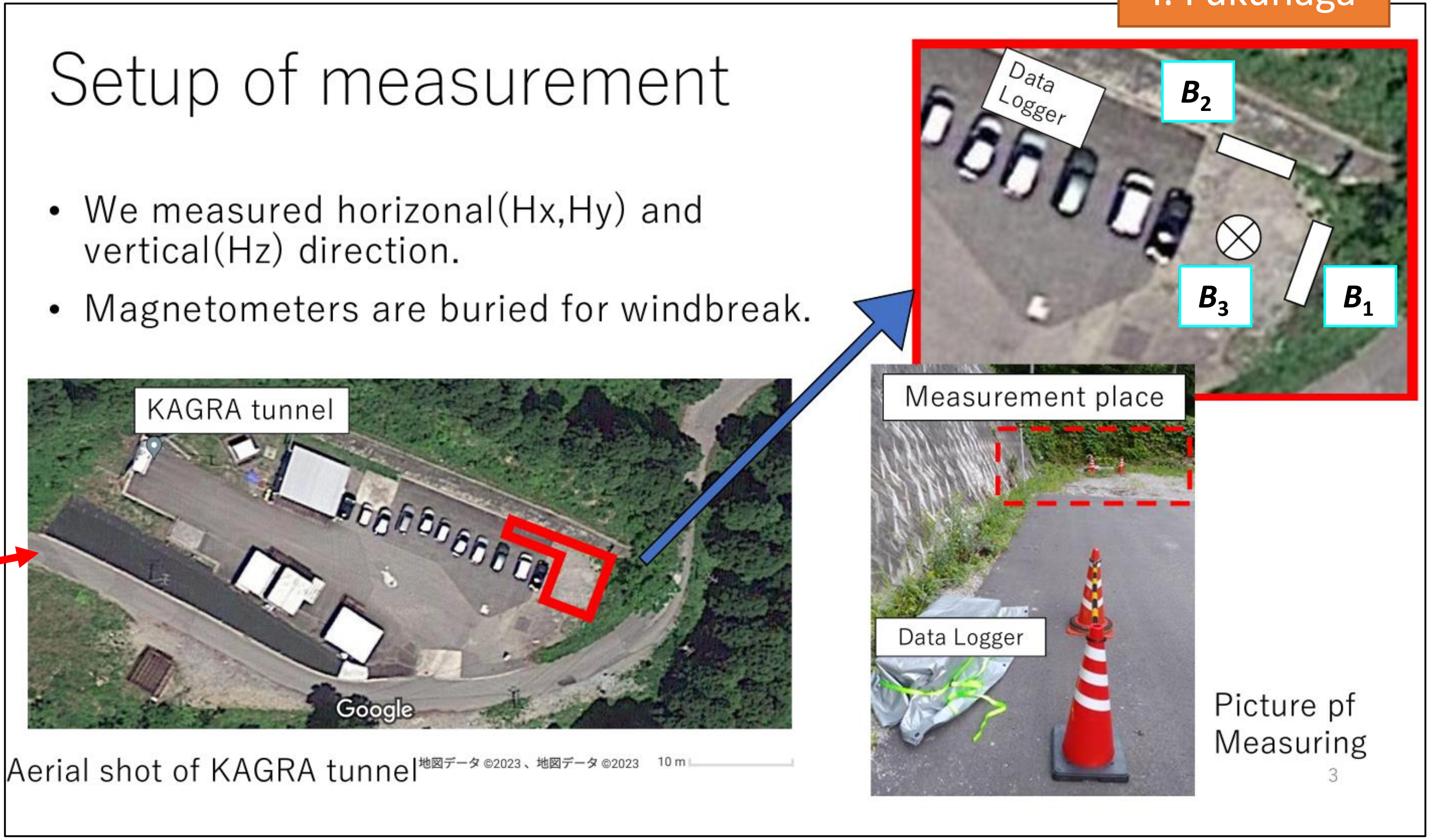
- How it will behave at ET (triangle-circulated vacuum tube)?
  - need simulations?
- Can we mitigate this effect? (*e.g.*, inserting non-metal tubes)

Backup

Measurements at KAGRA outside

I. Fukunaga





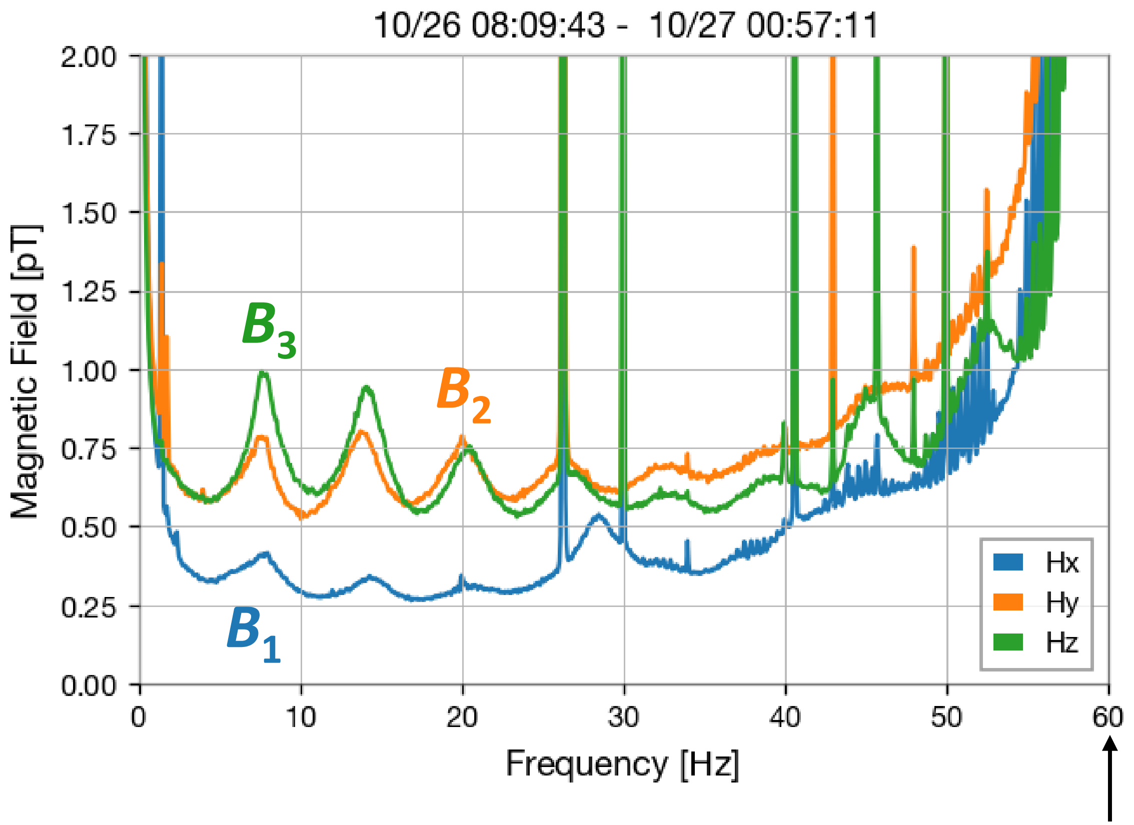
- Period: Aug. 26 - Dec. 13 in 2022
- Sensors: Metronix MFS-06e, EFP-06
- Data Logger: ADU-08e

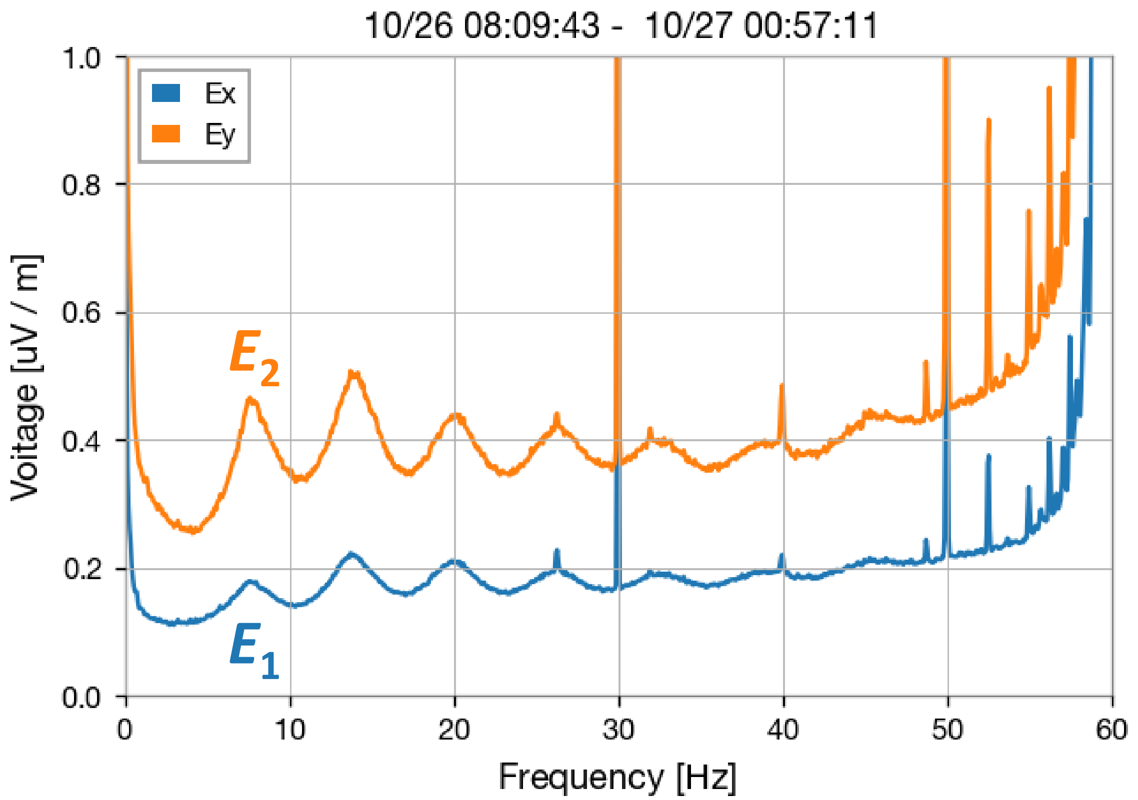
Direction of the magnetometers (clockwise from North)

- B_1 : 250° → 200° (changed in Oct.)
- B_2 : 110°
- B_3 : Vertical

Measurements at KAGRA outside

Example of the Schumann resonance spectrum





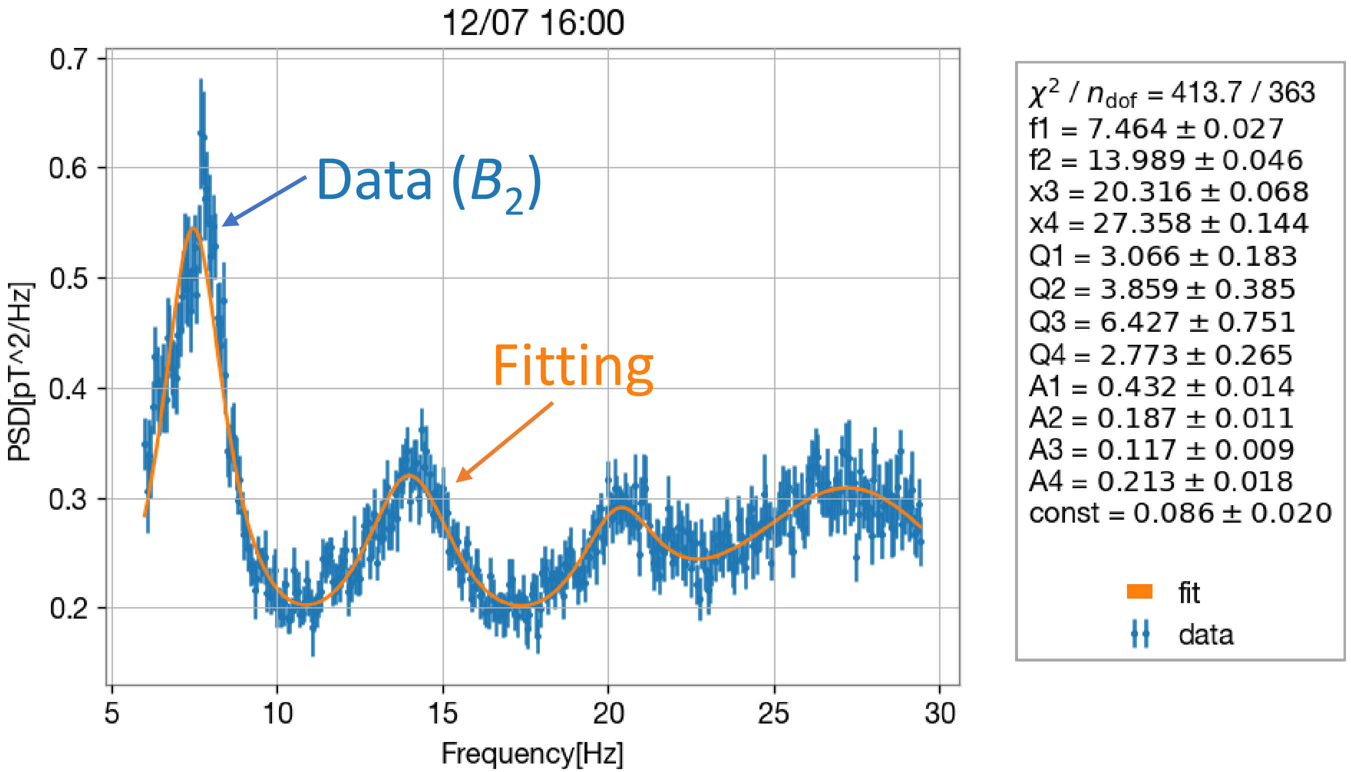
AC mains power (60Hz)

Measurements at KAGRA outside

χ^2 fitting

- PSD for fitting
  - Duration：1 hour
  - FFTlength：16 second
  - Overlap：50%

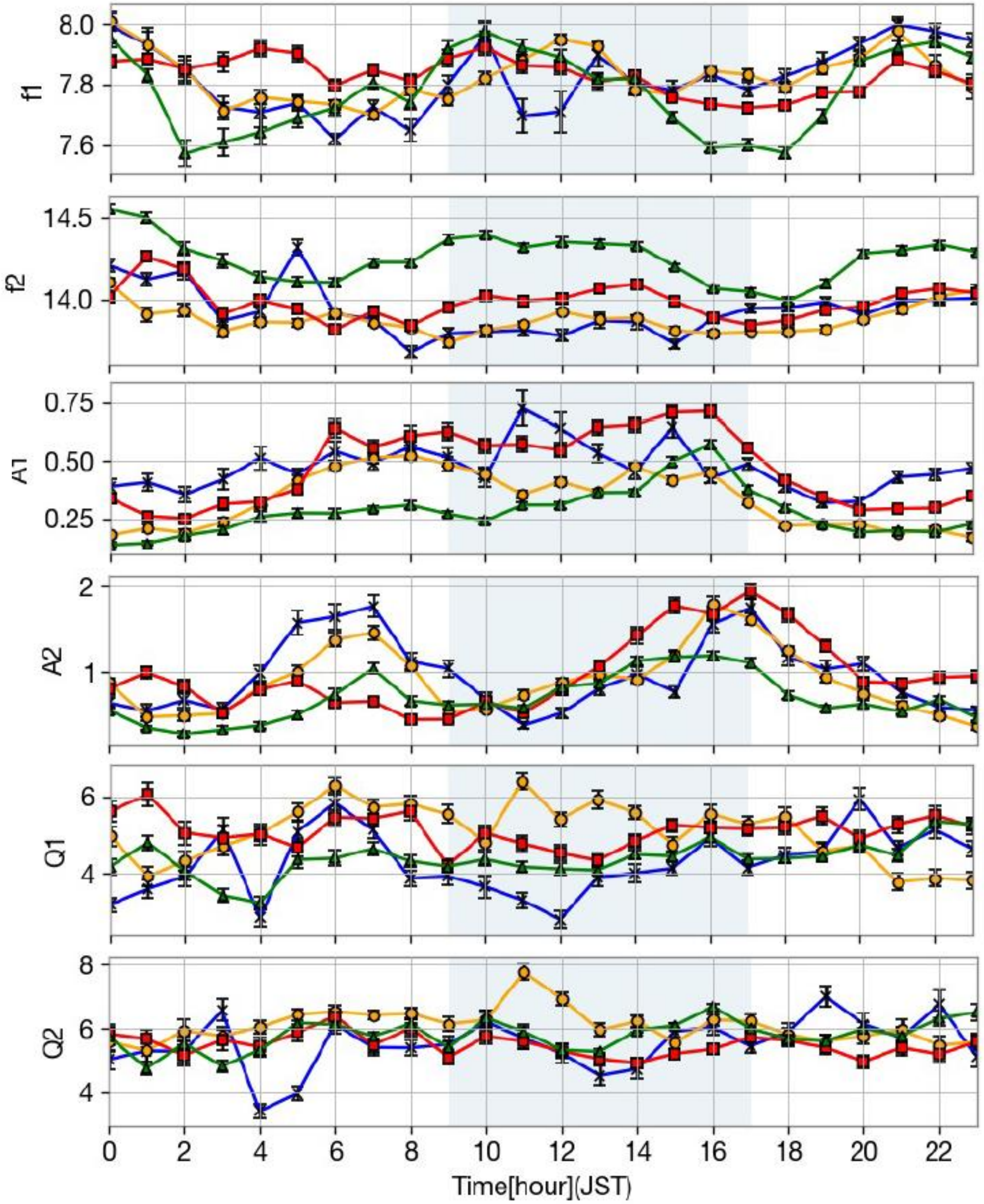
→449 PSDs



Spectrum used in a single fitting

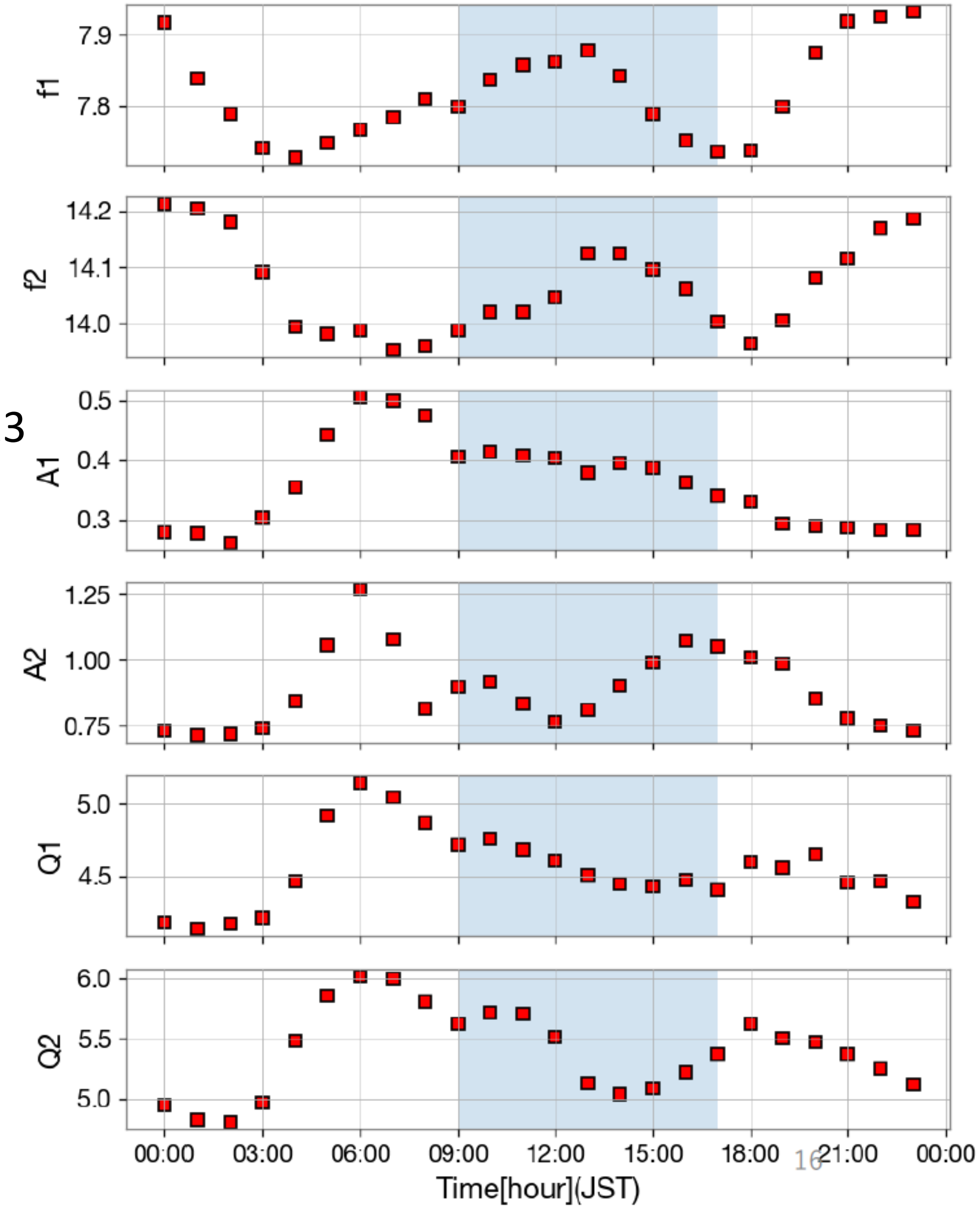
- Value：median($=P_{50}$)
- Error：$\frac{P_{53}-P_{47}}{2}$ (P_n: n percentile)
- Model：$P(f) = \sum_{i=1} A_i \frac{(f_i/2Q_i)}{(f-f_i)^2+(f_i/2Q_i)^2} + constant$

Measurements at KAGRA outside

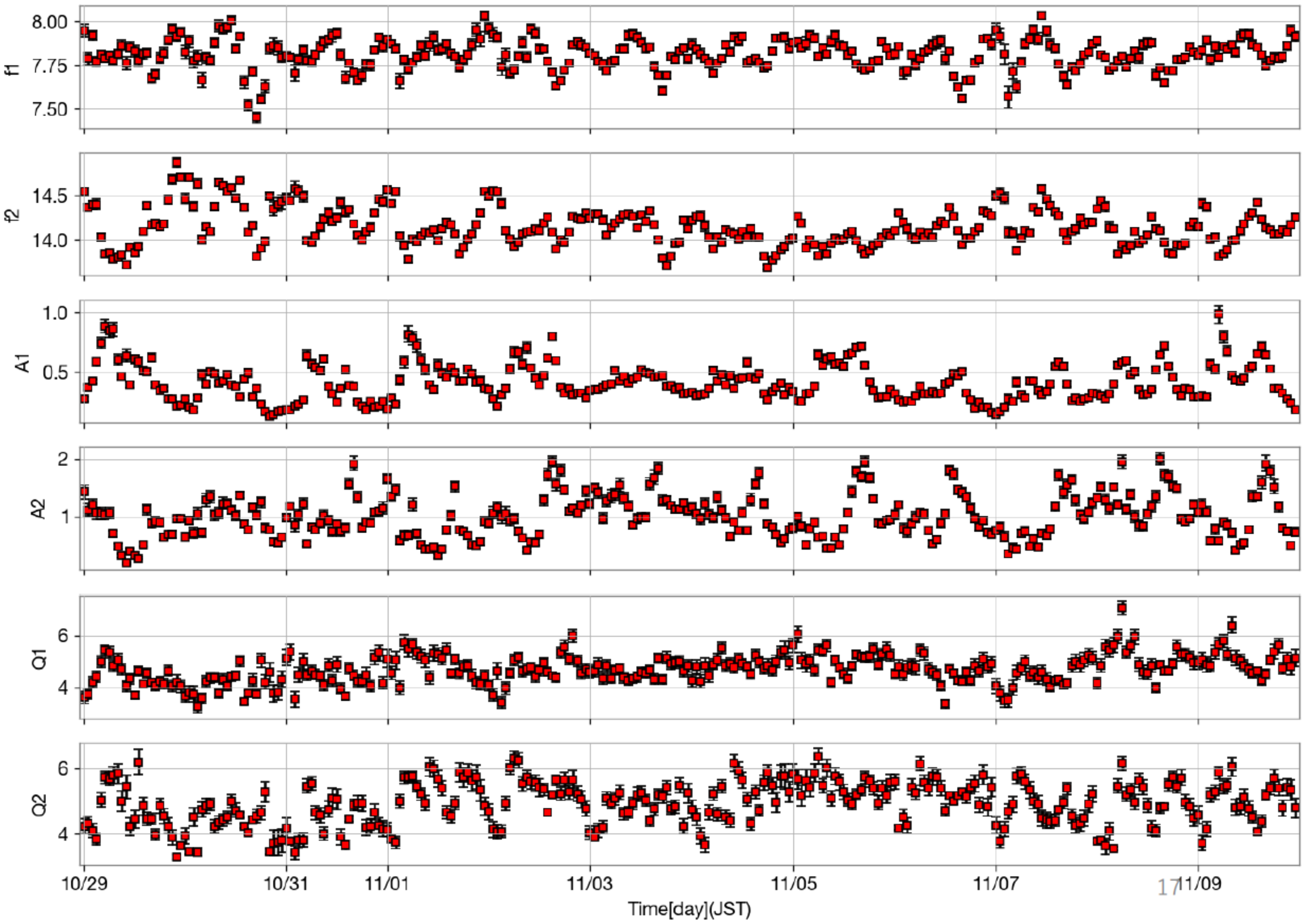


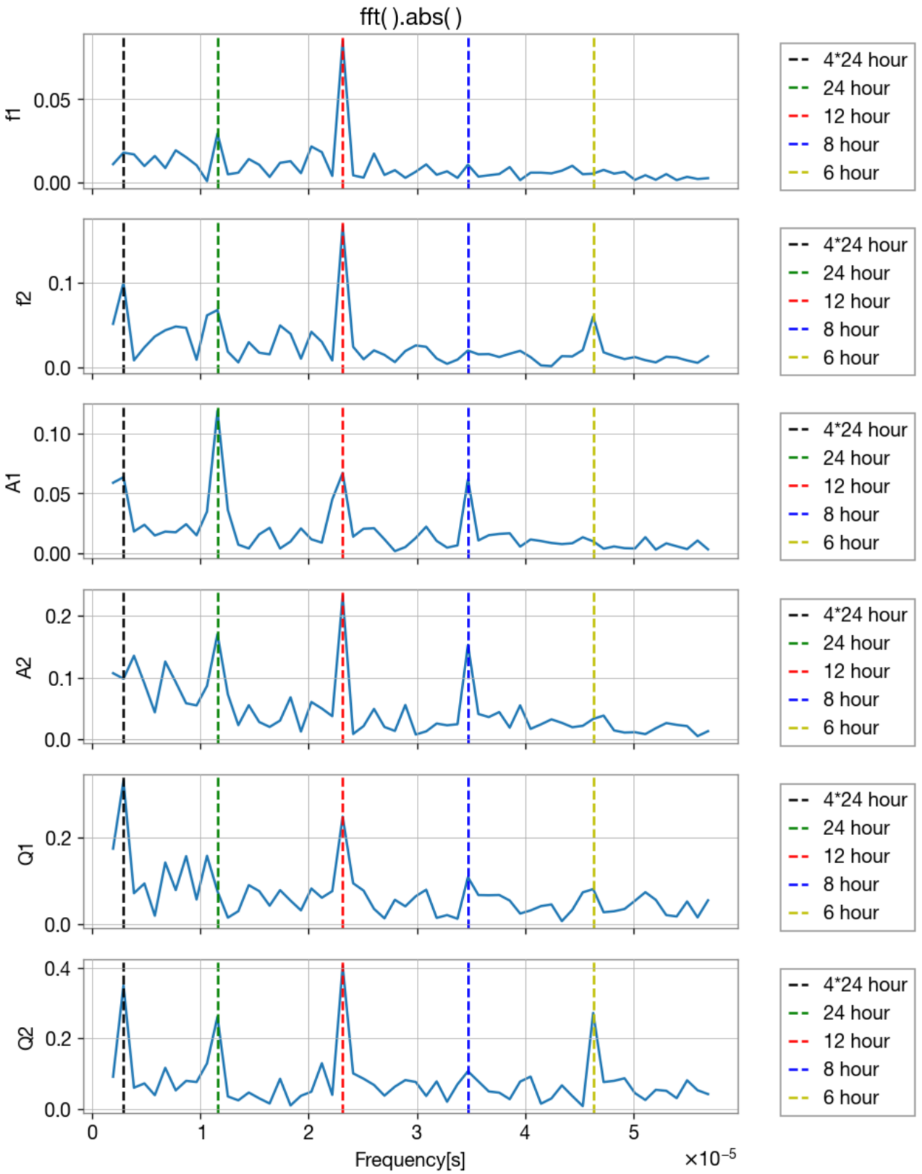
Oct. 26
Nov. 11
Dec. 07
Dec. 10

Average for Oct.28-Dec.13
(some days are dropped)



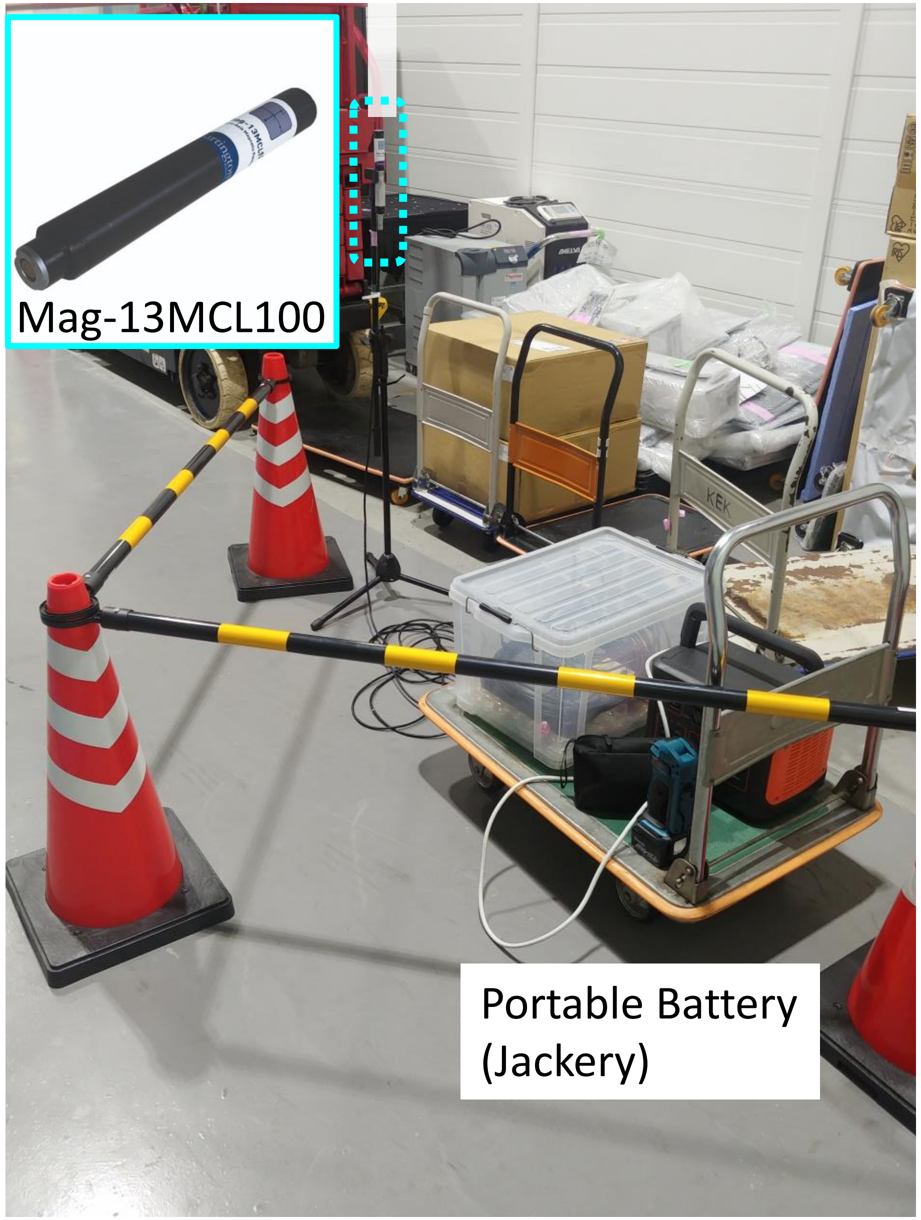
KAGRA outside





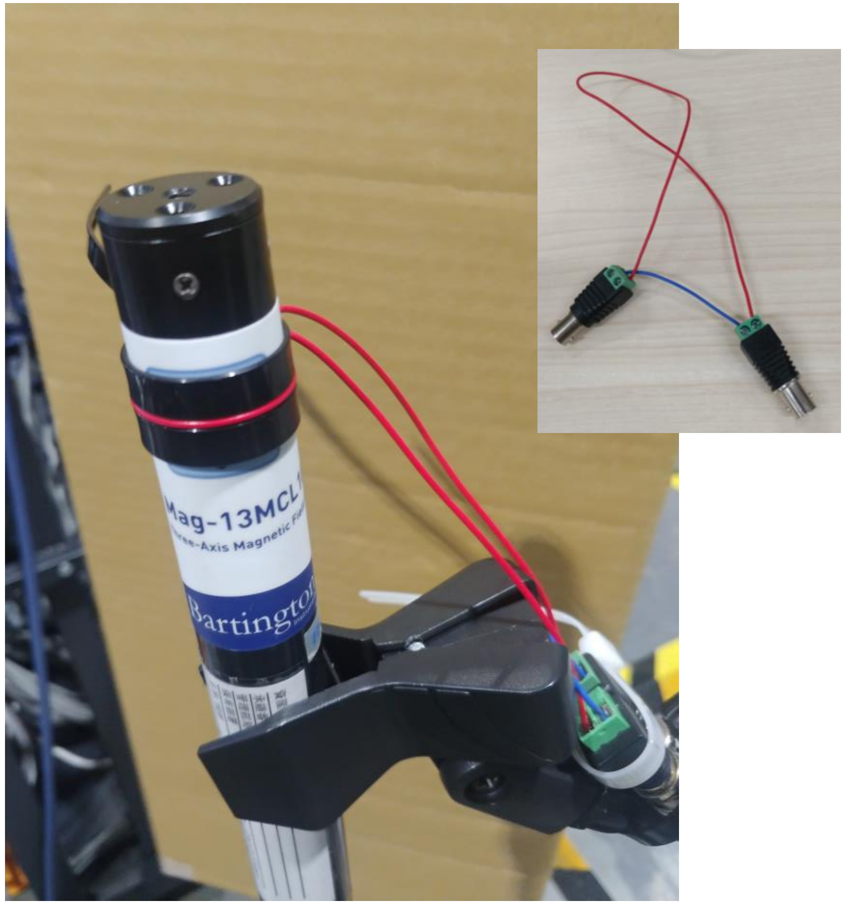
Setup

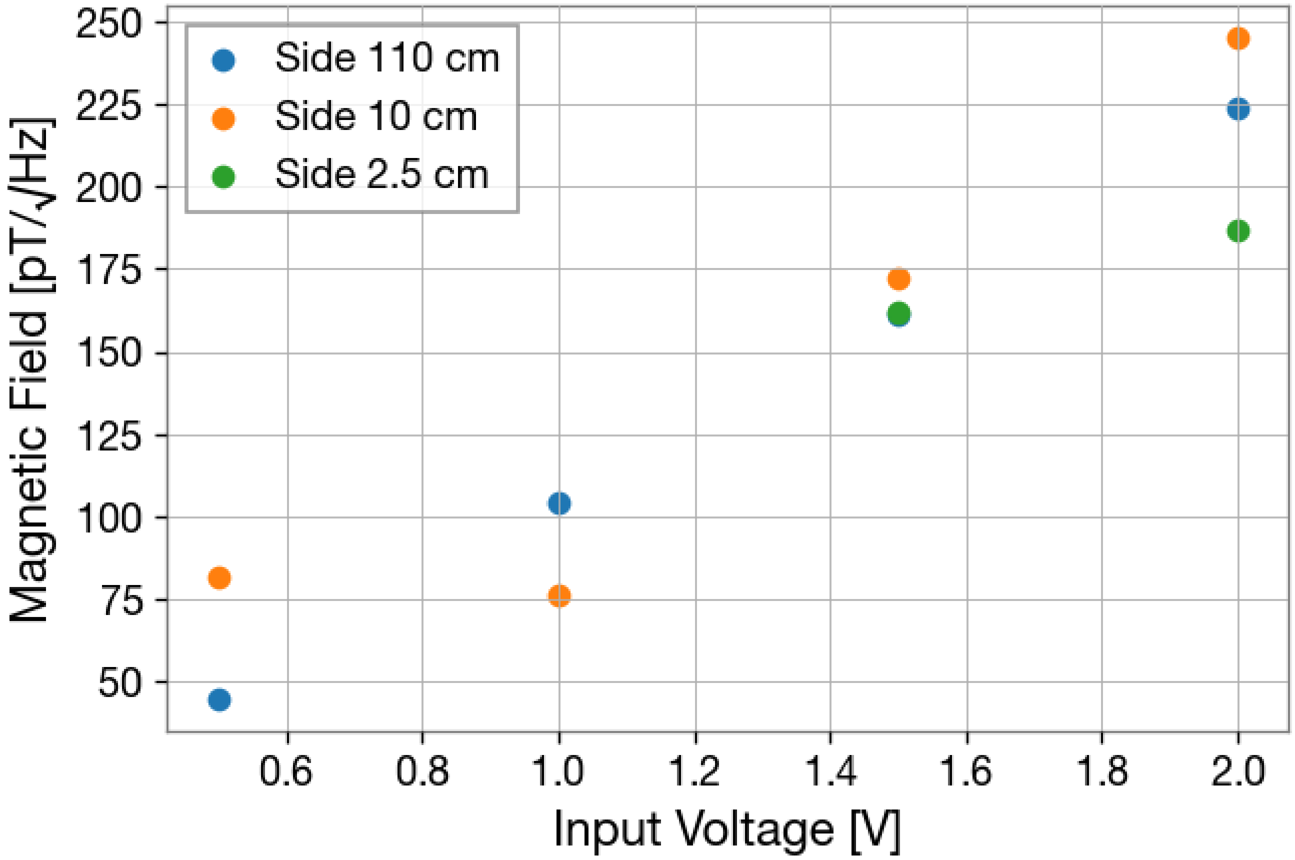
- Magnetometer : Bartington Mag-13MCL
  - 3-axial, DC – 3kHz
  - Noise level : 2~4 pT/√Hz for each axis
- Power supply for Mag-13 : PSU1
- Data logger : GRAPHTEC GL980
  - ±20mV range (Min.), 16 bit
  - 200 S/s, 10 min data
  - 50Hz low pass filter
  - NTP clock (no GPS)



Calibration of the sensor response

It was not changed near the vacuum tube.



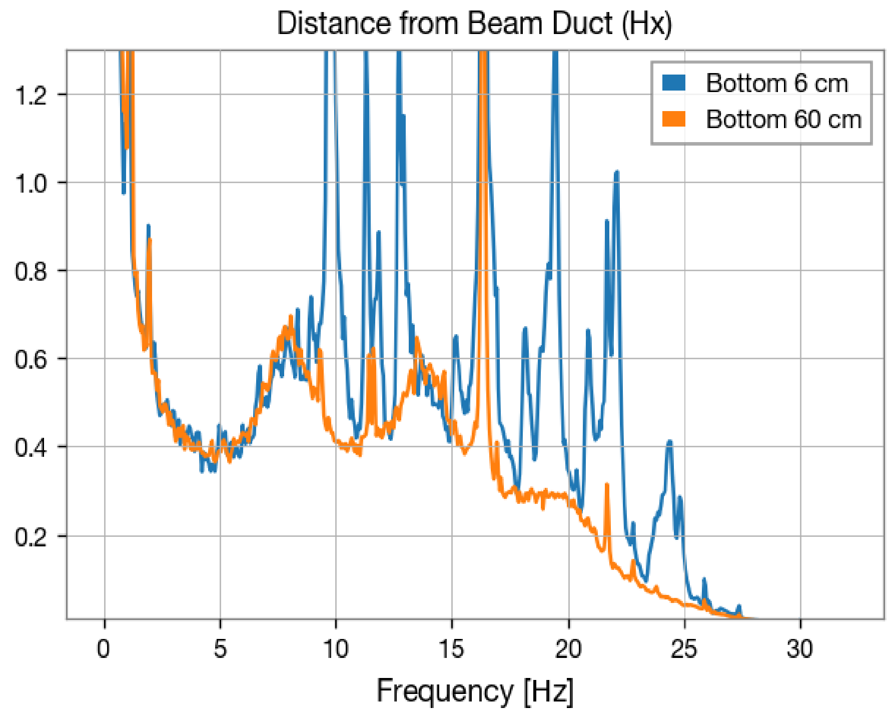


Measurements @ CLIO

CLIO, a prototype of KAGRA, is constructed in the same mountain.

- Arm length is 100m
- measured by a Metronix MFS-06e
- Amplitude of the Schumann resonance was not changed when we change the distance from the tube.

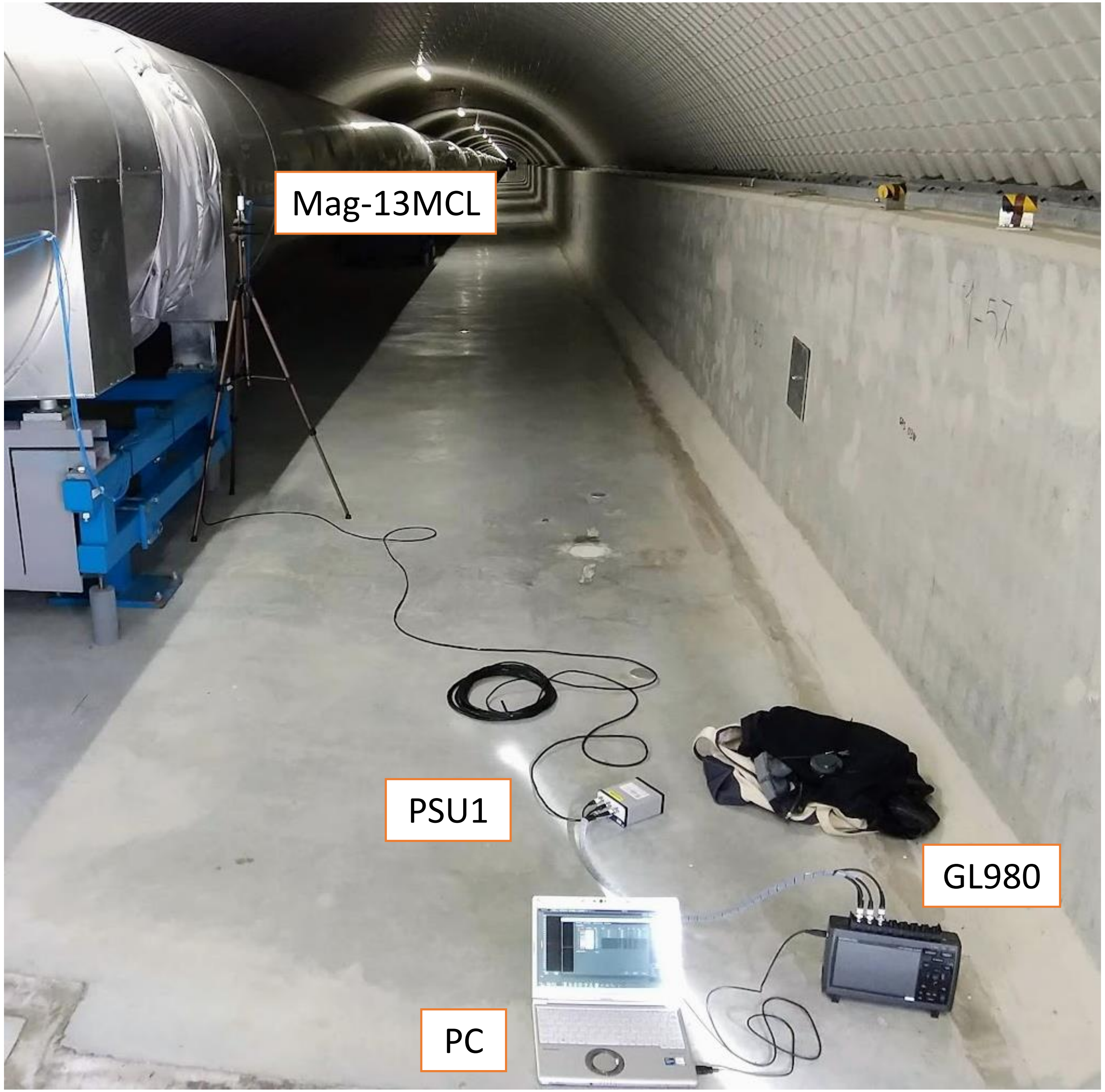
2022-8-24



Measurements@Virgo

- Nov. 11, 900m of the West arm

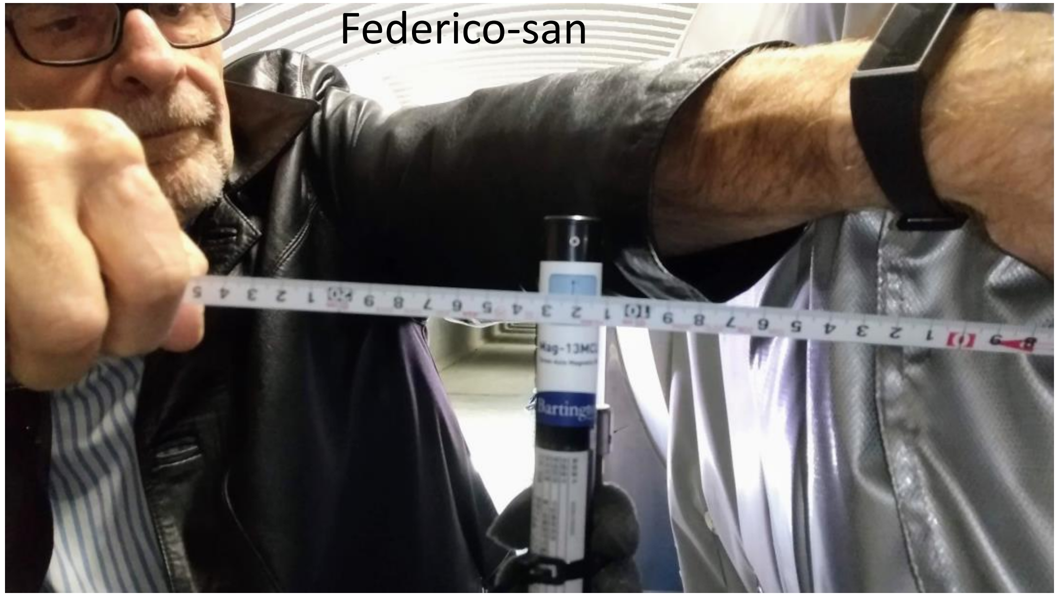
- Magnetometer : Bartington Mag-13MCL
  - 3-axial
  - DC – 3kHz
  - Noise level : 2~4 pT/√Hz for each axis
- Power supply for Mag-13 : PSU1
  - AC or battery
  - DC cut filter
- Data logger : GRAPHTEC GL980
  - Max. 8 channels, 1 MS/s
  - ±20mV range (Min.), 16 bit
  - 200 S/s, 10 min data
  - 50Hz low pass filter
  - NTP clock (no GPS)

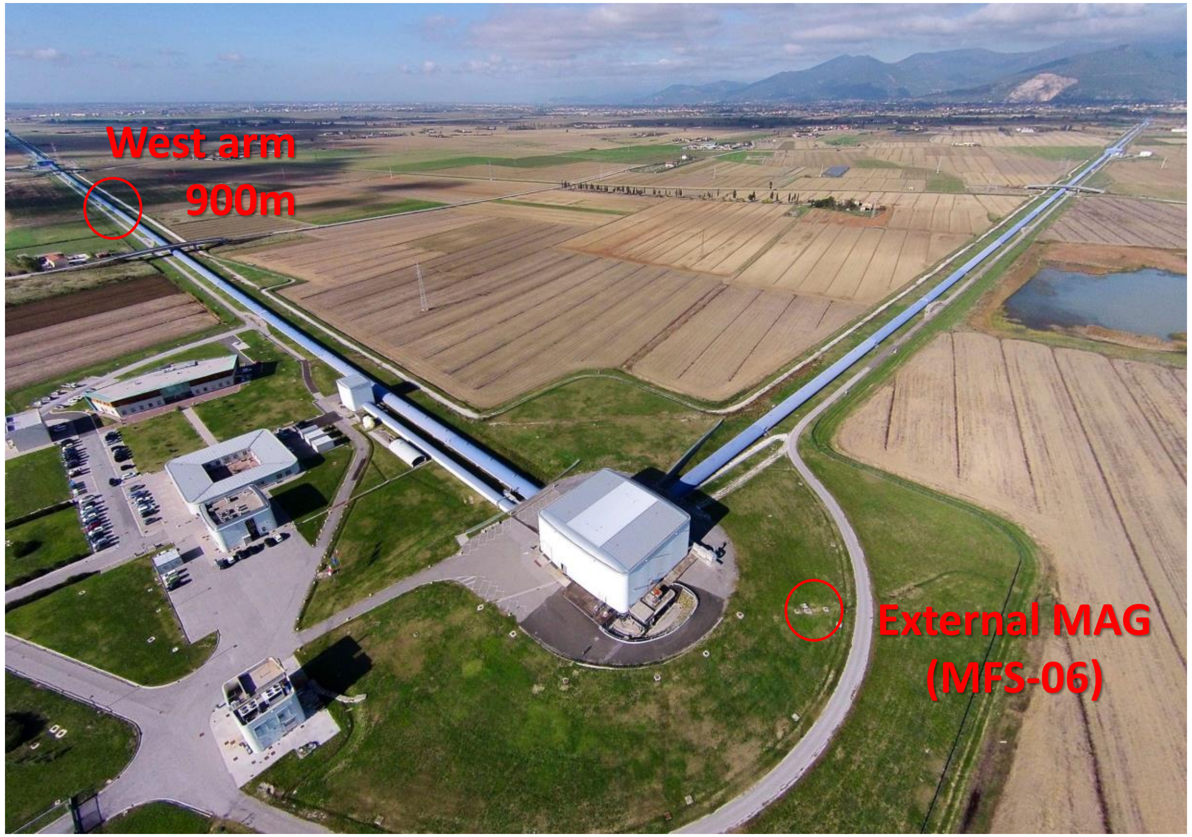


Measurements@Virgo

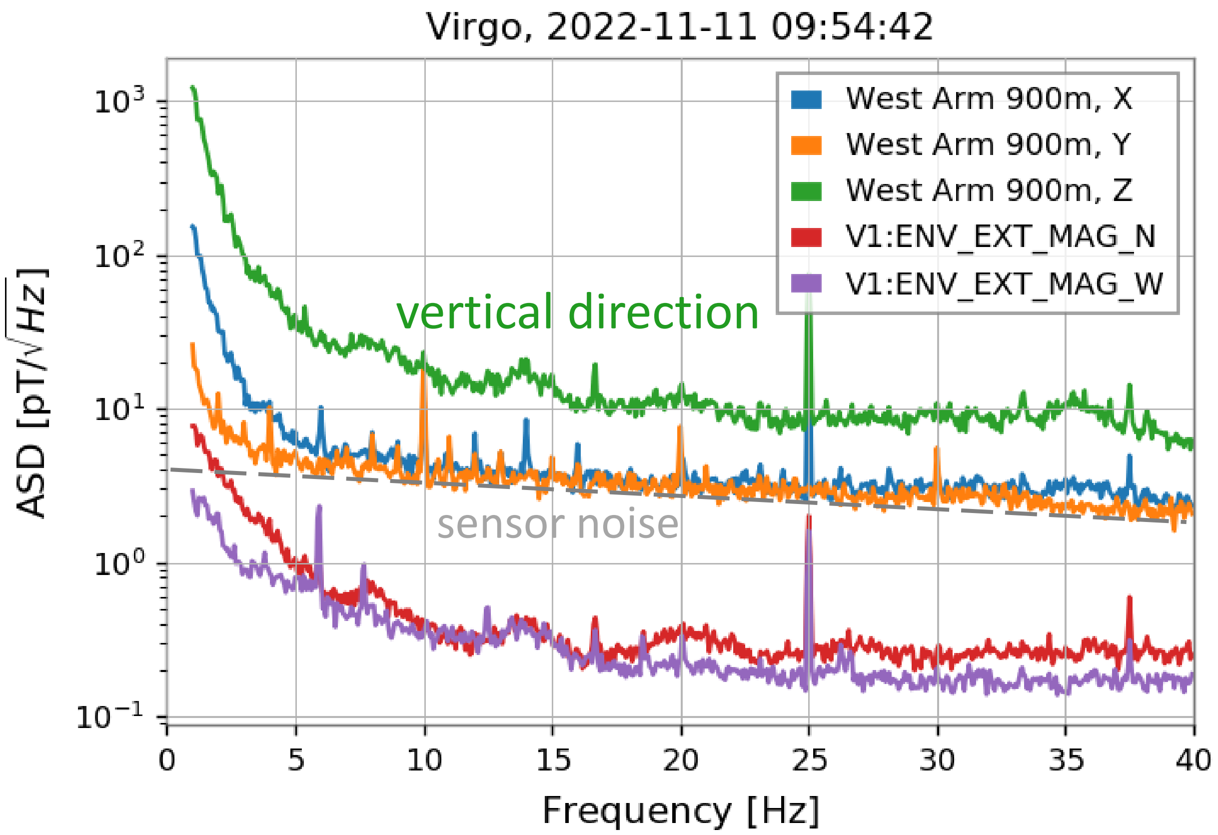
We performed the same measurements at Virgo site.

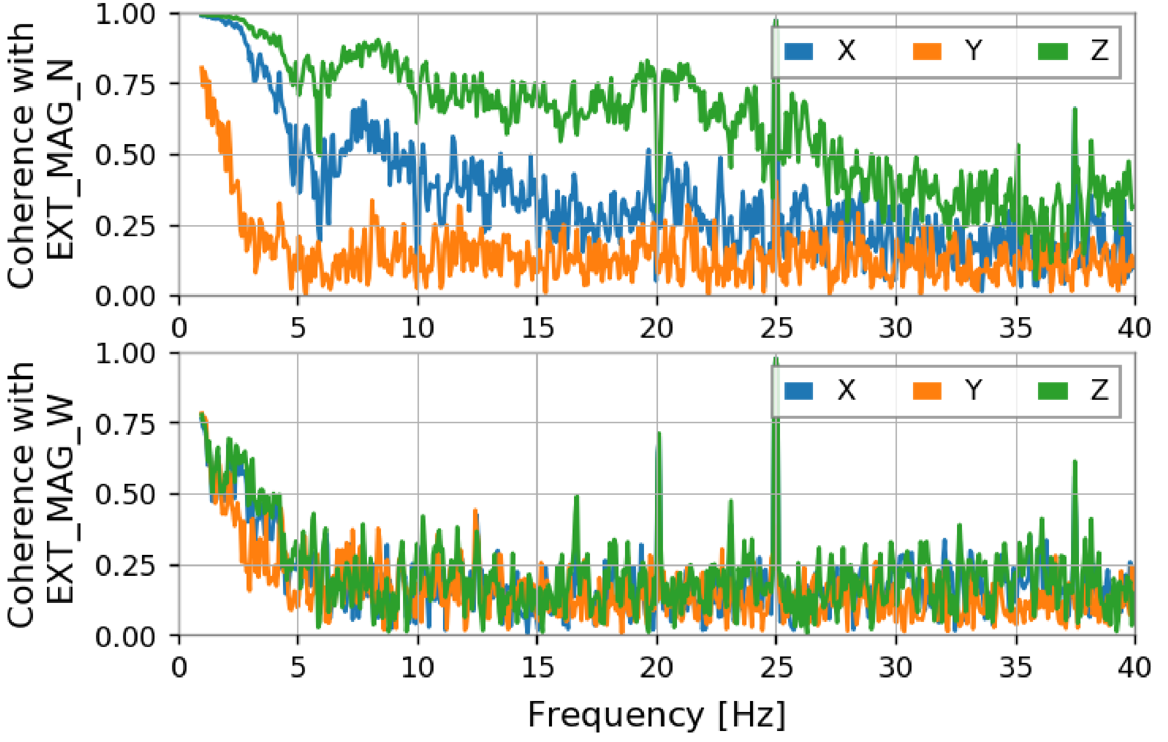
- In the West arm tunnel, 900 m point
- Side of the vacuum tube (12 cm from the outer surface)
- The same setup used at KAGRA

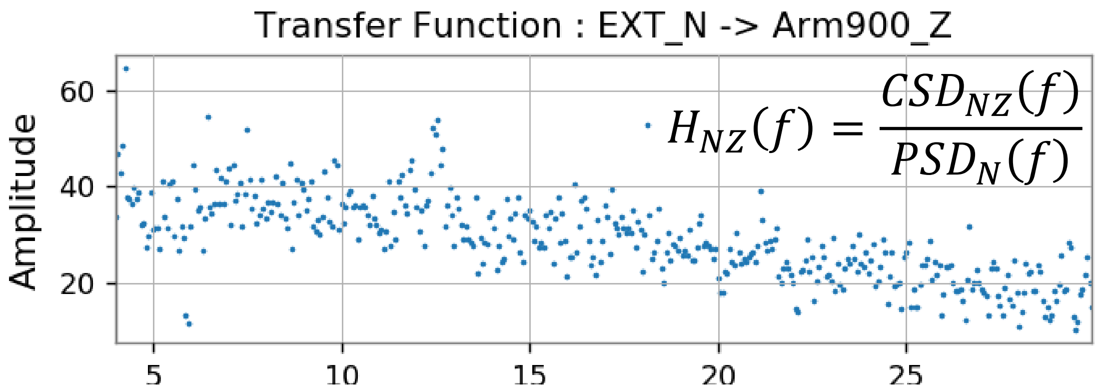




Measurements@Virgo







- The significant value of coherence with EXT. MAG. was derived.
  - Amplified Schumann resonance was observed at Virgo.
  - Amplification gain ~ 40
- Follow-up measurements are performed by Francesca Bucci.