Magnetic Noise Injection Scripts and Preliminary Results for The Virgo Detector

Catalina-Ana Miritescu[1], Irene Fiori[2], Maria Concetta Tringali[2], Federico Paoletti[3], Rosario De Rosa[4], Andrea Chincarini[5]

[1] Institut de Física d'Altes Energies (IFAE), Barcelona, Spain. [2] European Gravitational Observatory (EGO), Pisa, Italy. [3]INFN-Pisa, Italy. [4]INFN-Napoli, Italy. [5]INFN-Genova, Italy.

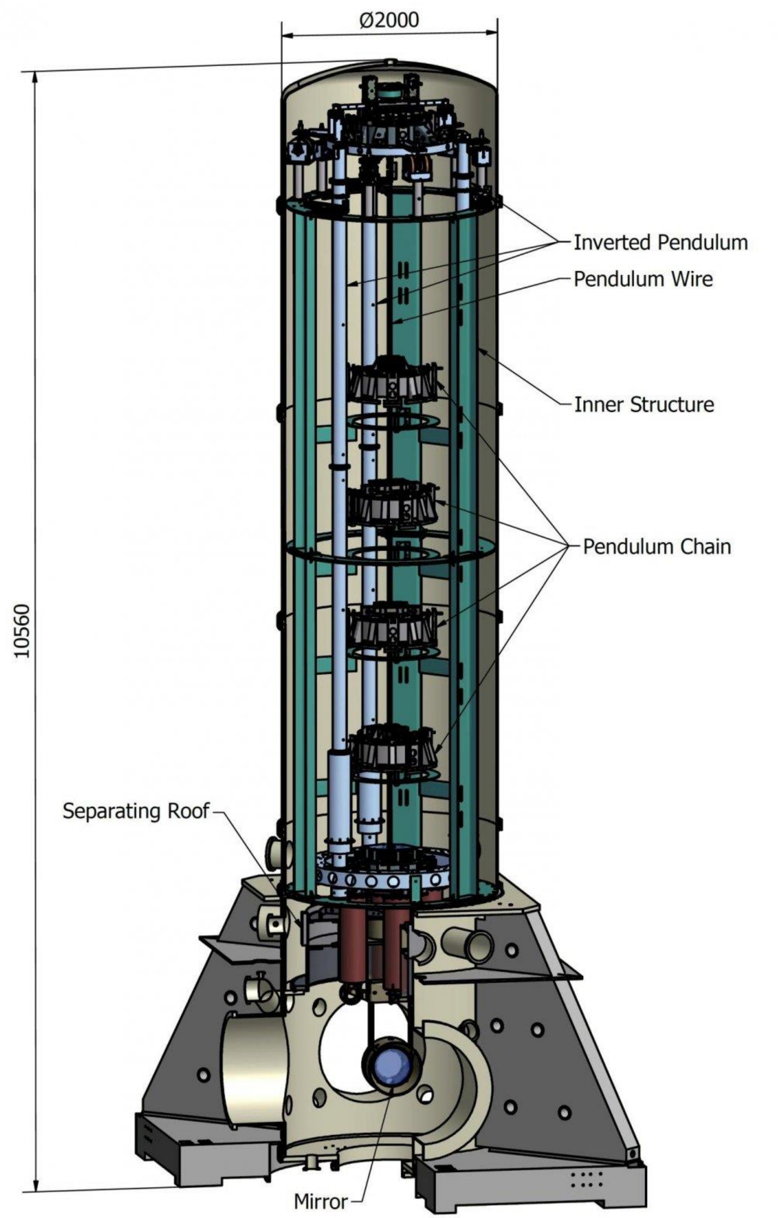
Outline

- Motivation
- Equipment used
- Scripts development
  - Lines injections
  - Colored noise injections
  - Sweep injections (building specific)
  - Coupling function calculations
- Preliminary results

Image from www.virgo-gw.eu

Motivation

- Detectors need high sensitivity ⟶ noise sources need to be understood
- The **electronics** surrounding the interferometer create **electromagnetic fields** which could show up in the **detector strain**
- Most critical coupling locations are next to the elements carrying permanent magnets:
  - Test masses;
  - Optical benches;
  - Suspension systems with cables and electronics.



Understanding Magnetic Noise

- Before O4:
  - magnetic injections campaigns
  - coupling functions calculations
- During O4:
  - periodic injections to monitor any coupling function variations via a Metatron (Graef Rollins J. 2016 Review of Scientific Instruments 87 094502) node for automatic injections
- Post O4:
  - full analysis
- All scripts have been developed in Python employing ACL functionality (R. Bonnand, A. Masserot, B. Mours, L. Rolland, E. Pacaud, M. Was, and D. Passuello. The Algorithms for Control and Locking (Acl) Server Documentation. Technical Report VIR-0XXX-16, 2023).

Equipment Used

Figure 1. The coil of height 4.2m and width of 4.5m, with 86 loops.

Figure 2. METRONIX Magnetometers (black tubes). One axis each tube.

Figure 3. Triaxial Bartington magnetometers.

Positions

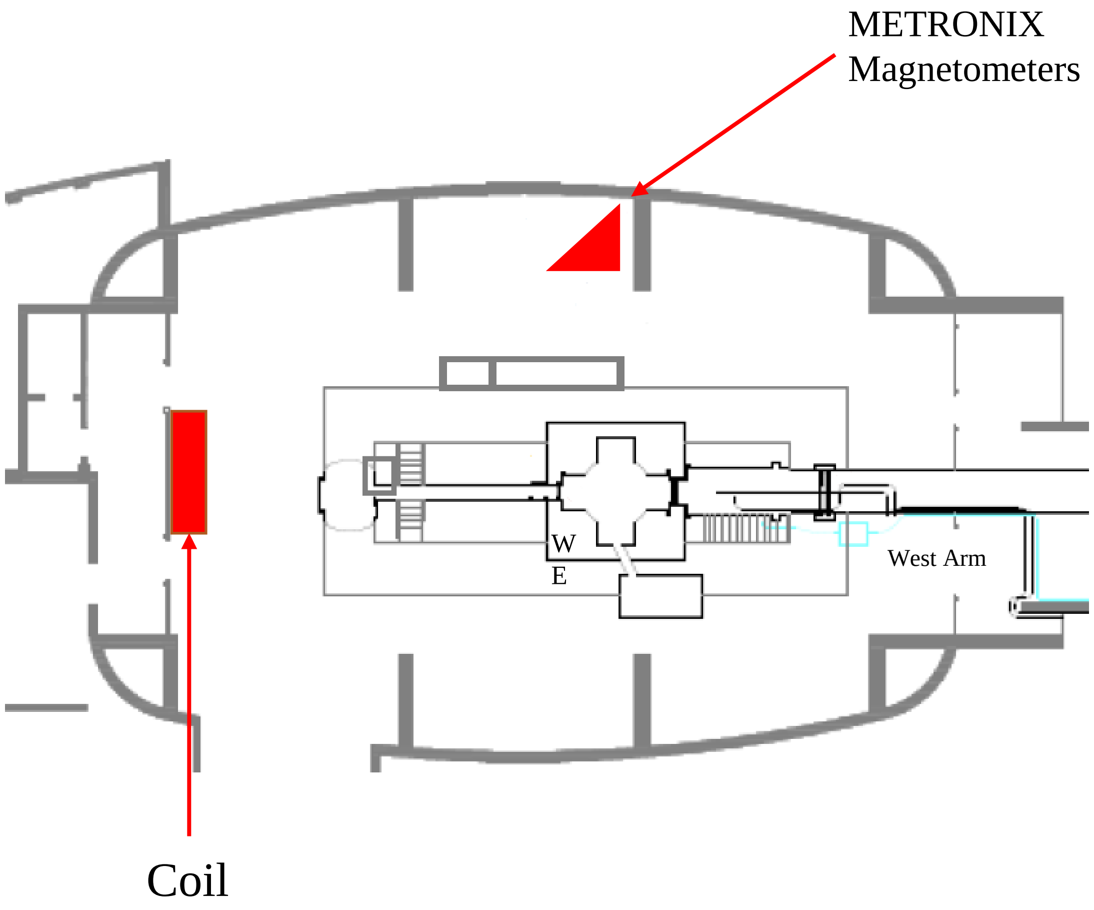


Figure 4. West End Building (WEB) equipment position. Image from https://logbook.virgo-gw.eu/virgo/?r=59354.

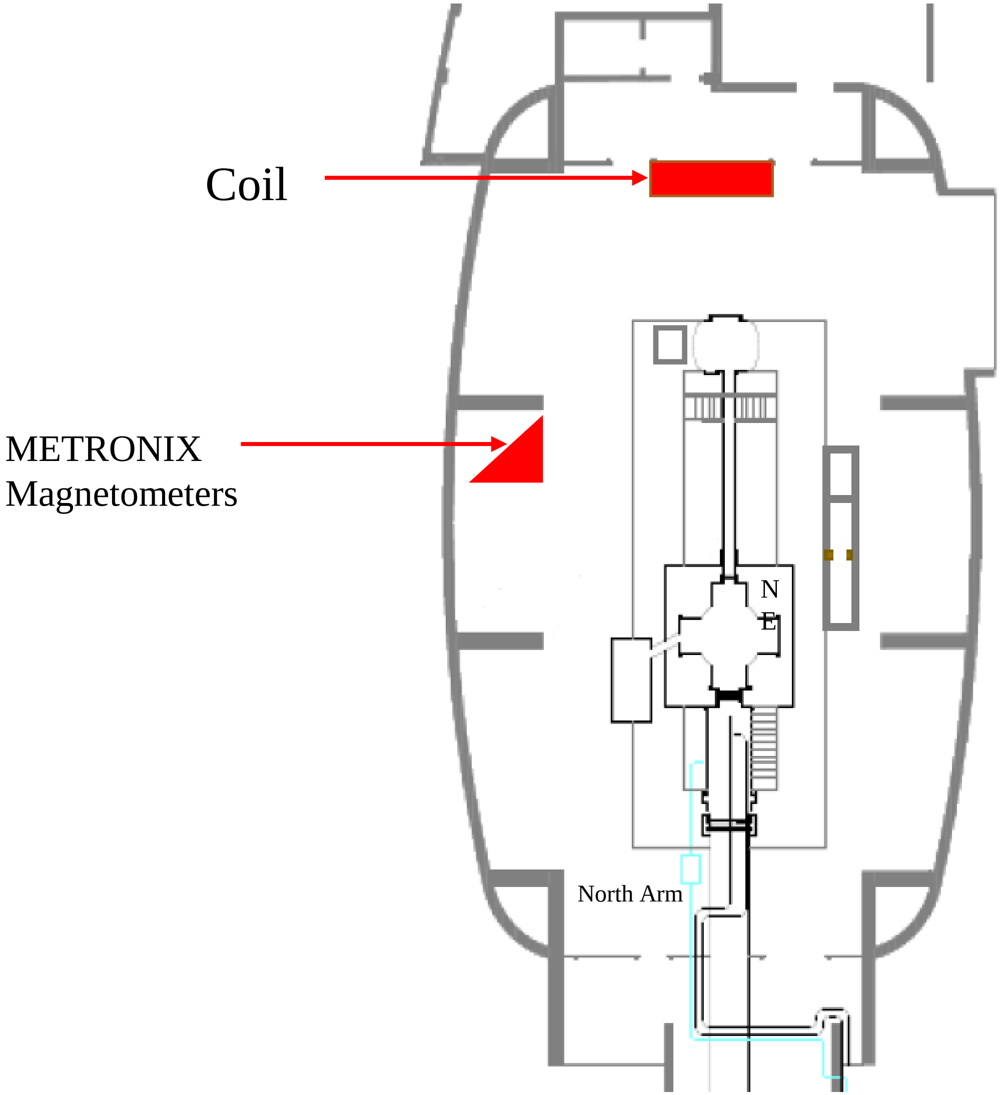


Figure 5. North End Building (NEB) equipment position. Image from [https://logbook.virgo-gw.eu/virgo/?r=59354.](https://logbook.virgo-gw.eu/virgo/?r=59354)

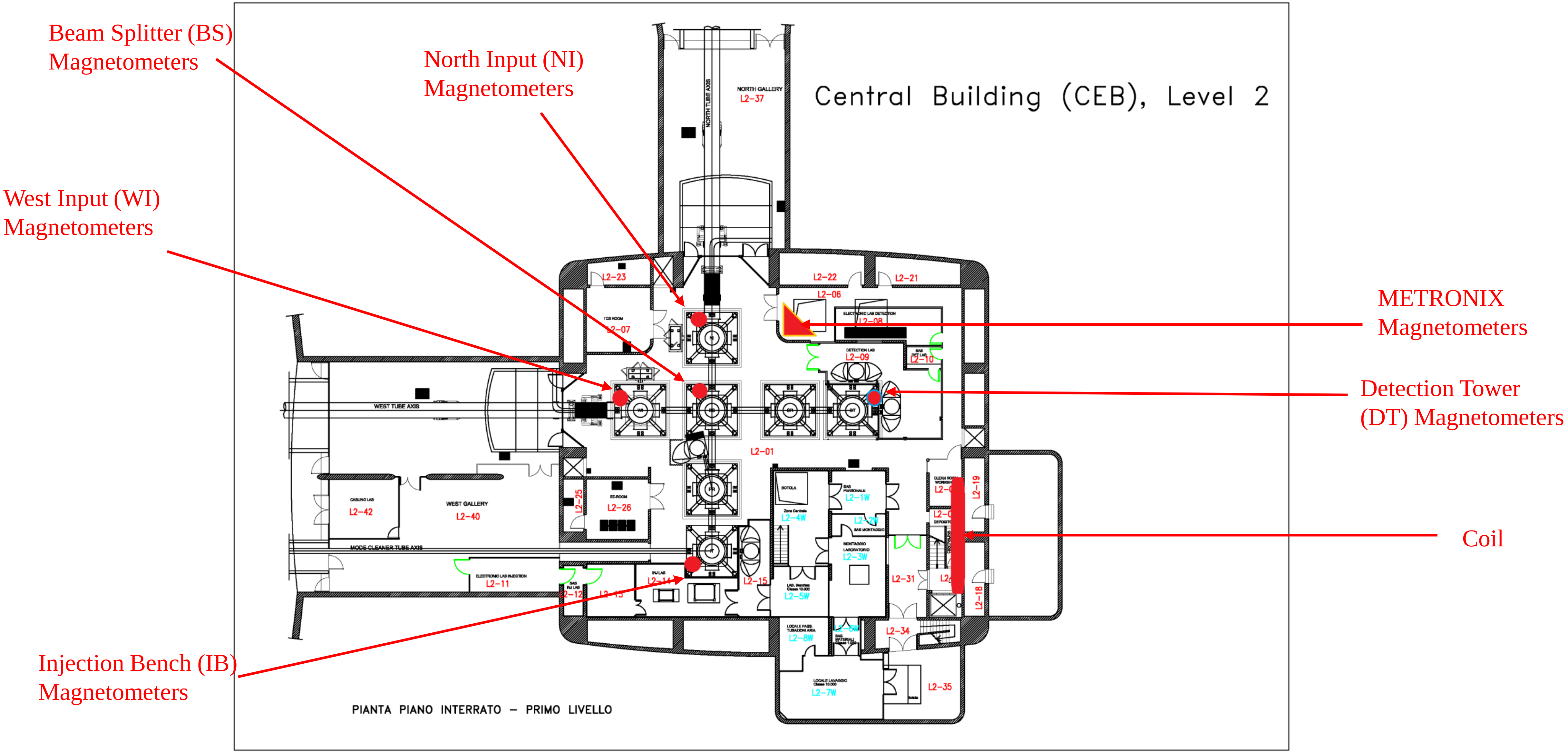


Figure 6. Central Building (CEB) equipment position. Image from https://logbook.virgo-gw.eu/virgo/?r=59354.

Saturation Limits

- **Power amplifier limits: 72Vpk** and **6Apk**.
- The coil behaves as a **resistance at low frequencies** (under 10Hz), resulting in a maximum Digital to Analogue Converter (DAC) voltage of 6V in order to not saturate the **current of the amplifier**.
- The coil's **inductance** becomes dominant at **high frequencies** (above 10Hz), resulting in a maximum DAC voltage of 9V in order to not saturate the **voltage of the amplifier**.
- Additional restrictions in NEB and WEB to not saturate the **magnetometers**: at 10 Hz the max DAC voltage is 1V; at 33 Hz the max DAC voltage is 3.5V; at 45 Hz the mac DAC voltage is 5V; at 70 Hz the max DAC voltage is 8V; above 100Hz a max DAC voltage of 9V.

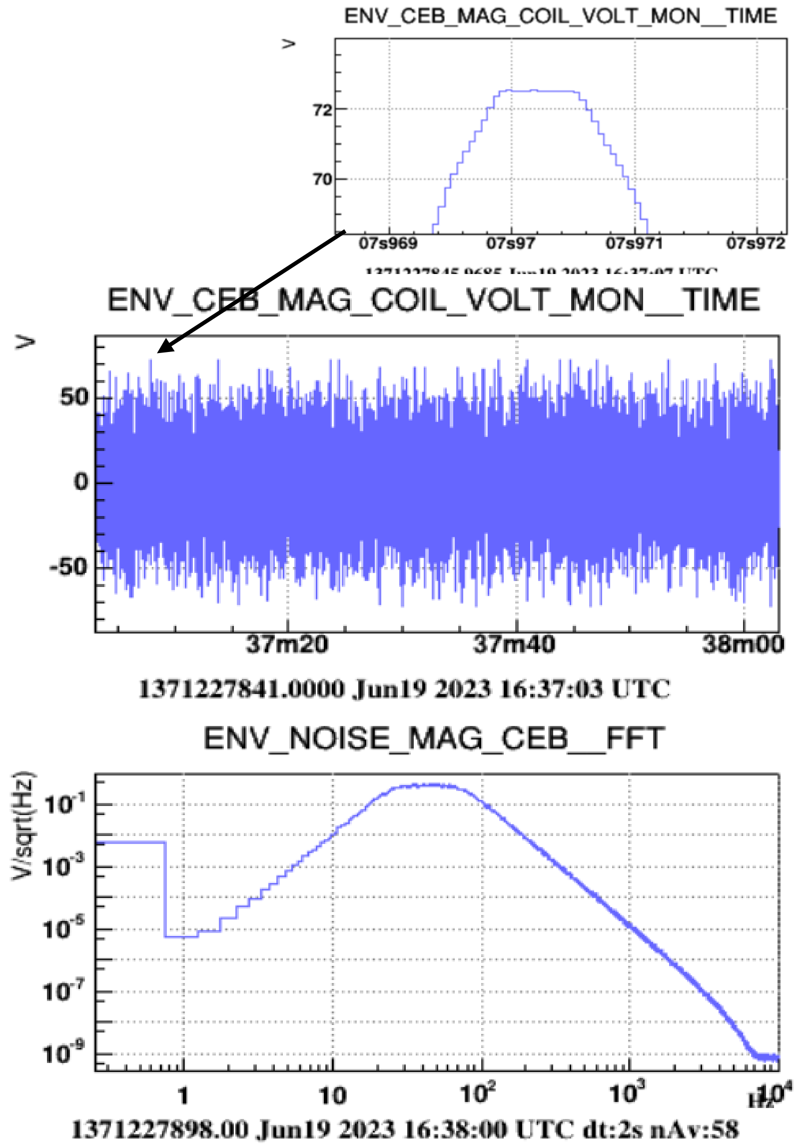


Figure 7. Example of voltage saturation. Image obtained using dataDisplay.

Magnetic Lines Injection

- Send a sinusoidal signal $V = V_0 \sin(2 \times \pi \times f \times t)$ to the Digital to Analogue Converter (DAC) to create a line in the FFT plot;
- Parameters to vary (in configuration file):
  - Amplitude V_0 (V),
  - Frequency f (Hz),
  - Duration of injection t (s).
- Advantages: the line spectral amplitude increases with the squared root of injection time, thus we can probe small couplings for long injections.
- Disadvantages: the coupling function is determined at specific discrete frequencies, particularities at other frequencies might not be observed.

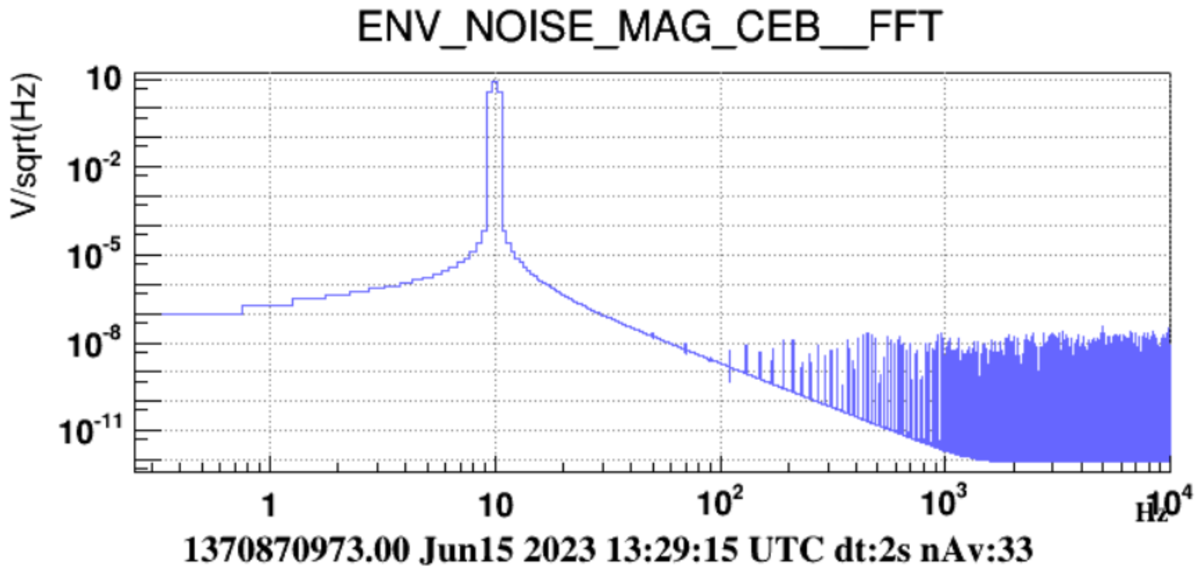
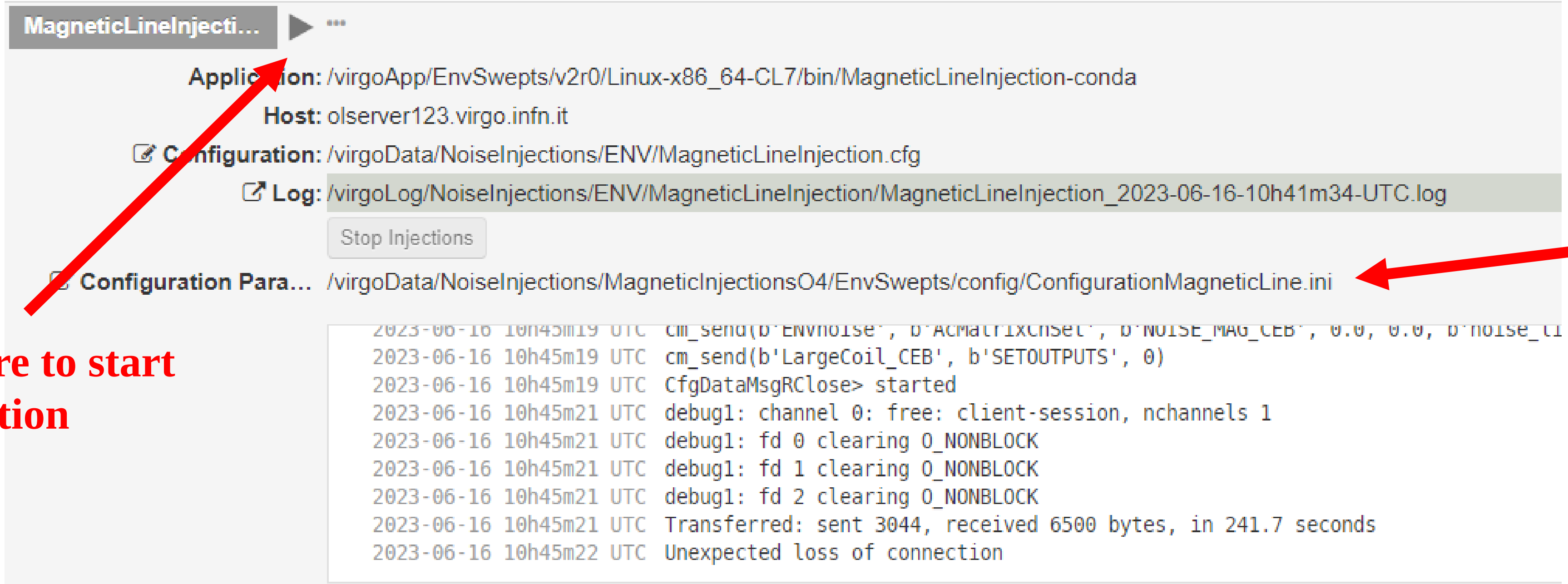


Figure 8. Magnetic line injection at $f = 10Hz$. Image obtained using dataDisplay.

Lines Injections Script - MagneticLineInjection

- Automatic Virgo Process Monitor (VPM) lines injection process



Click here to edit the configuration file

Click here to start the injection

Example Plots

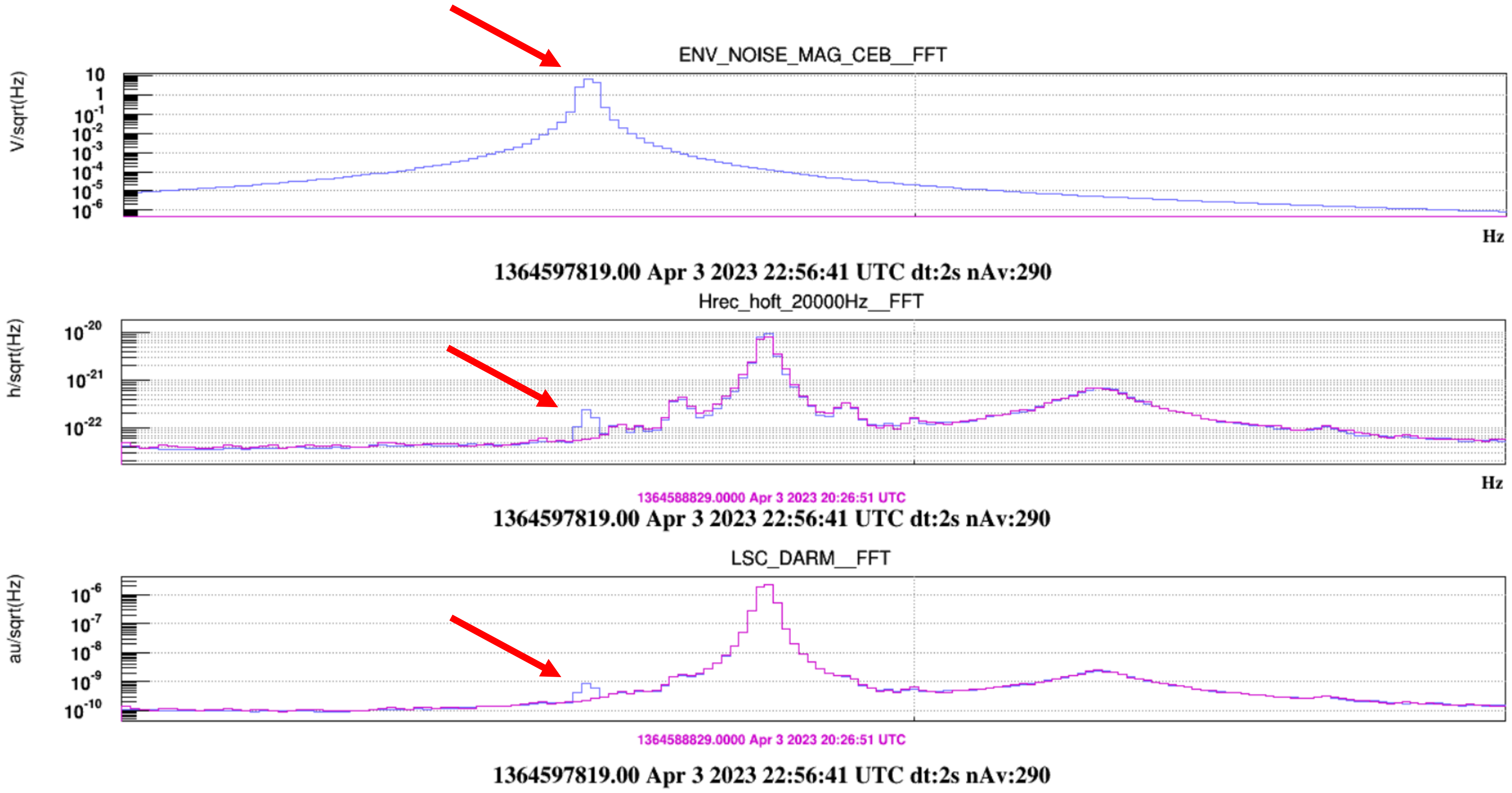


Figure 9. Magnetic line injection at $f = 480Hz$, with the line showing in Hrec and DARM. The pink line represents the background signal, while the blue line represents the injection. Image obtained using dataDisplay.

Magnetic Colored Noise Injections

- Send a gaussian white noise with a specific amplitude spectral density ($\frac{V}{\sqrt{Hz}}$) to the Digital to Analogue Converter (DAC), to which a filter is applied;
- Parameters to be varied:
  - Amplitude spectral density ($\frac{V}{\sqrt{Hz}}$),
  - Frequency f (Hz) where the filter is applied,
  - Bandwidth of the filter to be applied Δf (Hz),
  - Duration t (s) of the injection.
- Advantages: a larger range of frequencies can be probed.
- Disadvantages: gaussian noise amplitude doesn't increase with time – limited energy.

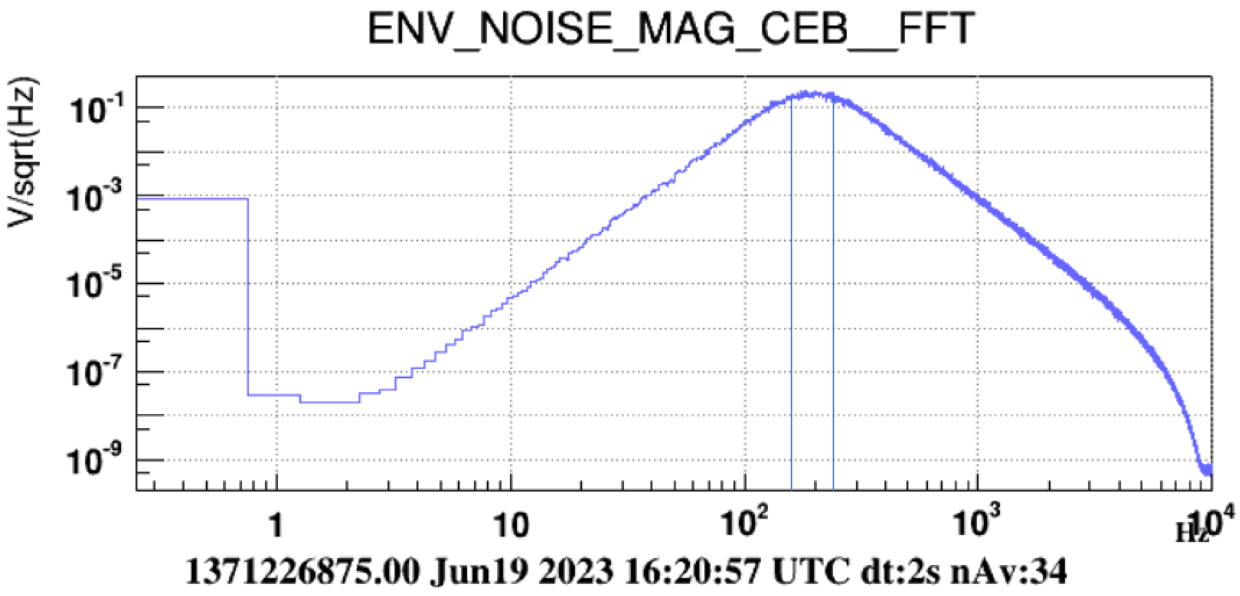


Figure 10. Magnetic colored noise injection of amplitude 0.2V at central frequency $f = 200Hz$, with a bandwidth of $\pm 50Hz$. Image obtained using dataDisplay.

Example Plots

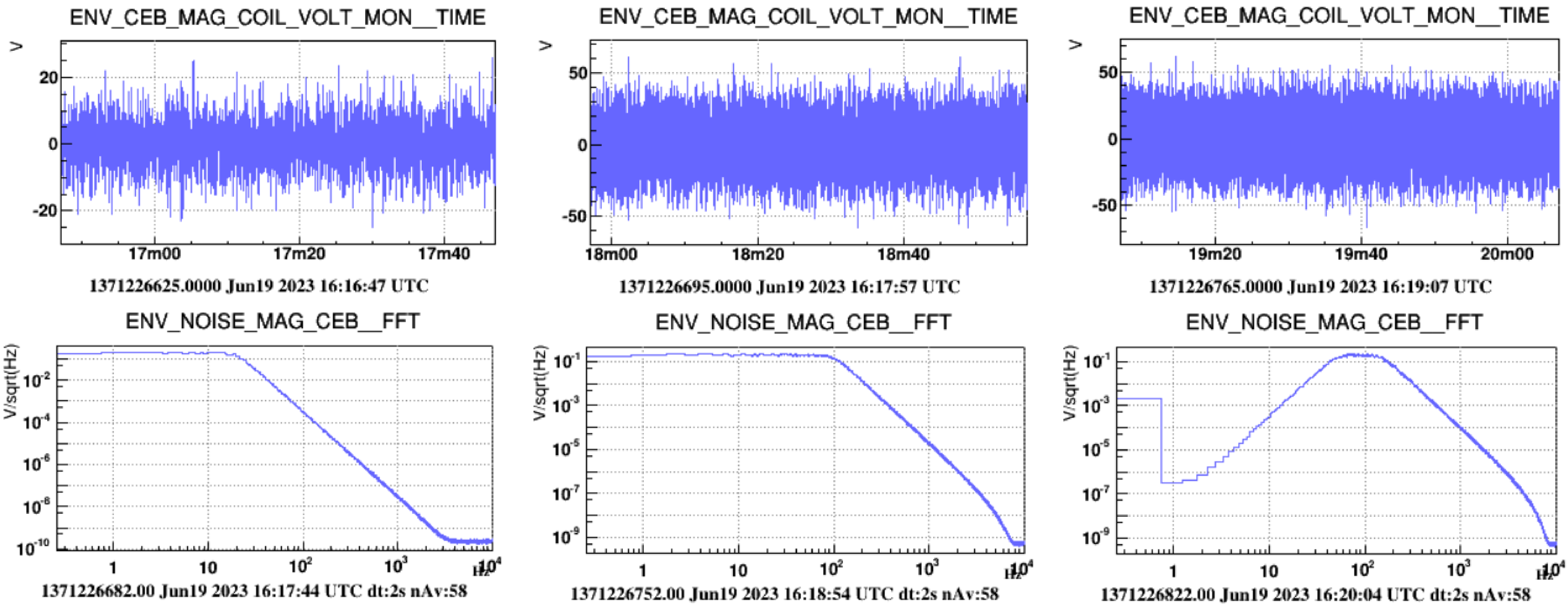


Figure 11. Magnetic colored noise injections of amplitude spectral density 0.2 $\frac{V}{\sqrt{Hz}}$: (left) central frequency $f = 10Hz$ and bandwidth of $\pm\ 10Hz$; (center) central frequency $f = 50Hz$ and bandwidth of $\pm\ 50Hz$; (right) central frequency $f = 100Hz$ and bandwidth of $\pm\ 50Hz$. Image obtained using dataDisplay.

Magnetic Sweep Noise Injections

- Send a sweep line of constant amplitude from a starting frequency to an ending frequency, with a specified duration. All parameters can be modified in the configuration file.
- Advantages: we can probe all frequencies, with more energy than the colored noise injections.
- Disadvantages: limited time for each frequency compared to line injections.

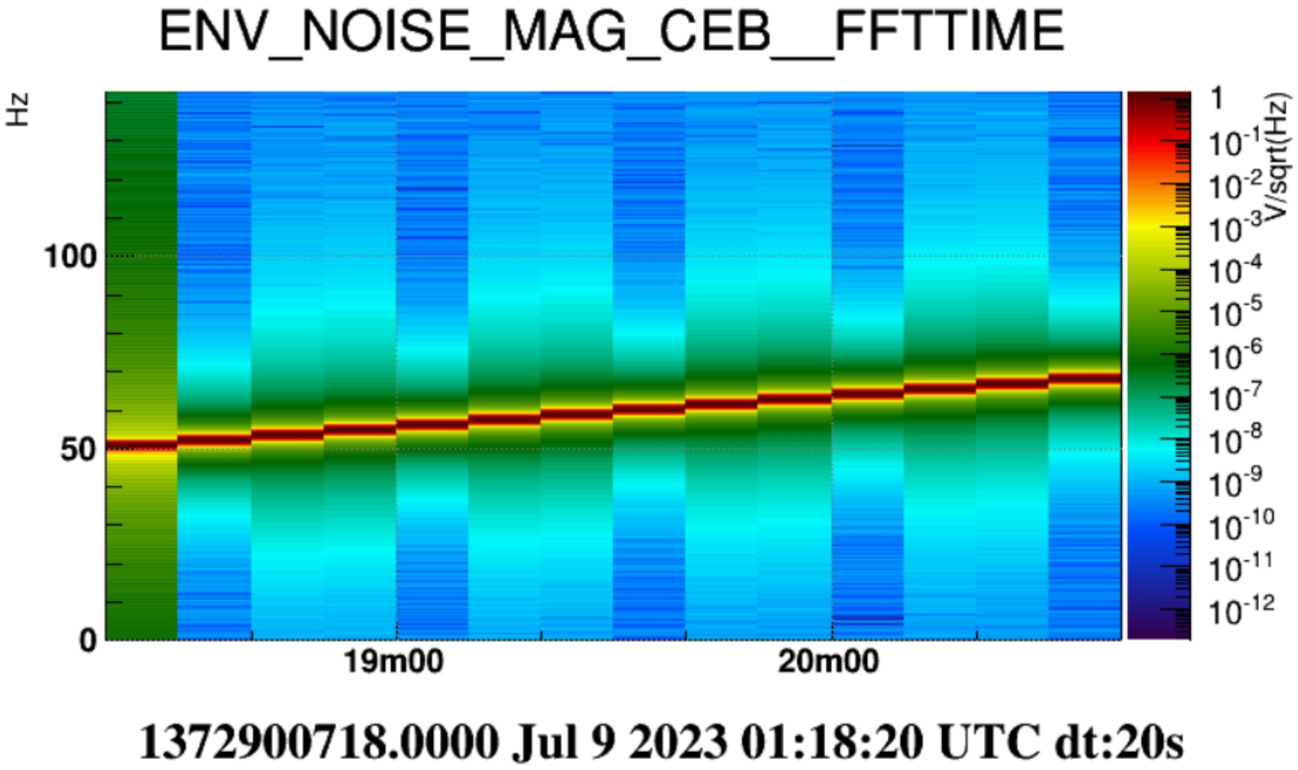


Figure 12. Magnetic sweep injections from $f = 50Hz$ to $f = 70Hz$, with a duration of 100s and amplitude of 2V. Image obtained using dataDisplay.

Transfer Function Formula

Using the formulas from https://arxiv.org/abs/2101.09935 :

$$TF(f) = \sqrt{\frac{Y_{inj}^2(f) - Y_{bkg}^2(f)}{X_{inj}^2(f) - X_{bkg}^2(f)}}$$

$$TF_{UL}(f) = \frac{Y_{bkg}(f)}{\sqrt{X_{inj}^2(f) - X_{bkg}^2(f)}}$$

Upper Limit when $\frac{X_{inj}}{X_{bkg}} > 10$ and $\frac{Y_{inj}}{Y_{bkg}} < 2.$

Measured value when $\frac{X_{inj}}{X_{bkg}} > 10$ and $\frac{Y_{inj}}{Y_{bkg}} > 2.$

X_{inj} - value of the witness sensor during injection
X_{bkg} - value of background at witness sensor
Y_{inj} - value of h_{rec} during injection
Y_{bkg} - value of h_{rec} background

Injections Performed Before O4a

CEB	NEB	WEB
April 4th - 20 logarithmically spaced **lines** between **10.5Hz** and **985.5Hz**, lines 10.5-90Hz were injected for 300s, lines 114-985.5kHz were injected for 900s, all at about the **maximum current** in the coil (amplitude in volts 9V). The injection was performed **twice.**	**April 21st** - First injection in NEB: **20** logarithmically spaced **lines** between **10.5Hz** and **985.5Hz**, all injected for 600s, varying amplitude for the first 10 (increasing from 1.1V to 8.7V), constant 9V amplitude for the remaining 10.	**April 21st** - First injection in WEB: **20** logarithmically spaced **lines** between **10.5Hz** and **985.5Hz**, all injected for 600s, varying amplitude for the first 10 (increasing from 1.1V to 8.7V), constant 9V amplitude for the remaining 10.
April 18th - Third injection in CEB: 20 logarithmically spaced **lines** between **10.5Hz** and **985.5Hz**, lines 10.5-35Hz were injected for 300s, line 44Hz was injected for 900s, lines 55-90Hz were injected for 300s, line 114Hz was injected for 1800s, lines 145-985.5Hz were injected for 900 s, all at about the **maximum current** in the coil (amplitude in volts 9V)	**May 2nd** - Second injection in NEB: **20** logarithmically spaced **lines** between **10.5Hz** and **985.5Hz**, all injected for 600s, varying amplitude for the first 10 (increasing from 1.1V to 8.7V), constant 9V amplitude for the remaining 10.	**May 2nd** - Second injection in WEB: **20** logarithmically spaced **lines** between **10.5Hz** and **985.5Hz**, all injected for 600s, varying amplitude for the first 10 (increasing from 1.1V to 8.7V), constant 9V amplitude for the remaining 10 – Interferometer UNLOCKED during line 14 injection.
April 17th – **Sweep** injection between 1Hz and 1000Hz, with amplitude of 9V and duration of 1800s.	**April 17th** – **Sweep** injections between 8Hz and 80Hz, with amplitude of 1V and duration of 300s; between 40Hz and 100Hz, with amplitude of 2V and duration of 300s; 70Hz and 1000Hz, with amplitude of 4V and duration of 600s.	**April 17th** – **Sweep** injections between 8Hz and 80Hz, with amplitude of 1V and duration of 300s; between 40Hz and 100Hz, with amplitude of 2V and duration of 300s; 70Hz and 1000Hz, with amplitude of 4V and duration of 600s

Injections Performed Before O4b

CEB	NEB	WEB
December 30th - Lines at frequencies 2.5Hz, 3.5Hz, 4.5Hz, 5.6Hz, 6.5Hz, 7.5Hz, 9.0Hz, 10.6Hz (each with a duration of 900s), 12.0Hz, 13.6Hz, 15.0Hz, 19.0Hz, 22.0Hz, 24.0Hz (each for 600s), with amplitudes varying from 6V to 9V.	**December 30th - Lines** at frequencies 2.5Hz, 3.5Hz, 4.5Hz, 5.6Hz, 6.5Hz, 7.5Hz, 9.0Hz, 10.6Hz (each with a duration of 900s), 12.0Hz, 13.6Hz, 15.0Hz, 19.0Hz, 22.0Hz, 24.0Hz (each for 600s), with amplitudes varying from 0.7V to 3V.	**December 30th - Lines** at frequencies 2.5Hz, 3.5Hz, 4.5Hz, 5.6Hz, 6.5Hz, 7.5Hz, 9.0Hz, 10.6Hz (each with a duration of 900s), 12.0Hz, 13.6Hz, 15.0Hz, 19.0Hz, 22.0Hz, 24.0Hz (each for 600s), with amplitudes varying from 0.7V to 3V.
December 31st – Sweep injection between 1Hz and 1000Hz, with amplitude of 9V and duration of 1800s, repeated **twice.**	**December 31st – Sweep** injections between 8Hz and 80Hz, with amplitude of 1V and duration of 300s; between 40Hz and 100Hz, with amplitude of 2V and duration of 300s; 70Hz and 1000Hz, with amplitude of 4V and duration of 600s. They were repeated **twice.**	**December 31st – Sweep** injections between 8Hz and 80Hz, with amplitude of 1V and duration of 300s; between 40Hz and 100Hz, with amplitude of 2V and duration of 300s; 70Hz and 1000Hz, with amplitude of 4V and duration of 600s. They were repeated **twice.**

Difference between CEB and NEB/WEB amplitudes: relative location of magnetometers and coil.

Preliminary Results

Observations:

- Measurements in agreement between the two different dates and between the two different buildings;
- Only upper limits at frequencies over 250 Hz;
- Proposal to add transformers to the coil’s circuit to enhance the strength of the signal at high frequencies.

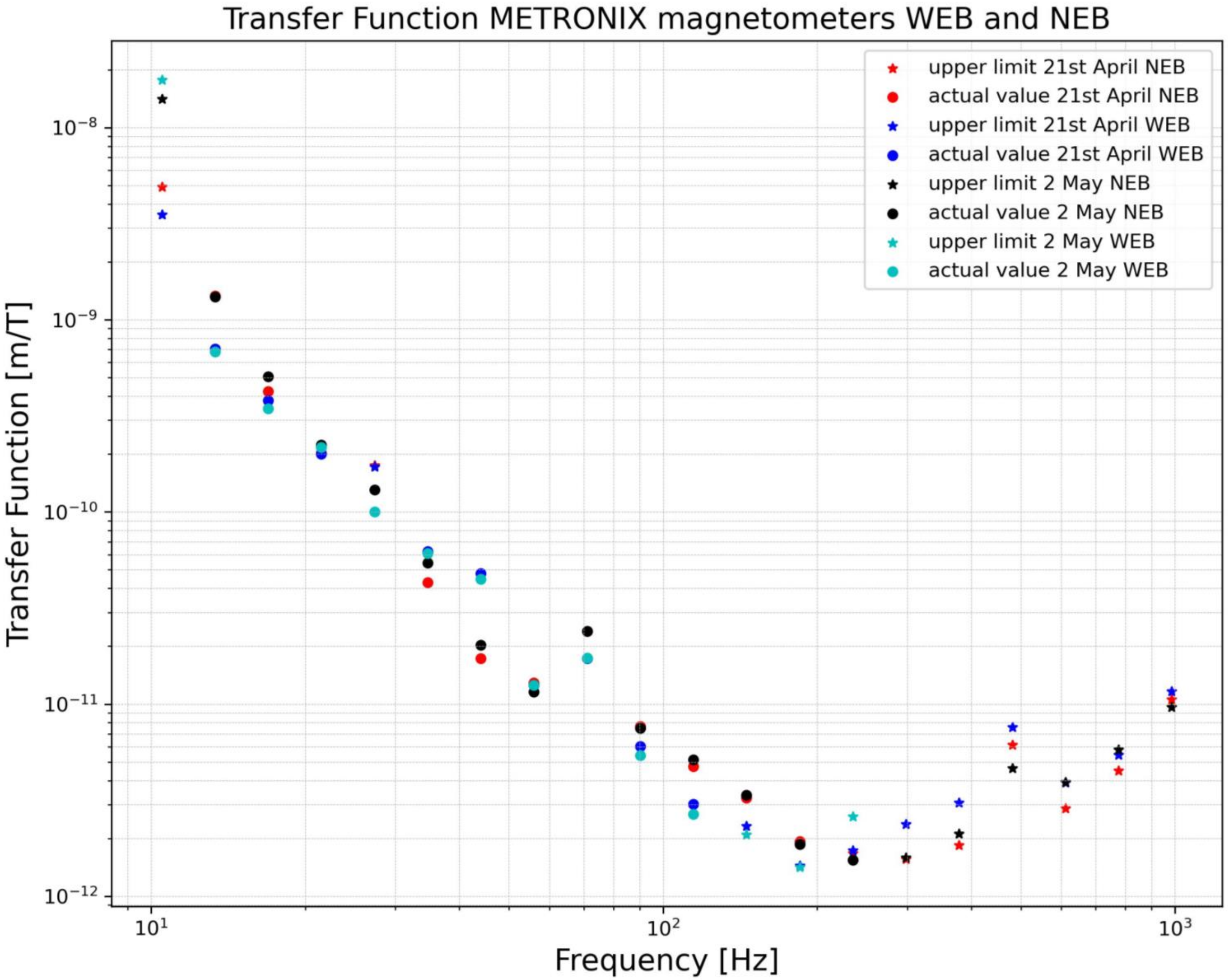


Figure 13. Transfer function values in End Buildings (NEB and WEB) using METRONIX single axial magnetometers.

Preliminary Results

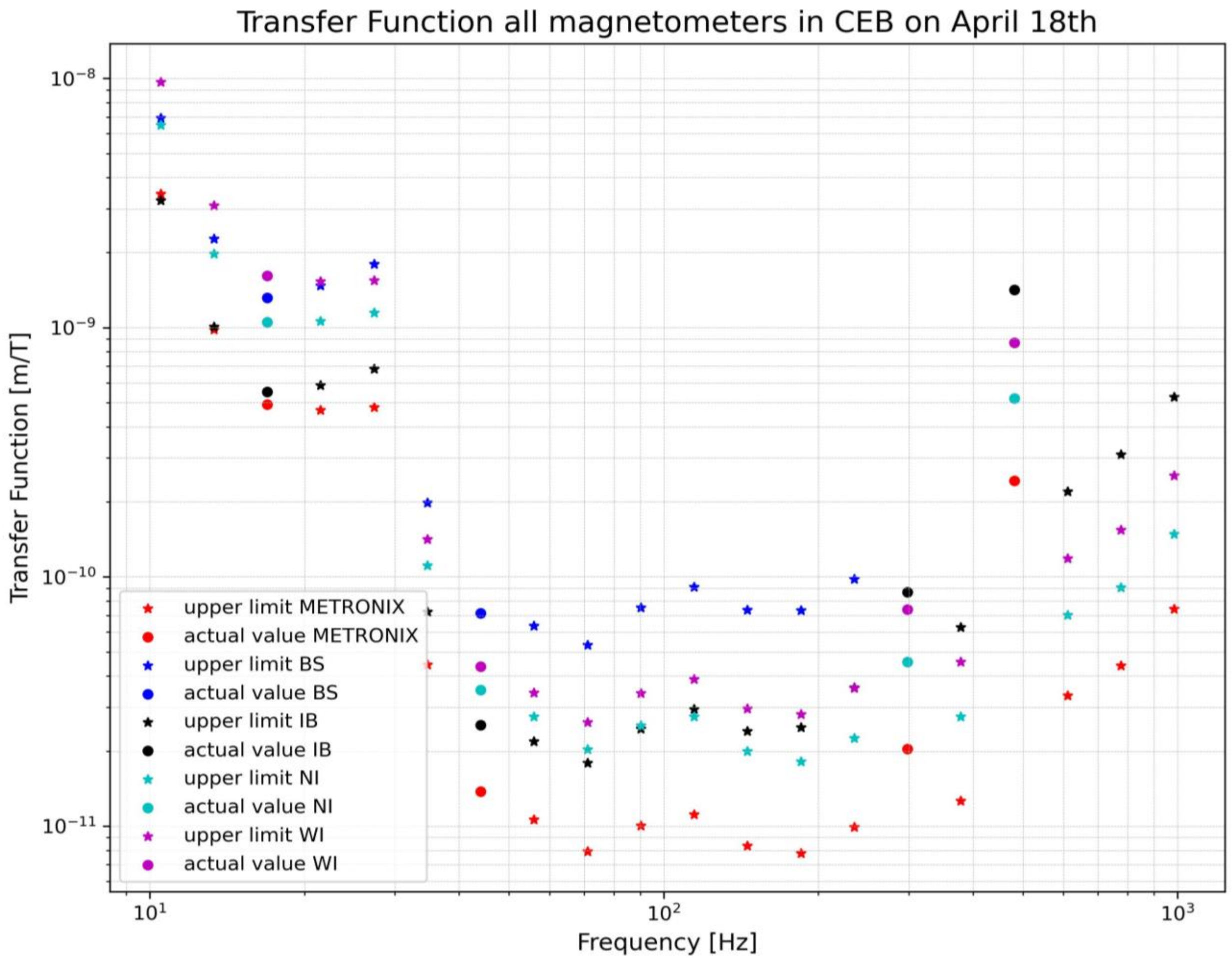


Figure 14. Transfer function values in Central Building (CEB) using all magnetometers.

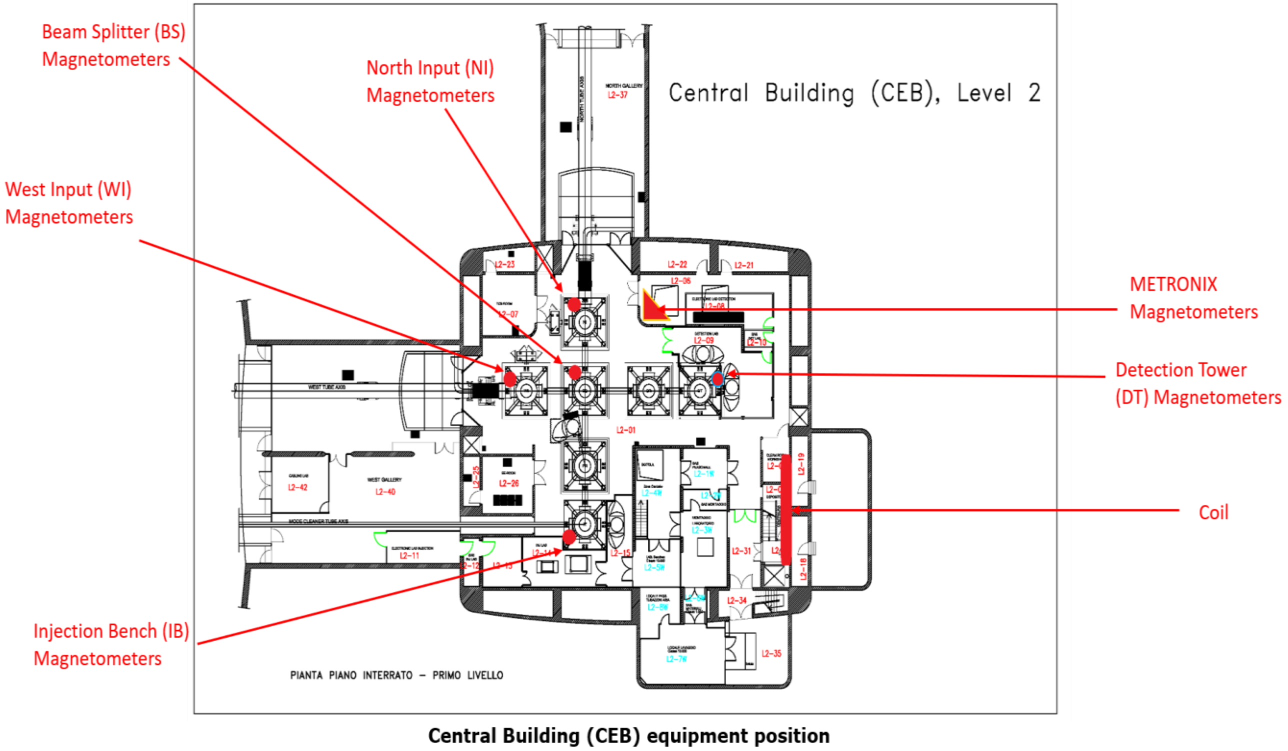


Figure 15. Magnetometers positions in CEB.

Observations:

- Variation of the transfer function not only with frequency, but also with position in the Central Building due to non uniformity of the injected magnetic field throughout CEB volume.
- Work in progress: extracting an effective coupling function by using close field injections together with the far field ones.

Preliminary Results – Lines vs Sweep

Observations:

- Sweep injection produced manually in WEB.
- Good agreement between coupling function values obtained from automatic lines injections and from manual sweep injections.
- Yellow peaks correspond to enhanced coupling of the detector at the mechanical resonances of the super attenuator.

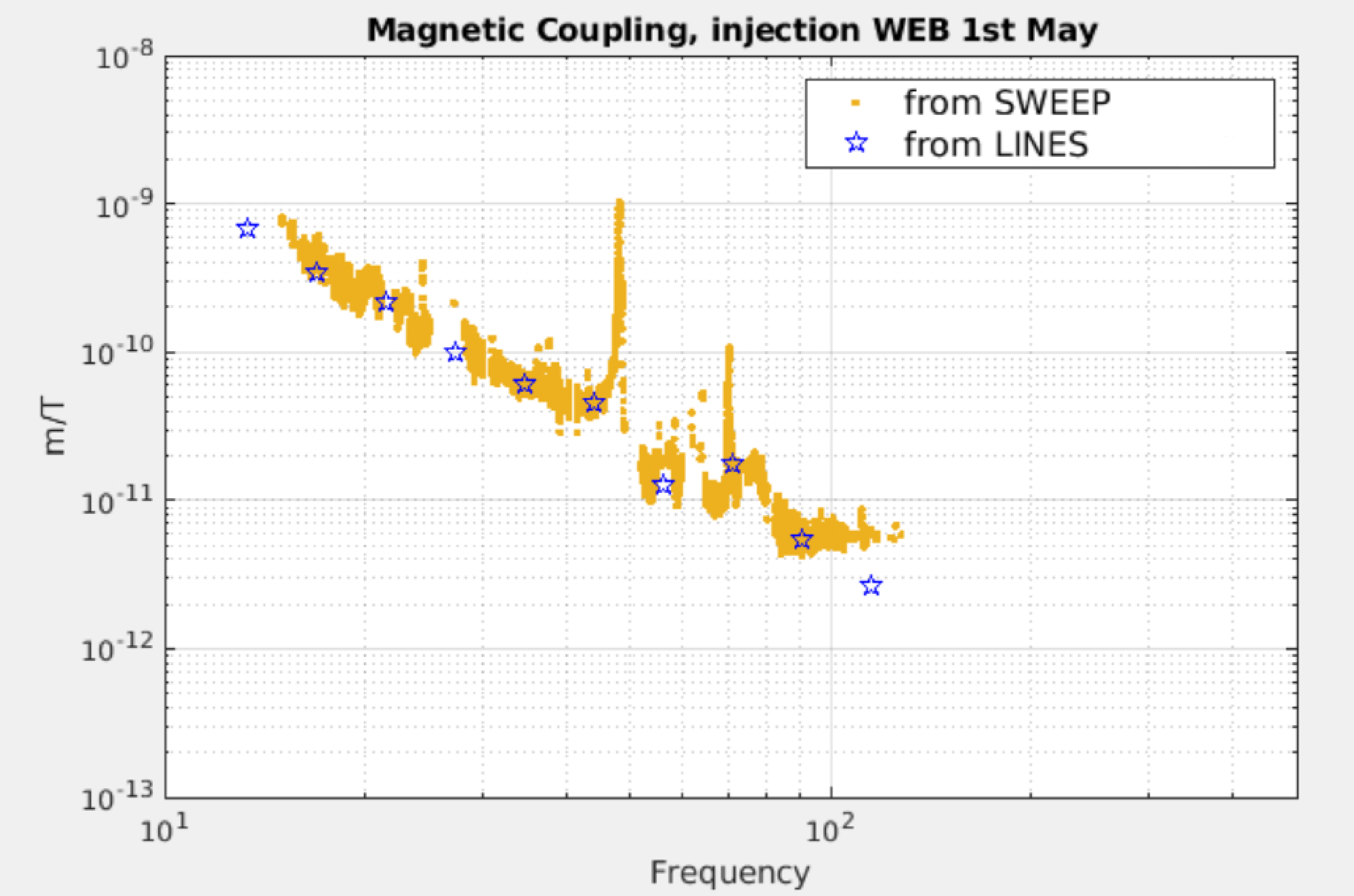
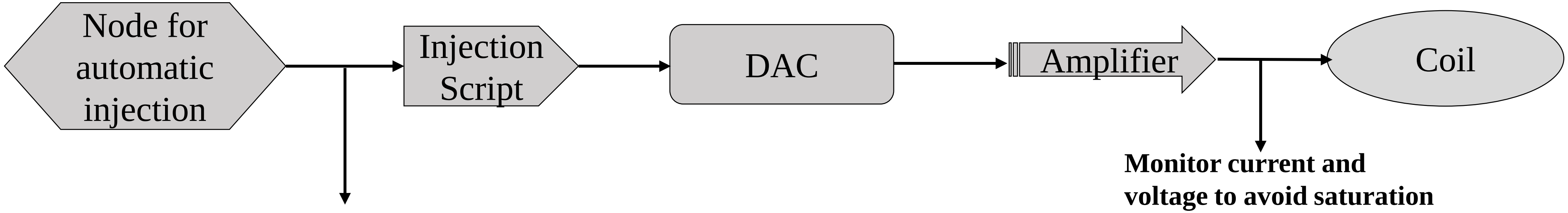


Figure 16. Sweep and lines coupling function values calculated for injections done in the same night at WEB.

Thank you!
Questions?

Extra Slides

Circuit



Injection starts when:

- ITF status = LOW_NOISE_3
- ITF mode = "Commissioning"

Sequence of magnetic injections:
- magnetic sweep in CEB, NEB, WEB;
- magnetic lines in CEB, NEB, WEB;
- acoustic colored in CEB.

Lines Injection Configuration File

```
[Main]
#Configuration file for the magnetic injection process

#DAC Channel List: NOISE_MAG_CEB, NOISE_WEB, Noise_NEB; if the injection needs to
#be repeated for a channel, the name can be added to the list as many times as
#necessary, as the program will perform the injection ONCE for each instance of
#a name
DOF = NOISE_NEB NOISE_WEB

#If you want to introduce your own frequency list change this parameter to 1
OwnFreq = 0

#If we want to introduce your own duration list change this parameter to 1
OwnDur= 1

#Separation in freq between injections, if 0 linear spacing if 1 logarithm spacing
LogSep = 1

#If we want to start from high frequency to low frequency set this parameter to 1; Boolean
HightoLow = 0

[SweepParam]
#Start and ending frequency, in Hz. Not needed if we are using our own list
Fstart = 10.5
Fstop = 985.5

#Number of points (Integer). Not needed if we are using our own freq list
Npoints = 20

#Number of averages (Integer). Not needed if we are using our own duration list
Navgs = 2

#Number of cycles (Integer). Not needed if we are using our own duration list
Ncycles = 1

#Minimum average time (float, seconds). Not needed if we are using our own duration list
Meas_time = 30
```

```
#In case of OwnFreq=1, introduce the list here, using only ONE white space as separation,
#eg: 20 52 65 87 875 (Order is not important)
FreqList = 25 50
#FreqList = 11 14 19 22 25 28 30 41 44.6 54 68 74 83 93 108
#FreqList = 25 28 30 41 44.6 54 68 74 83 93 108 127 133 139 146 152 158 165 171 177 184 190 196 20
329 336 342 348 355 361 368 368 373 378 383 388 393 398 404 409 414 419 424 429 434 440 460 466 47
598 605 611 618 624 630 637 643 649 656 662 668 675

#In case of OwnDur=1 introduce the list here using only one white space as separation.
#It has to have the same length as FreqList
DurList = 60 60
#DurList = 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600 600
#Durlist = 460 460 240 120 60 30 30 30 30 30 30 30 30 30 30
#Durlist = 30 30 30 30 30 30 30 30 30 30 30 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60
60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60

[FreqsAmp]
#Frequencies and amplitudes to use as reference for the interpolation of calculating
#amplitudes at every frequency
#use only ONE white space as separation eg: 20 30 50 100 500.
Freq= 10 33 45 70 100 1000
#Freq= 11 25 41 120 213 413
#If only one element is introduced in Amp then it will be considered the same for all frequencies
#Amp= 0.9 0.81 0.72 0.54 0.27
#Amp= 0.45 0.4 0.36 0.26 0.15
Amp= 1 3.5 5 8 9 9
#Amp= 0.055 0.05 0.046 0.036 0.020
#Amp= 0.55 0.55 0.5 0.46 0.36 0.20

[Output]
#Path to save the output file eg: Documents/Output/
Path = /virgoData/NoiseInjections/MagneticInjectionsO4/output/

[Quiet]
#Duration of quiet time channel sampling. The program waits for this amount of time before startin
#This will be needed to compute the transfer function.
Quiet_length = 300
```

Output File

- Text file with the name: MagneticLine_*channel used*-*start time*.txt
  - E.g. MagneticLine_NOISE_MAG_CEB-1364588720.txt

```
QUIET_TIME_START QUIET_DURATION INJECTION_TYPE CHANNEL
1364588720 300 LINE NOISE_MAG_CEB
START_TIME DURATION FREQUENCY AMPLITUDE
1364589034 300 10.5 9
1364589340 300 13.3353 9
1364589646 300 16.9363 9
1364589952 300 21.5096 9
1364590258 300 27.3178 9
1364590564 300 34.6944 9
1364590870 300 44.063 9
1364591176 300 55.9613 9
1364591482 300 71.0725 9
1364591788 300 90.2643 9
1364592094 900 114.638 9
1364593000 900 145.594 9
1364593906 900 184.909 9
1364594812 900 234.84 9
1364595718 900 298.254 9
1364596624 900 378.792 9
1364597530 900 481.077 9
1364598436 900 610.982 9
1364599342 900 775.966 9
1364600248 900 985.5 9
```

Colored Noise Injection Configuration File

```
[Main]
#Configuration file for the magnetic colored noise injection process

#DAC Channel List: NOISE_MAG_CEB, NOISE_WEB, Noise_NEB; if the injection needs to
#be repeated for a channel, the name can be added to the list as many times as
#necessary, as the program will perform the injection ONCE for each instance of
#a name
DOF = NOISE_MAG_CEB

#If you want to introduce your own central frequency list, change this
#parameter to 1. The frequency list MUST be a subset of the frequencies for
#which filters have been defined in ENVnoise_Filters config
OwnFreq = 1

#If we want to introduce your own duration list, change this parameter to 1.
OwnDur = 1

#Separation in freq between injections, if 0 linear spacing if 1 logarithm
#spacing.
LogSep = 0

#If we want to start from high frequency to low frequency set this parameter
#to 1. Boolean
HightoLow = 0

[SweepParam]
#Start and ending frequency, in Hz. Not needed if we are using our own list
Fstart = 100
Fstop = 250

#Number of points (Integer). Not needed if we are using our own freq list
Npoints = 40

#Number of averages (Integer). Not needed if we are using our own duration list
Navgs = 2

#Number of cycles (Integer). Not needed if we are using our own duration list
Ncycles = 1

#Minimum average time (float, seconds). Not needed if we are using our own
#duration list:
Meas_time = 30
```

```
#In case of OwnFreq=1 introduce the list here, using only ONE white space
#as separation, eg: 20 52 65 87 875 (Order is not important)
FreqList = 10 100 200 500
#FreqList = 11 14 19 22 25 28 30 41 44.6 54 68 74 83 93 108
#FreqList = 25 28 30 41 44.6 54 68 74 83 93 108 127 133 139 146 152 158 165 171 177 184 190 196
361 368 368 373 378 383 388 393 398 404 409 414 419 424 429 434 440 460 466 472 478 485 491 497
662 668 675

#In case of OwnDur=1 introduce the list here using only one white space as
#separation. It has to have the same length as FreqList
DurList = 60 60 60 60
#Durlist = 460 460 240 120 60 30 30 30 30 30 30 30 30 30 30
#Durlist = 30 30 30 30 30 30 30 30 30 30 30 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 6
60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60 60

#Bandwidth desired for each filter. If only one value is given, this value will
#be used for all filters; otherwise the number of bandwidths needs to be equal
#to the number of frequencies
WidthList = 5 25 50 50


[FreqsAmp]
#Frequencies and amplitudes to use as reference for the interpolation of calculating amplitudes
#use only ONE white space as separation eg: 20 30 50 100 500.
Freq= 10 500
#Freq= 11 25 41 120 213 413
#If only one element is introduced in Amp then it will be considered the same for all frequencie
#Amp= 0.9 0.81 0.72 0.54 0.27
#Amp= 0.45 0.4 0.36 0.26 0.15
Amp= 0.2
#Amp= 0.055 0.05 0.046 0.036 0.020
#Amp= 0.55 0.55 0.5 0.46 0.36 0.20

[Output]
#Path to save the output file eg: Documents/Output/
Path = /virgoData/NoiseInjections/MagneticInjectionsO4/output/

[Quiet]
#Duration of quiet time channel sampling. The program waits for this amount of time before start
#This will be needed to compute the transfer function.
Quiet_length = 15
```

Sweep Injection Configuration File

```
[Main]
#Configuration file for the magnetic injection process

#DAC Channel List: NOISE_MAG_CEB, NOISE_WEB, Noise_NEB; if the injection needs to
#be repeated for a channel, the name can be added to the list as many times as
#necessary, as the program will perform the injection ONCE for each instance of
#a name
DOF = NOISE_MAG_CEB

[SweepParam]
#Start and ending frequency, in Hz.
Fstart = 10
Fstop = 20
#Duration of sweep
Duration = 100
#Amplitude of sweep
Amplitude = 2.0

[Output]
#Path to save the output file eg: Documents/Output/
Path = /virgoData/NoiseInjections/MagneticInjectionsO4/output/

[Quiet]
#Duration of quiet time channel sampling. The program waits for this amount of time before starting the injections.
#This will be needed to compute the transfer function.
Quiet_length = 15
```

Transfer Function Calculations

Welch’s power spectral density estimate parameters:

- Width around the frequency peak of $\pm$0.025 Hz for RMS calculations;
- Sampling frequency 2000 (channels have been decimated by 10 compared to the usual sampling frequency);
- FFT time window 100s – the larger the frequency width, the stronger the signal;
- Hann windows;
- Overlap between windows 50%.

Preliminary Results

Observations:

- Decreasing trend for frequencies between 10Hz and 100Hz, increasing trend for higher frequencies;
- Coupling reduced for 18th April;
- Outliers around 40-50Hz – further investigation needed.

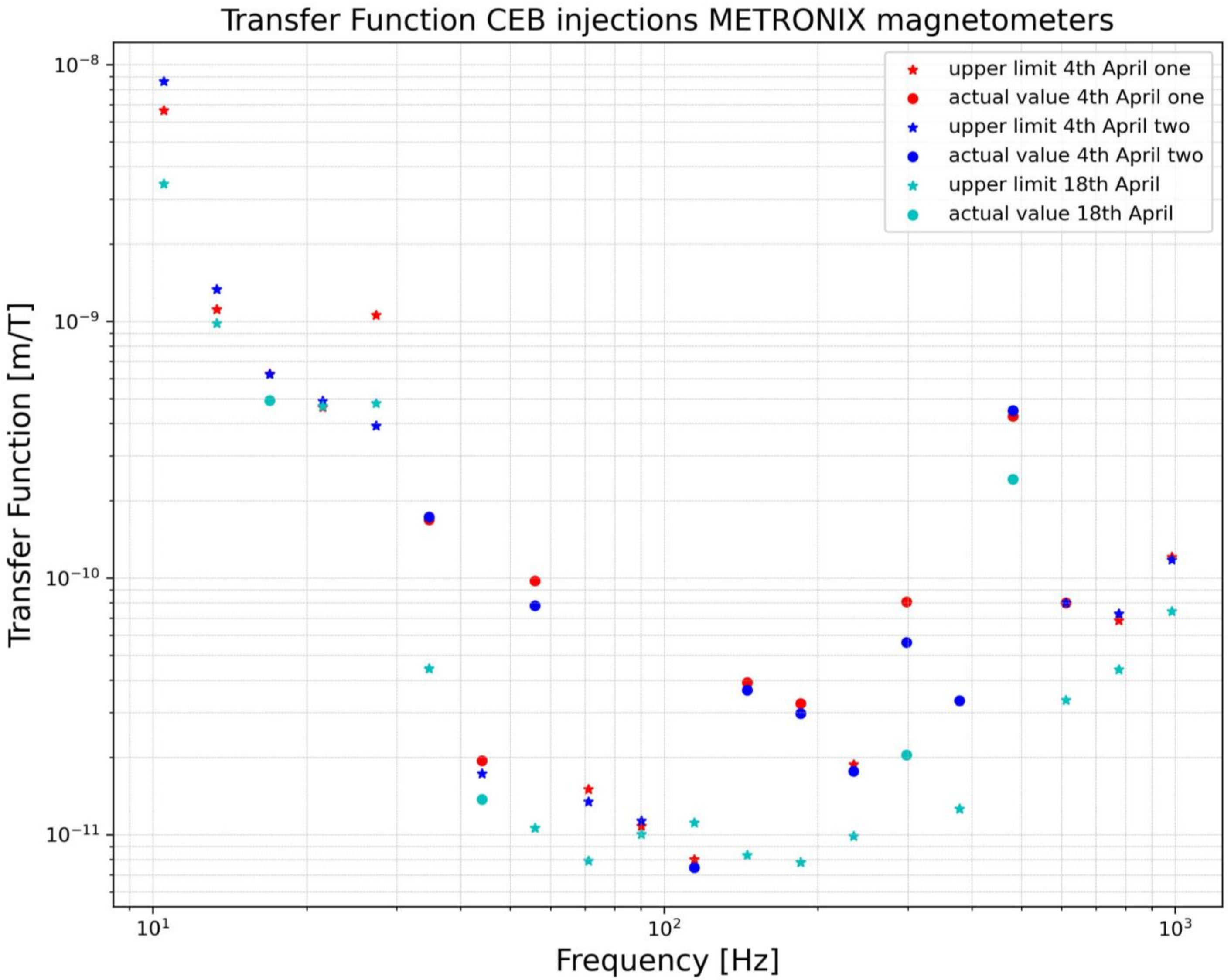


Figure 15. Transfer function values in Central Building (CEB) using METRONIX single axial magnetometers.

Preliminary Results - December Injections

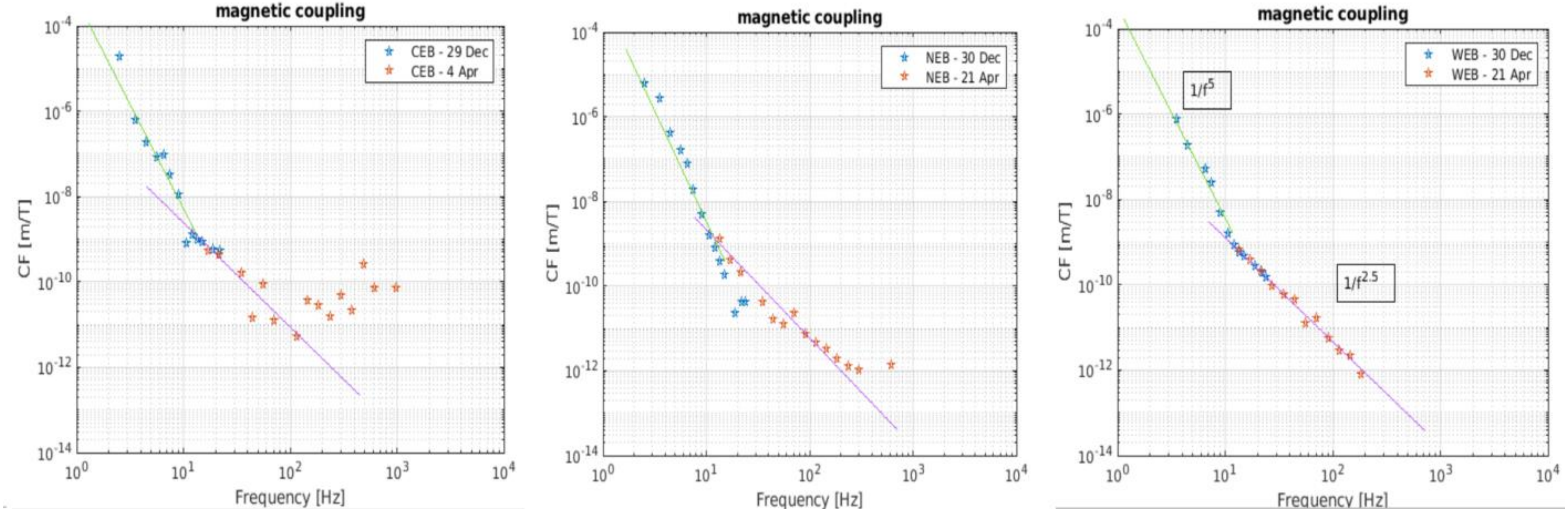


Figure 20. Magnetic coupling function calculated from line injections done in April 2023 vs. December 2023.

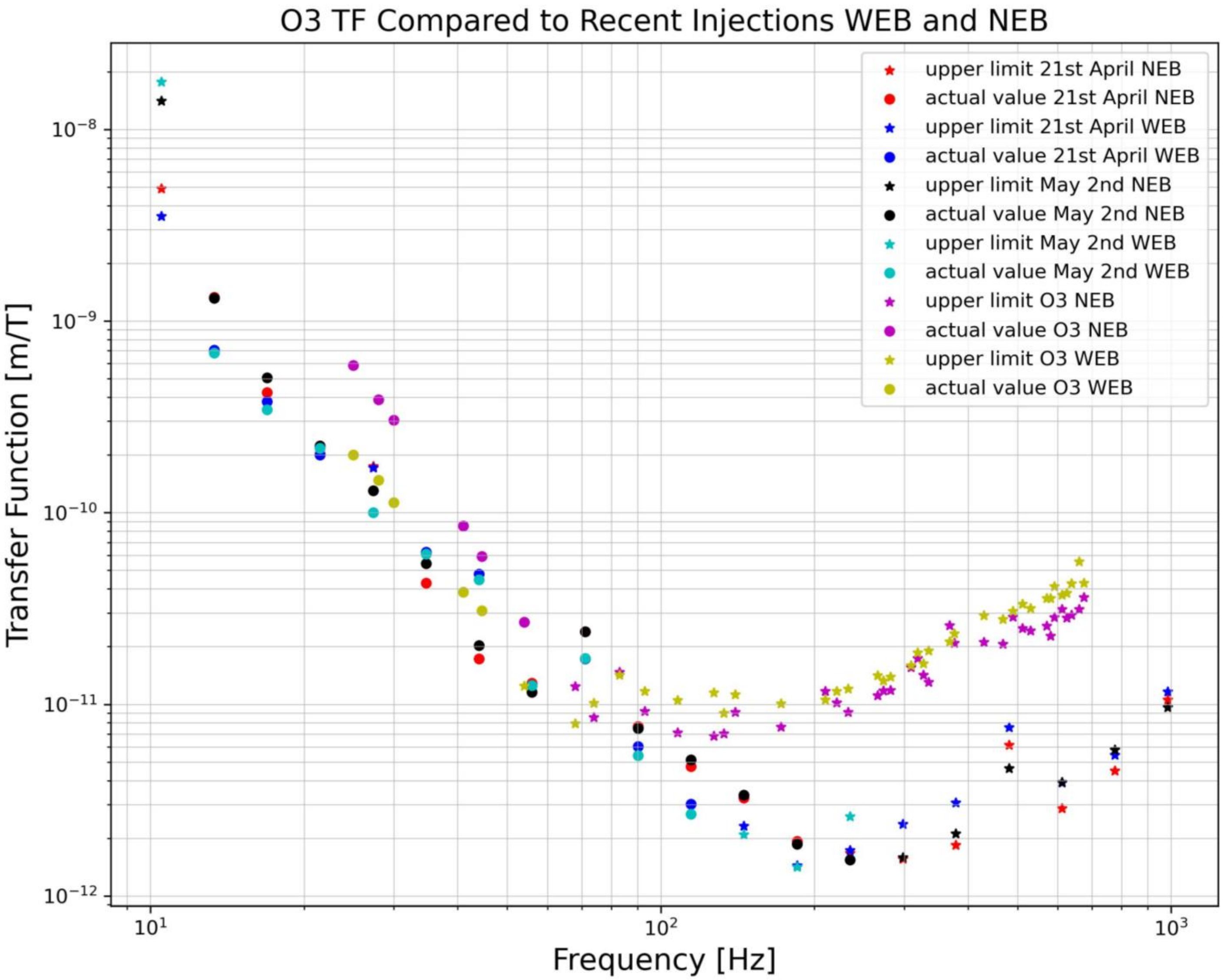


Figure 18. Transfer function values in NEB and WEB, O3 compared to recent injections. O3 data from https://doi.org/10.3390/galaxies8040082.

Preliminary Results – O3 comparison

Observations:

- Similar shape
- Approximately the same current location as O3 measurements, a more fair comparison of values
- More measured values now at low and high frequencies compared to O3

Preliminary Results – O3 comparison

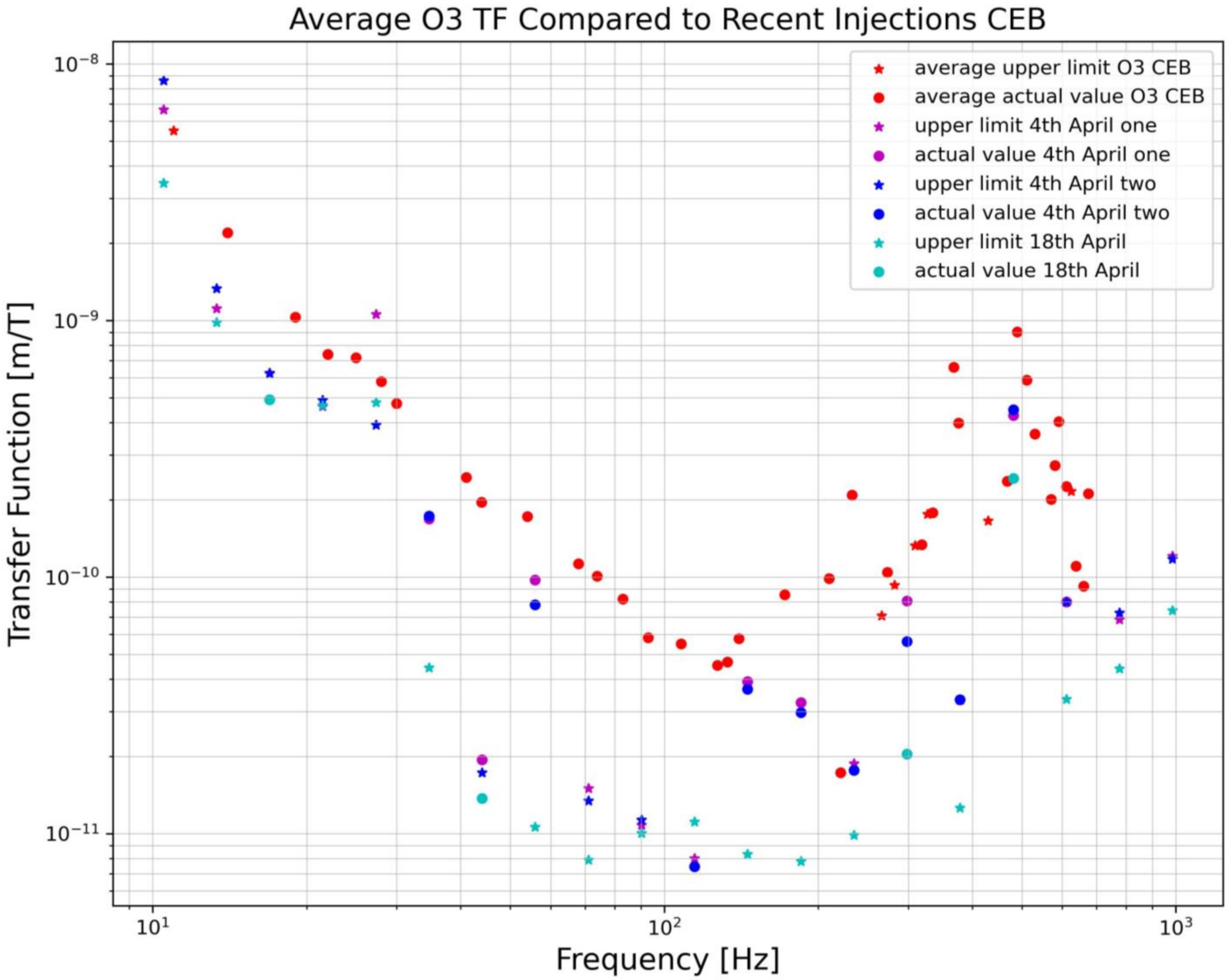


Figure 19. Transfer function values in CEB, O3 (red) compared to recent injections. O3 data from https://doi.org/10.3390/galaxies8040082.

Observations:

- Similar shape
- The coupling values measured during O3 cannot be directly compared to the ones obtained from these injections, as now we use a different coil at different location and with different orientation of the coil than O3