Atmospheric Newtonian Noise (NN): attenuation & cancellation strategies

D. Fiorucci[1], J. Harms[1], F. Paoletti[2], I. Fiori[3], M. Falxa[4],
M. Barsuglia[5], F. Gibert[6], F. Badaracco[1]

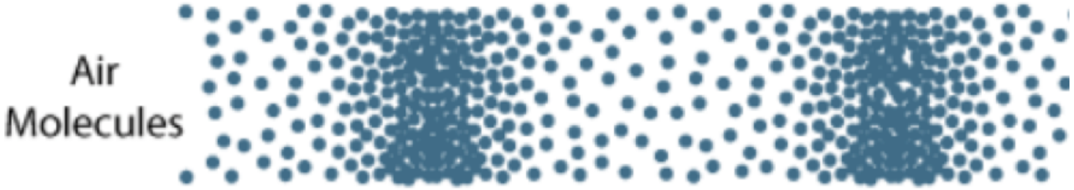
1. GSSI (Gran Sasso Science Institute)
2. INFN-Pisa
3. EGO (European Gravitational Observatory)
4. Université Paris Diderot
5. APC (Astroparticule et Cosmologie)
6. LMD (Laboratoire de Météorologie Dynamique)

GWADW

20/05/2019

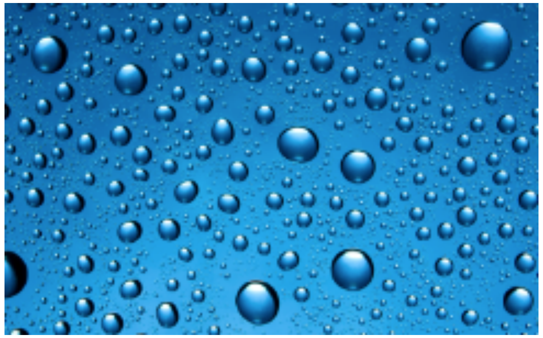
Atmospheric Newtonian Noise (NN)

Sources of atmospheric density perturbations[1]



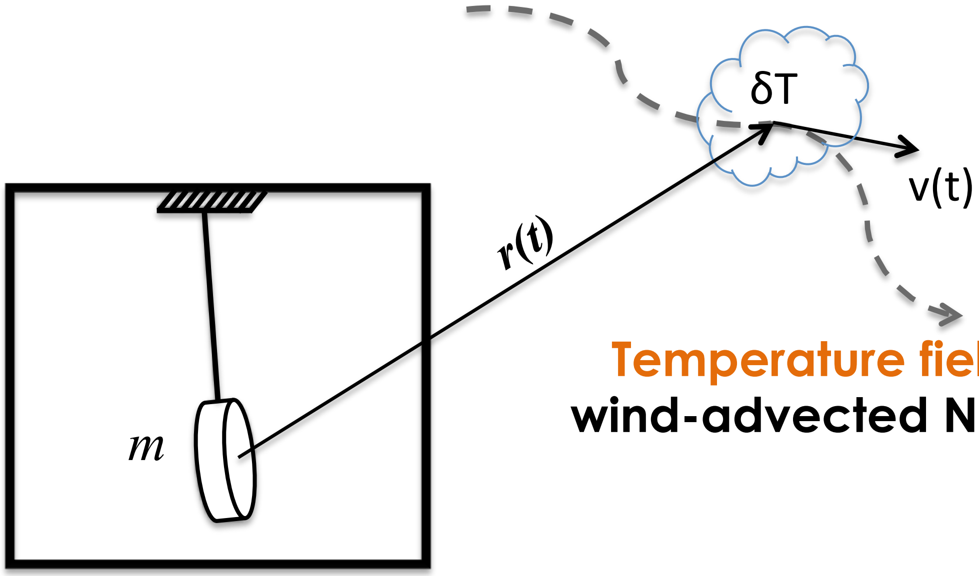
Pressure fields

e.g. infrasound waves producing infrasound NN [2, 3, 4]



Air humidity field

wind-advected NN [3]

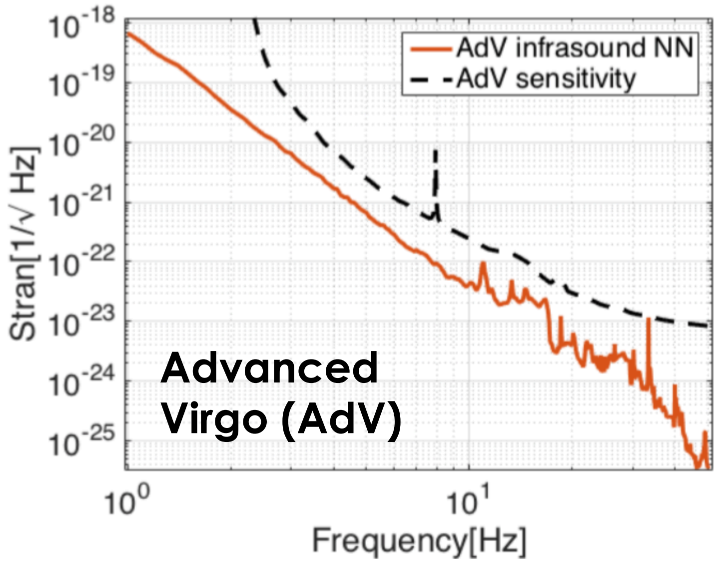


Temperature fields

wind-advected NN [2, 3]

[1] Stull, Meteorology [2] Saulson Phys. Rev. D **30**, 732, [3] J. Harms Terrestrial Gravity Fluctuations,
[4] Creighton CQG. **25** (2008) 125011, C.Cafaro, S. A. Ali arXiv:0906.4844 [gr-qc]

Impact of atmospheric NN on gravitational wave detectors



*

Infrasound NN (INN)

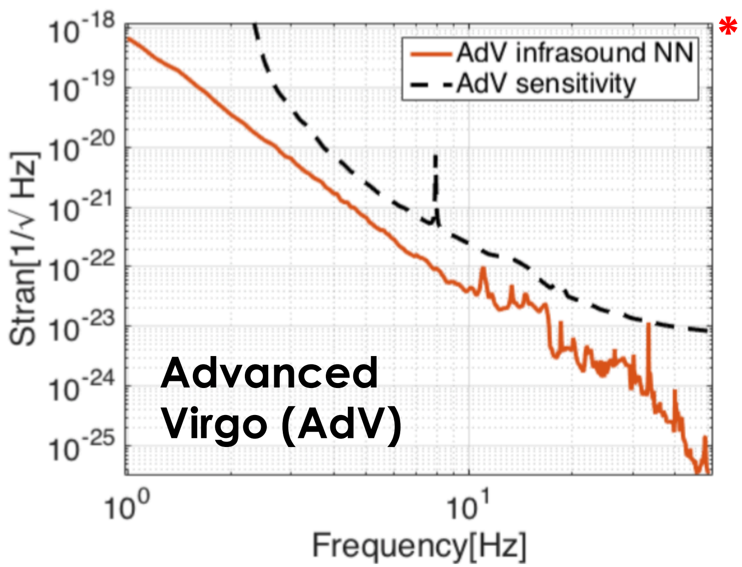
Current laser intererometers: INN can be significant (**above ~ 10 Hz**) due to building acoustic noise*

3G laser intererometers: INN can be significant (**above ~ 1 Hz**) depending on detector depth and building acoustic noise *

Low frequency detectors: INN expected to be higher than seismic NN **below ~ 1 Hz** **

* D.Fiorucci et al. PRD 97, 062003 (2018)
** J. Harms et al. PRD 88 (2013) no.12, 122003

Impact of atmospheric NN on gravitational wave detectors



Infrasound NN (INN)

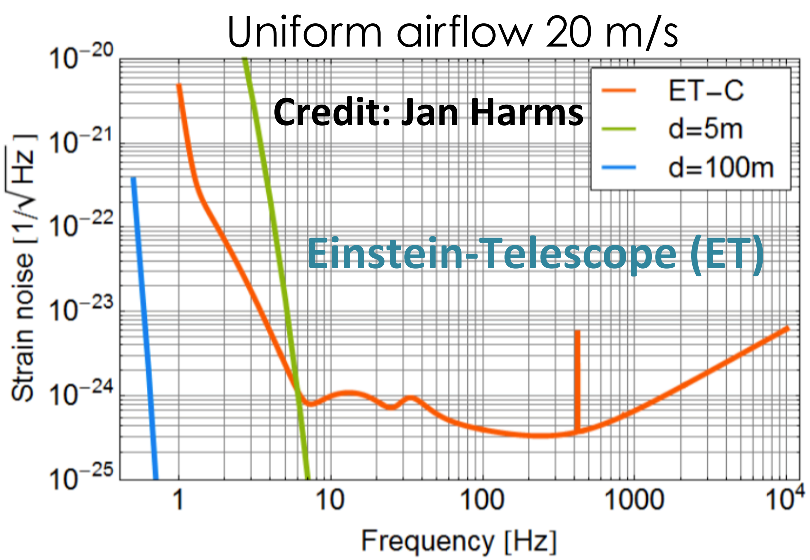
Current laser intererometers: INN can be significant (**above ~ 10 Hz**) due to building acoustic noise*

3G laser intererometers: INN can be significant (**above ~ 1 Hz**) depending on detector depth and building acoustic noise *

Low frequency detectors: INN expected to be higher than seismic NN **below ~ 1 Hz** **

Wind advected temperature fluctuation NN

To be considered for **3G laser interferometers and low frequency detectors** at the Earth surface **(below ~ 10 Hz)**



Atmospheric NN : attenuation & cancellation strategies

Infrasound NN

- Study of the detector building acoustic properties for attenuation and coherent cancellation of infrasound NN

- Coherent Infrasound NN suppression: sensor array optimization

Atmospheric NN

- LIDAR technologies for tropospheric sensing

- Coherent NN suppression with LIDAR: infrasound NN case

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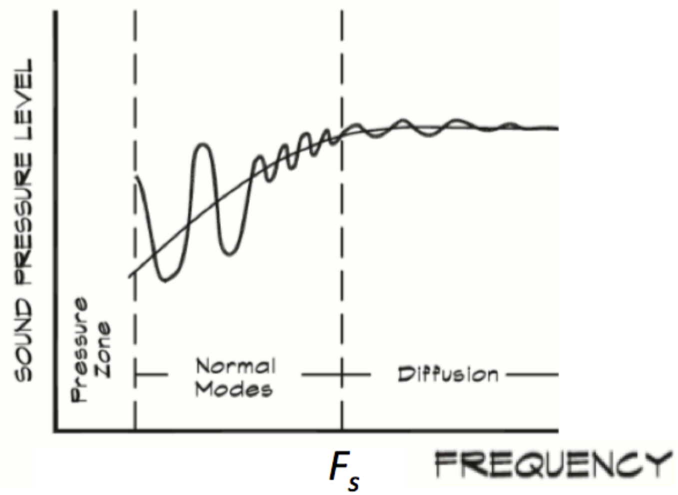
Acoustic characterization of the AdV buildings

Normal modes
➔ uneven sound level at different positions and frequencies



$$*F_s = 2000\sqrt{\frac{T_{60}}{V}}$$

Schroeder frequency

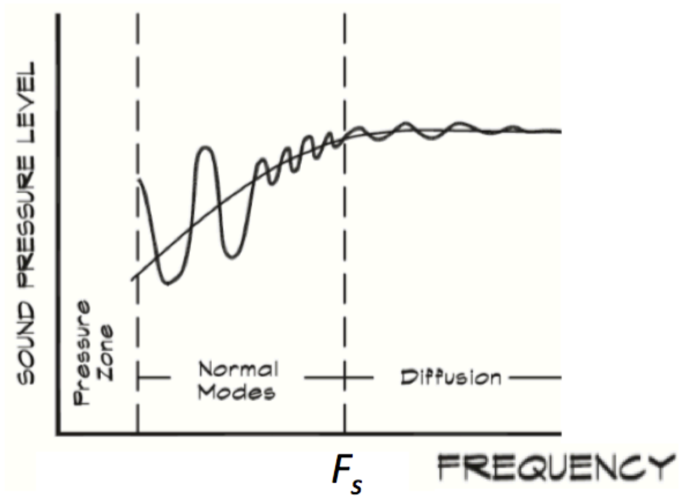
Reverberation time

Room volume

* Schroeder, The Journal of the Acoustic society of america, Vol.34 N° 1, 1962

Acoustic characterization of the AdV buildings

Normal modes
➔ uneven sound level at different positions and frequencies



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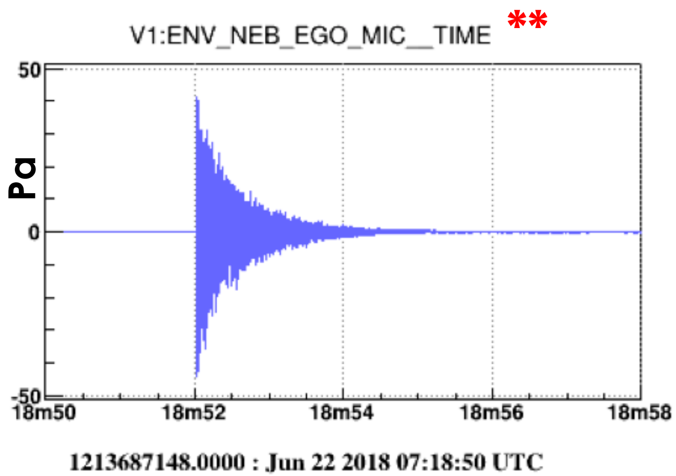


T_{60} ~ 4.5 s, V ~ 10625 m^3

F_s ~ 50 Hz

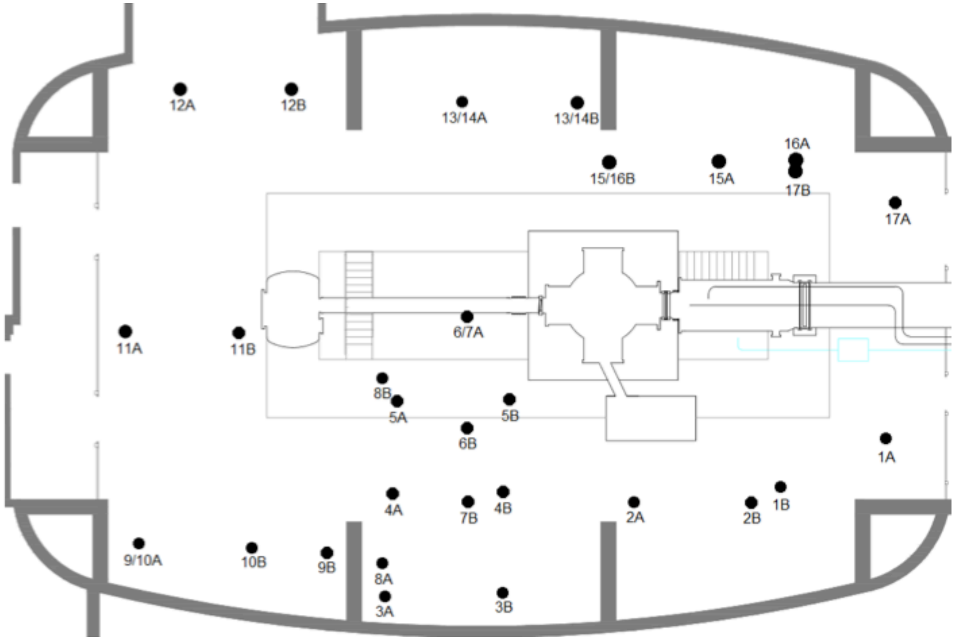
Below ~ 50 Hz acoustic building response dominated by building resonances

* Schroeder, The Journal of the Acoustic society of america, Vol.34 N° 1, 1962

** M. Falxa et al. Acoustic characterization of Advanced Virgo buildings
https://tds.virgo-gw.eu/?content=3&r=14737

Acoustic characterization of the AdV buildings

NEB measurements: not taken at the same time!



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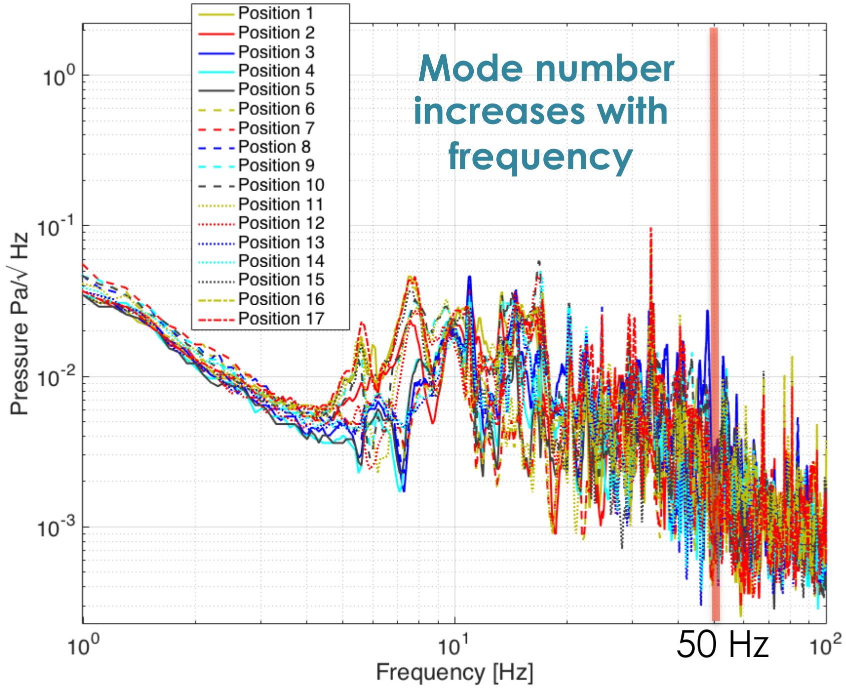

*** M. Falxa et al. Acoustic characterization of Advanced Virgo buildings**

Acoustic characterization of the AdV buildings

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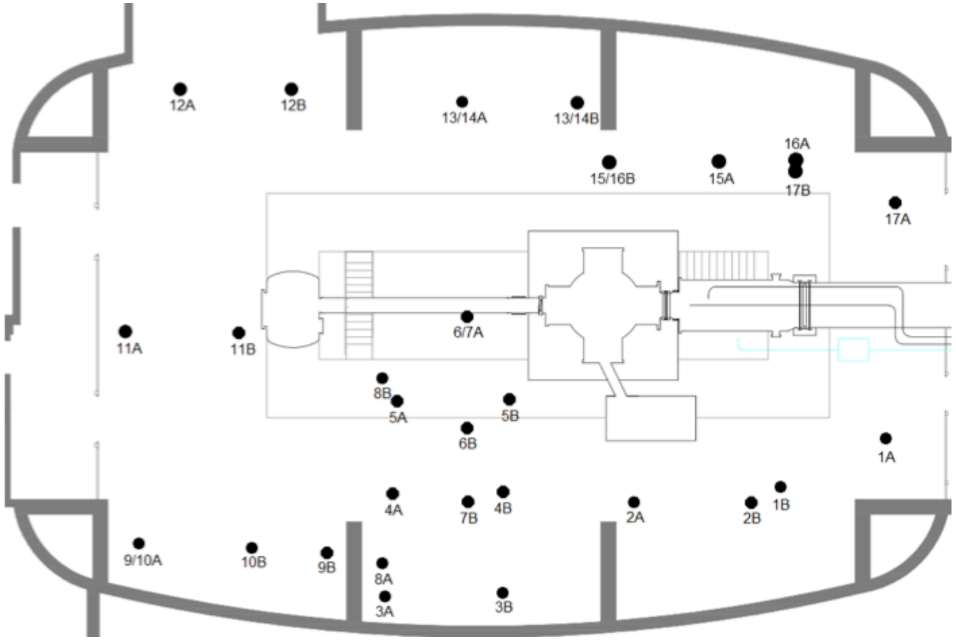

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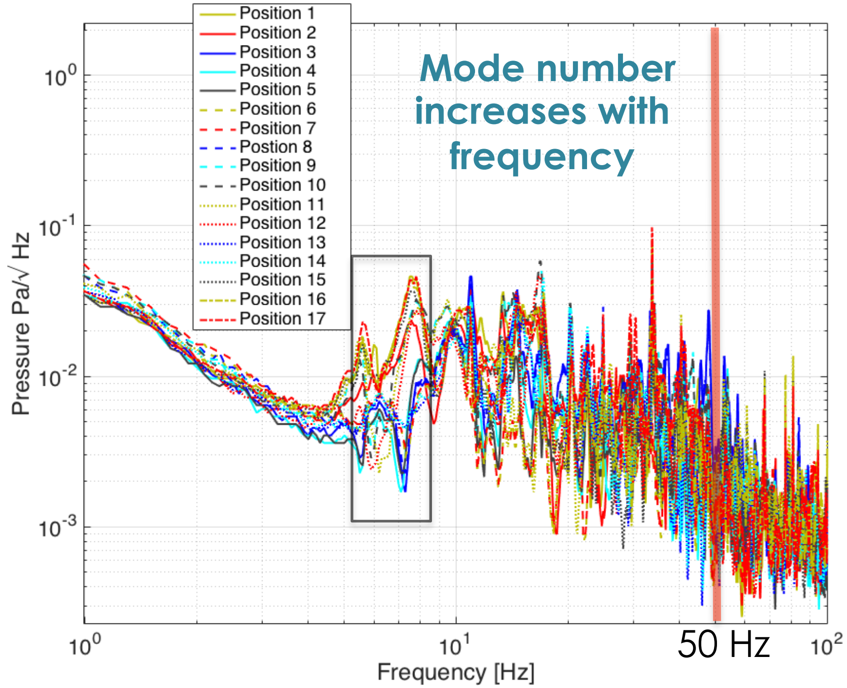
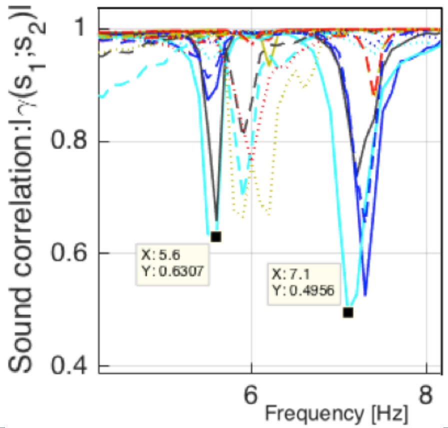
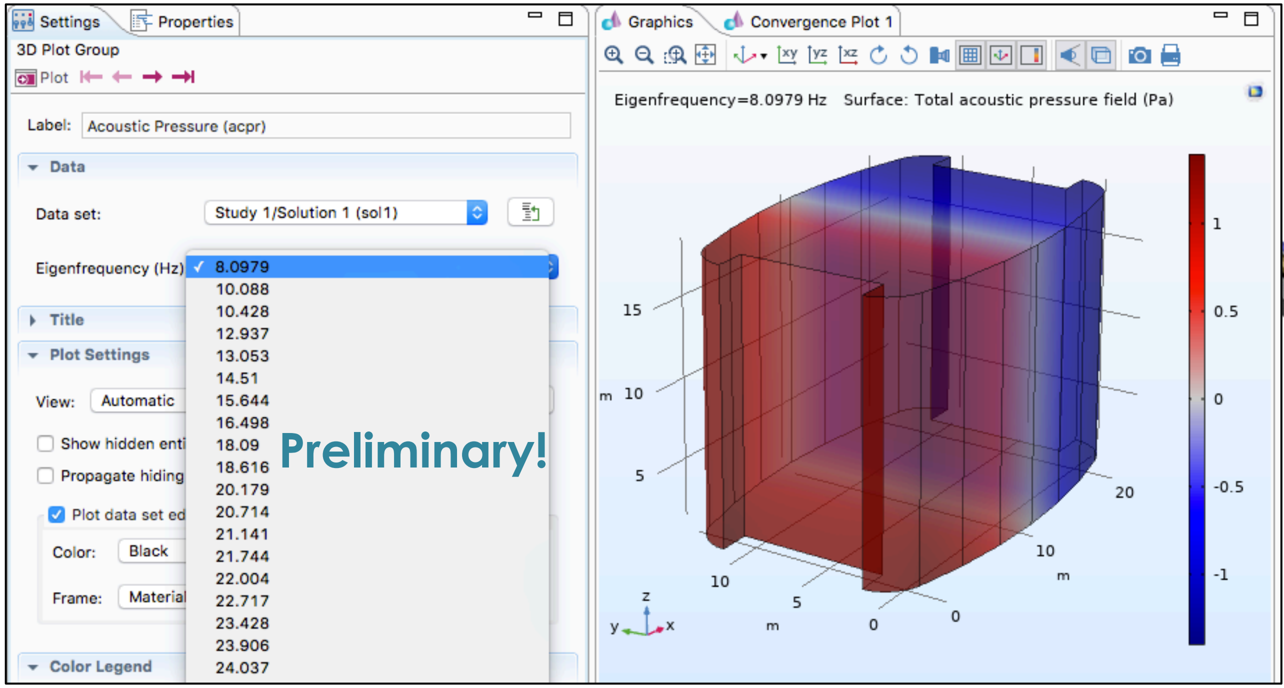
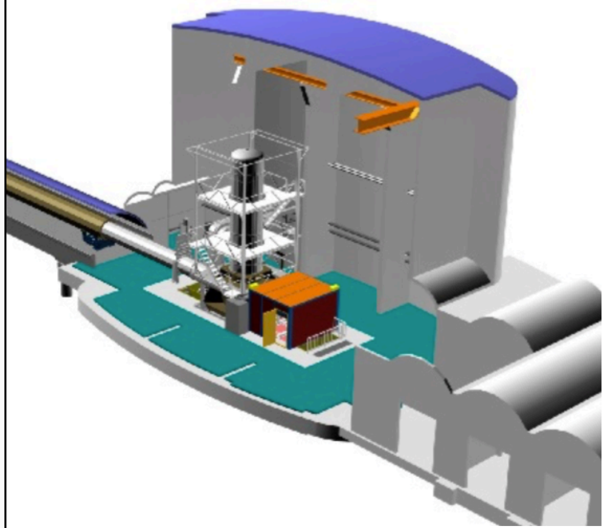


Lack of correlation at the frequencies of peaks/dips of the spectra



Acoustic characterization of the AdV buildings





FEM simulations of the NEB to find the building resonance frequencies and the corresponding pressure distributions for both passive and active mitigation of infrasound NN

Atmospheric NN : attenuation & cancellation strategies

Infrasound NN

- Study of the detector building acoustic properties for attenuation and coherent cancellation of infrasound NN
- Coherent Infrasound NN suppression: sensor array optimization

Atmospheric NN

- LIDAR technologies for tropospheric sensing
- Coherent NN suppression with LIDAR: infrasound NN case

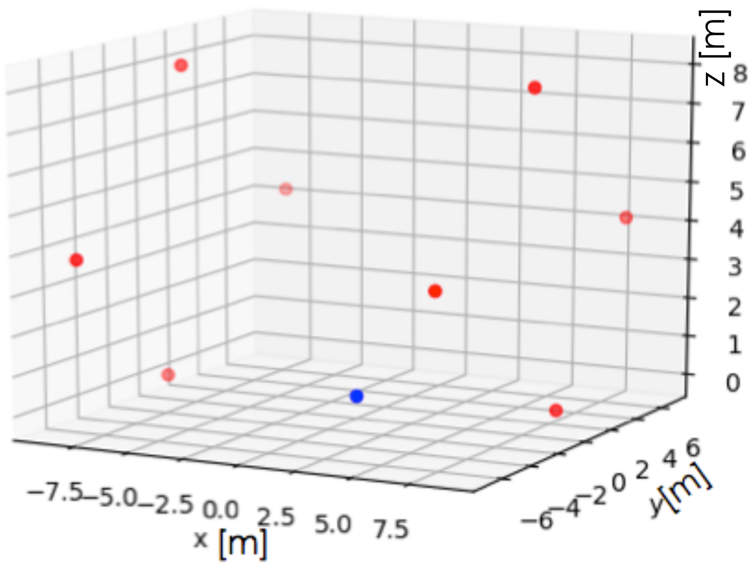
Infrasound NN : coherent noise cancellation

3D optimized array @ 10 Hz

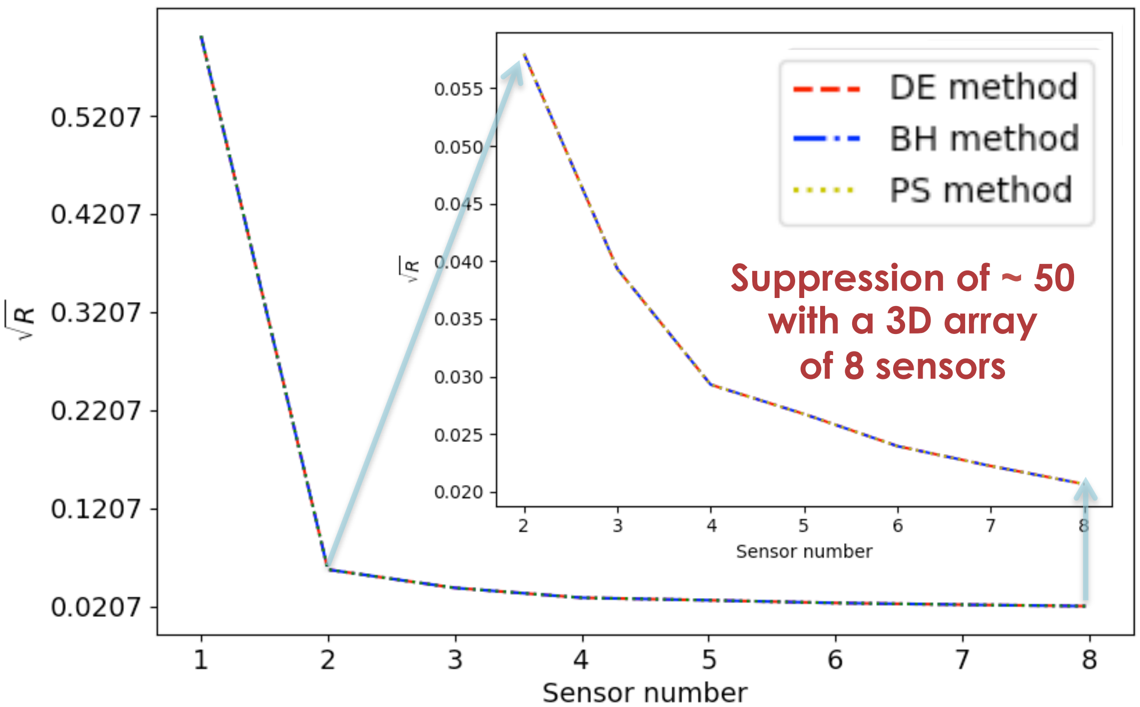
SNR 15

Suppression factor : $1/\sqrt{R(\omega)}$

$$R(\omega) = 1 - \frac{\vec{C}_{SN}^{T}(\omega) \cdot (\mathbf{C}_{SS}(\omega))^{-1} \cdot \vec{C}_{SN}(\omega)}{C_{NN}(\omega)}$$

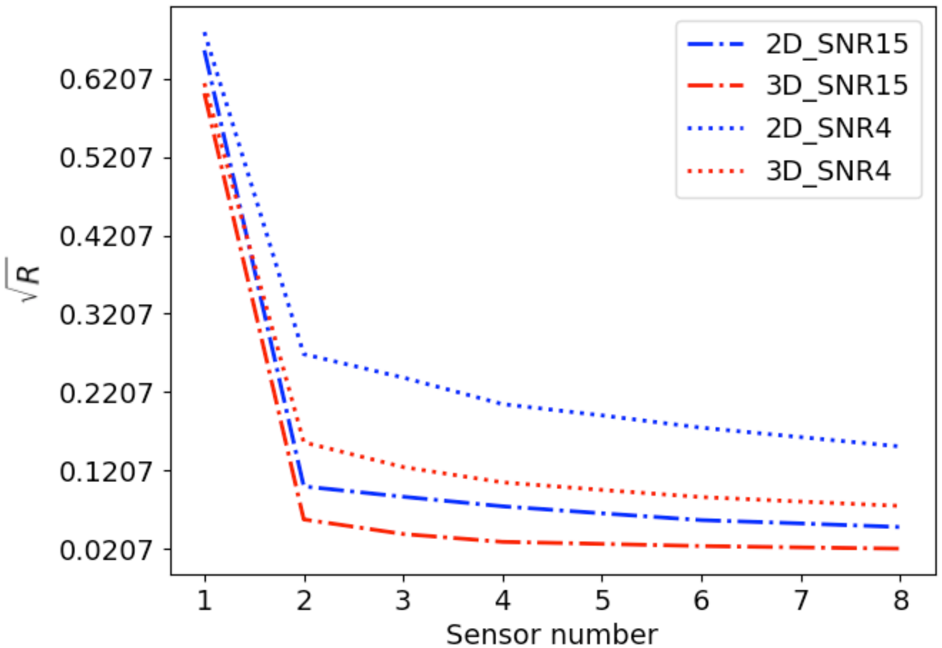


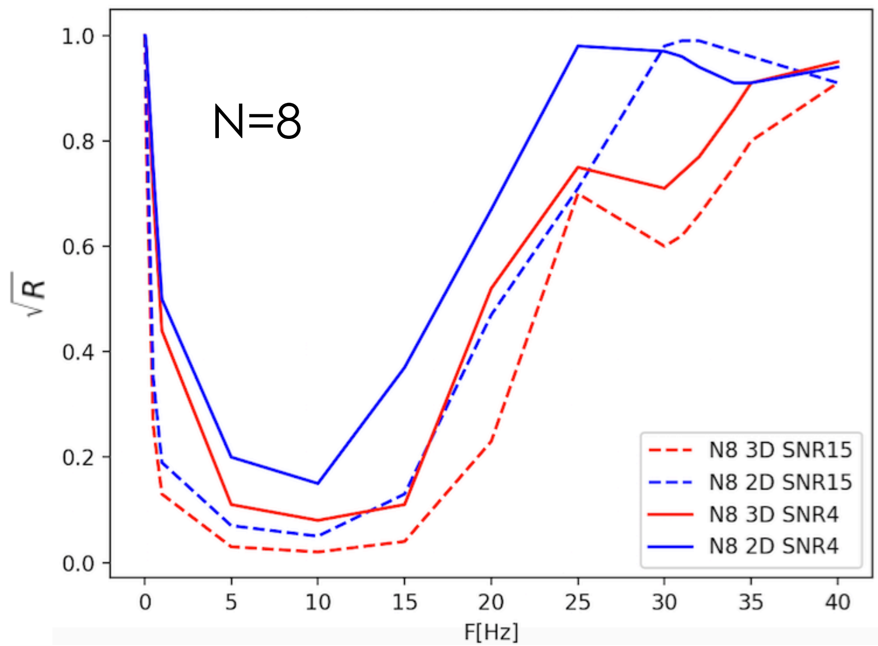
N=8



Infrasound NN : coherent noise cancellation

3D vs 2D optimized array @ 10 Hz and the effect of lowering the SNR





- With SNR 15, for a sensor number $\geq$2, a 3D array reduces the noise 2 times more than a 2D array
- A lower SNR decreases the noise suppression factor and narrows the frequency band of noise cancellation

Atmospheric NN : attenuation & cancellation strategies

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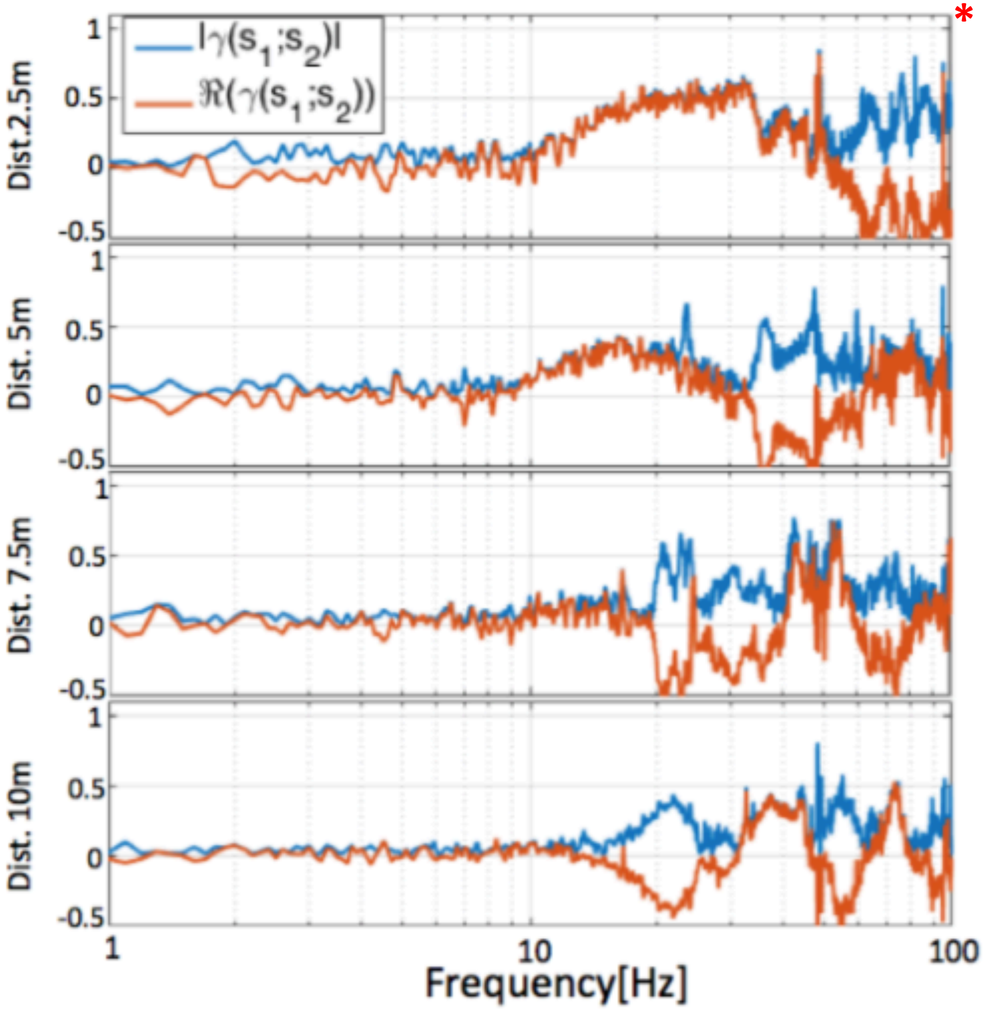
- Coherent NN suppression with LIDAR: infrasound NN case

Why exploring new atmospheric sensing strategies?

Sound correlation measured **outside the AdV NEB** with windshield on the two microphones.



Infrasound NN cancellation with microphones is challenging!

Study/test new wind shield design

Study/test new atmospheric sensing techniques

* D.Fiorucci, J.Harms, M. Barsuglia, I. Fiori, F.Paoletti, PRD 97, 062003 (2018)

**John M. Noble et al. Proc. Mtgs. Acoust. 21, 045005 (2014)

LIDAR for troposhere ($\lesssim$ 10 km) sensing

Tropospheric static pressure fluctuations (e.g. infrasounds) $\lesssim$ a few Pa[1]

Tropospheric temperature fluctuations $\sim$ a few K[1]

Tropospheric water vapor fluctuations $\sim$ 10 %[1]

LIDAR state of the art:

Temperature: **Raman LIDAR** (precision ~ 0.1 K fluctuations)[1,2]

Pressure: **Raman LIDAR** (precision ~ 0.1%)[1]

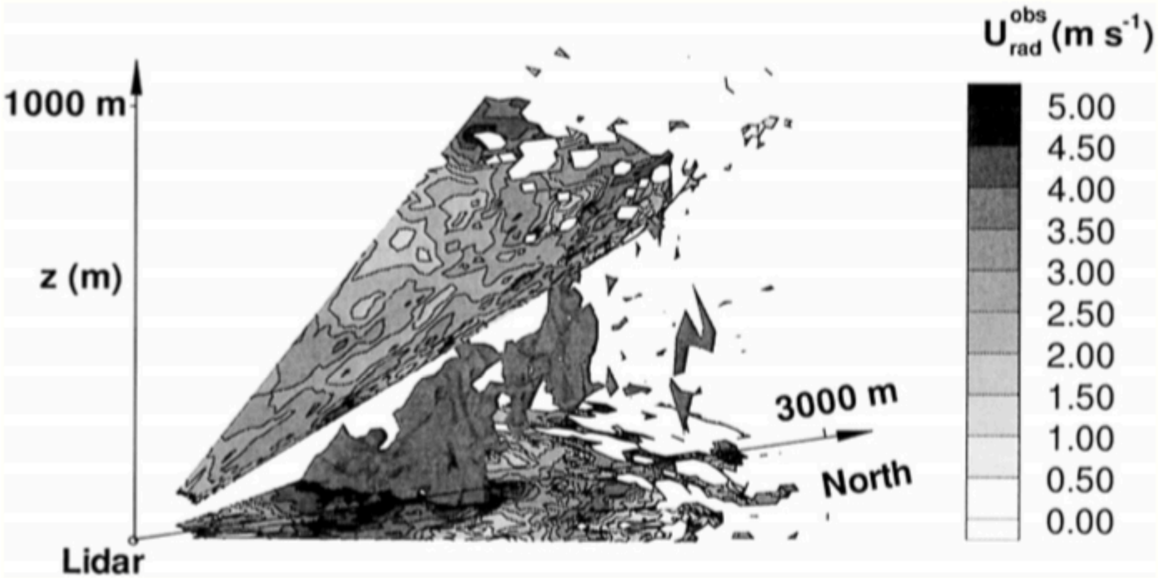
Water vapor: **Raman LIDAR** (precision ~ 15%)[3]
DIAL LIDAR (precision ~ 5%)[3]

Wind speed: **Doppler LIDAR** (precision ~ 0.1 m/s)[4]

[1] Private discussion with F. Gibert
[2] P. Di Girolamo et al., Atmos. Chem. Phys., 17, 745–767, 2017
[3] Behrendt,2005, Lidar: Range-Resolved Optical Remote Sensing of the Atmosphere
[4] Grund, C. et al, 2001, J. Atmos. Oceanic Technol., 18, 376–393

LIDAR for troposhere ($\lesssim$ 10 km) sensing

Volumetric * measurements of wind speed with high resolution doppler LIDAR



Combined system of Doppler LIDAR and Raman/DIAL LIDAR for coherent cancellation of NN from wind-driven temperature and humidity fields

Atmospheric NN : attenuation & cancellation strategies

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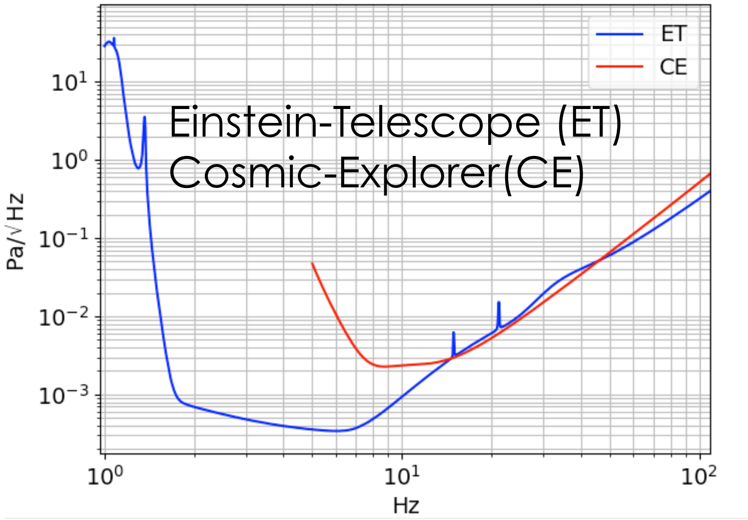
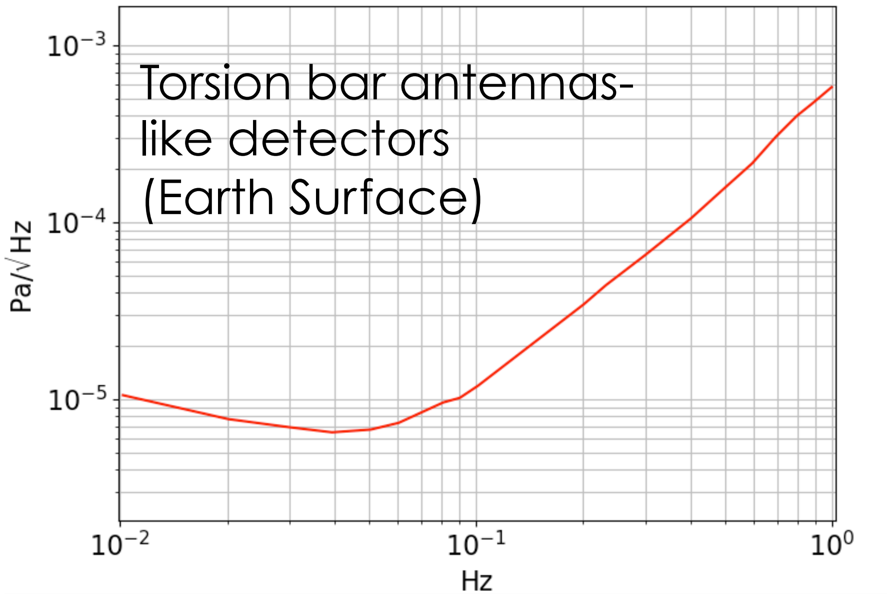
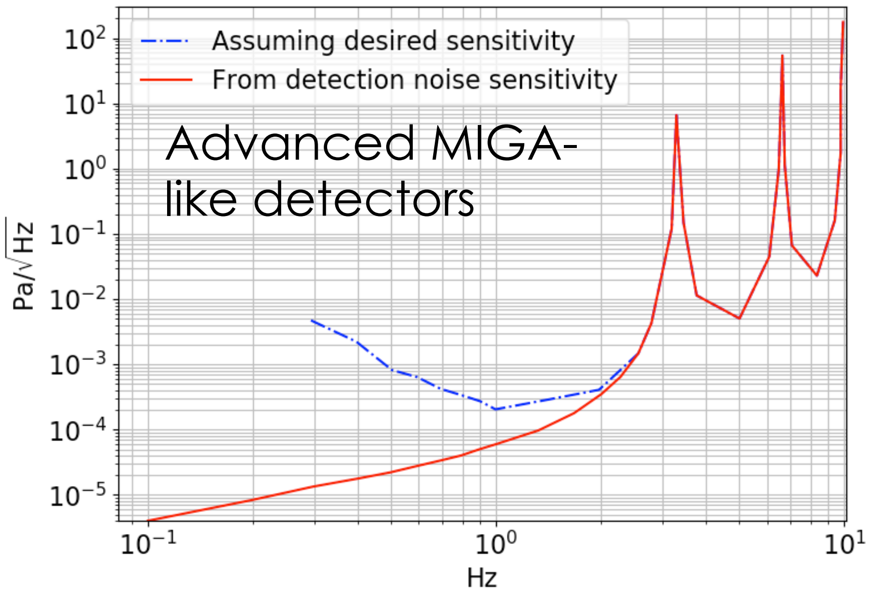
Pressure sensor requirements for infrasound NN suppression



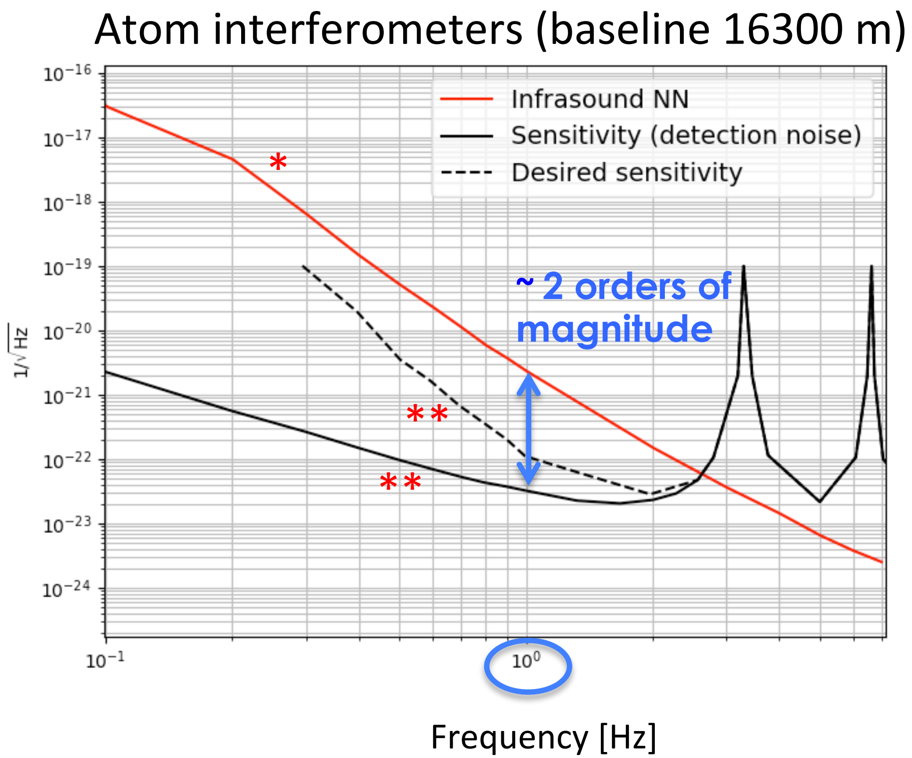
$$S(h,\omega) = TF(\omega)S(\delta p,\omega)$$



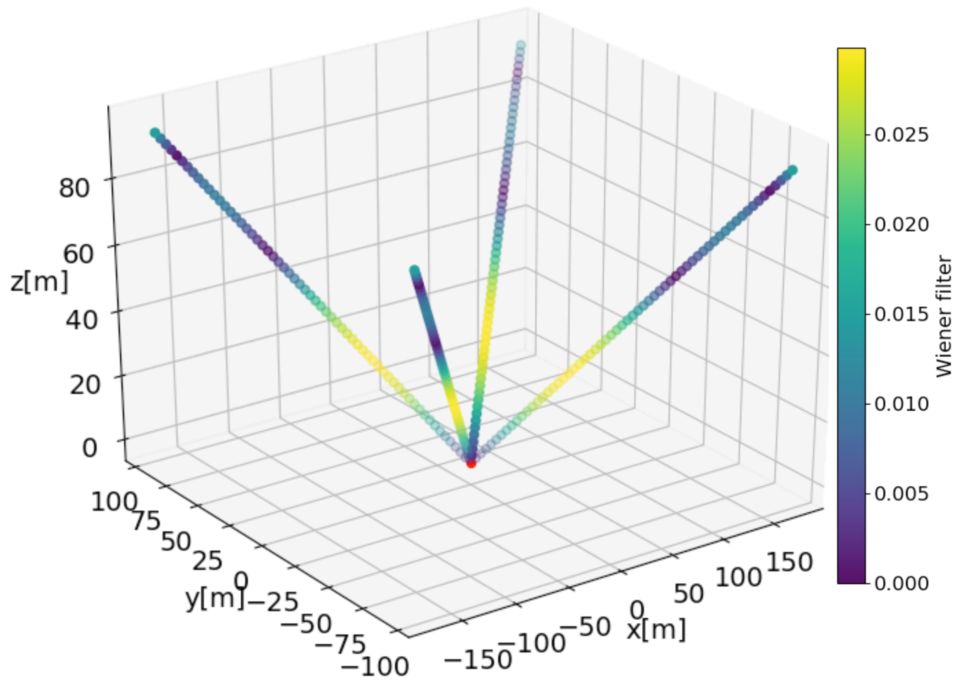


Coherent NN suppression with LIDAR: infrasound NN case

Assuming required sensitivity to pressure fluctuations for infrasound NN cancellation



$$1/\sqrt{R} \sim 100$$



1 Hz
SNR 15
Spatial sampling rate: **~** 4 m

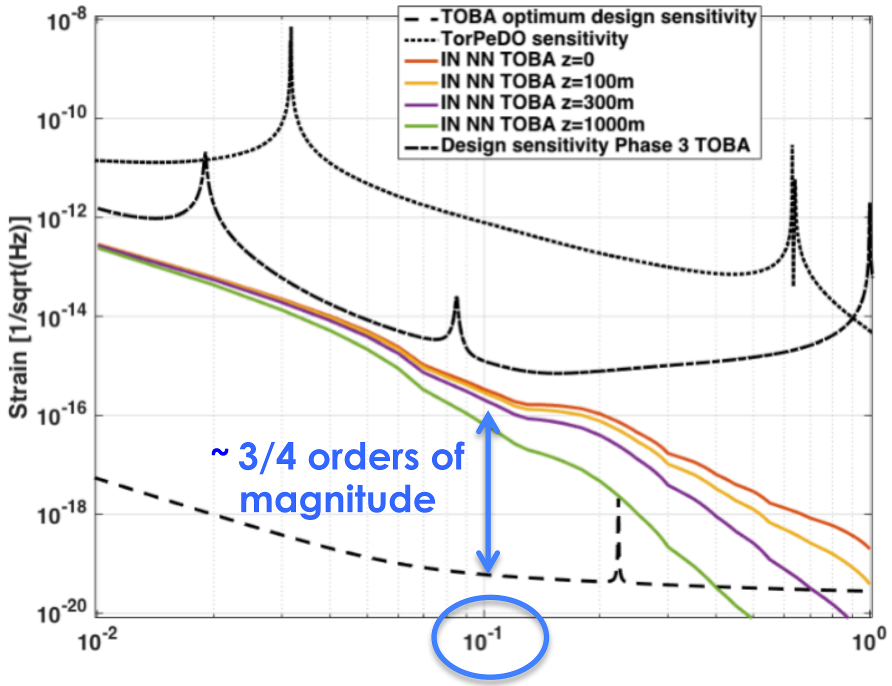
*Eq. 172, J.Harms, Terrestrial Gravity Fluctuations and GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L09803,2005

** W. Chaibi, Phys.Rev. D93 (2016) no.2, 021101

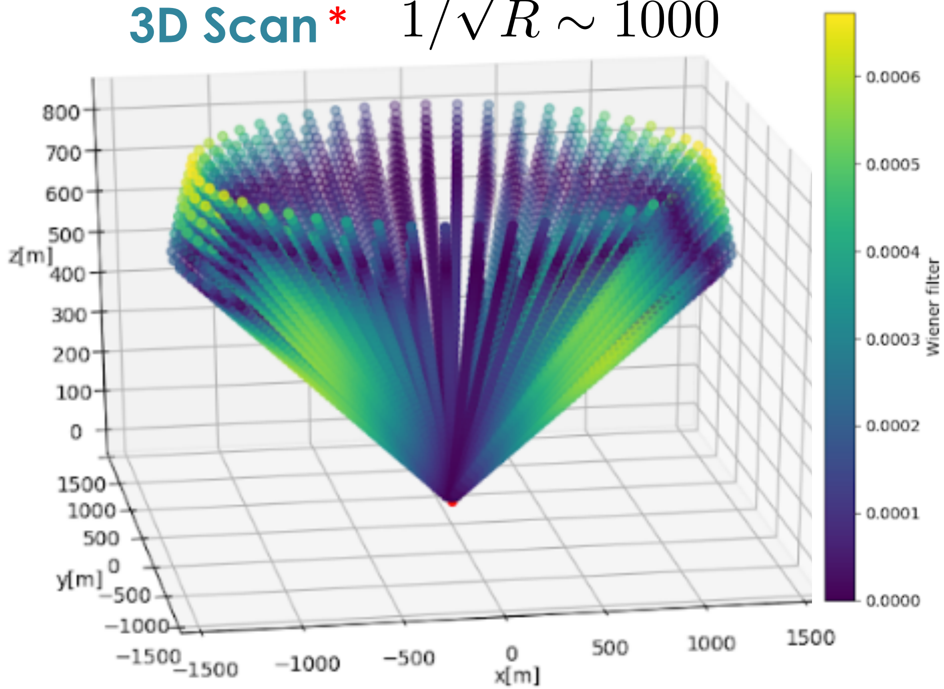
Coherent NN suppression with LIDAR: infrasound NN case

Assuming required sensitivity to pressure fluctuations for infrasound NN cancellation

Torsion bar antennas



3D Scan * $1/\sqrt{R} \sim 1000$



0.1Hz

SNR 15

Sampling Rate:

Spatial: ~ 4 m

Azimuthal ang.: ~ 7.5°

Vertical ang.: 2°

Conclusions & Perspectives

- **Study of the detector building acoustics:**

  - to dump acoustic noise (e.g. with acoustic absorbers)
  - to characterize the acoustic field inside the detector building for coherent infrasound NN cancellation

- **Coherent cancellation of infrasound NN** with **optimized arrays** was analyzed: **suppression of a factor 50 @ 10 Hz with a 3D array of 8 sensors.** Future work: broadband optimization

- Need for sensors with suitable sensitivity for coherent atmospheric NN cancellation.

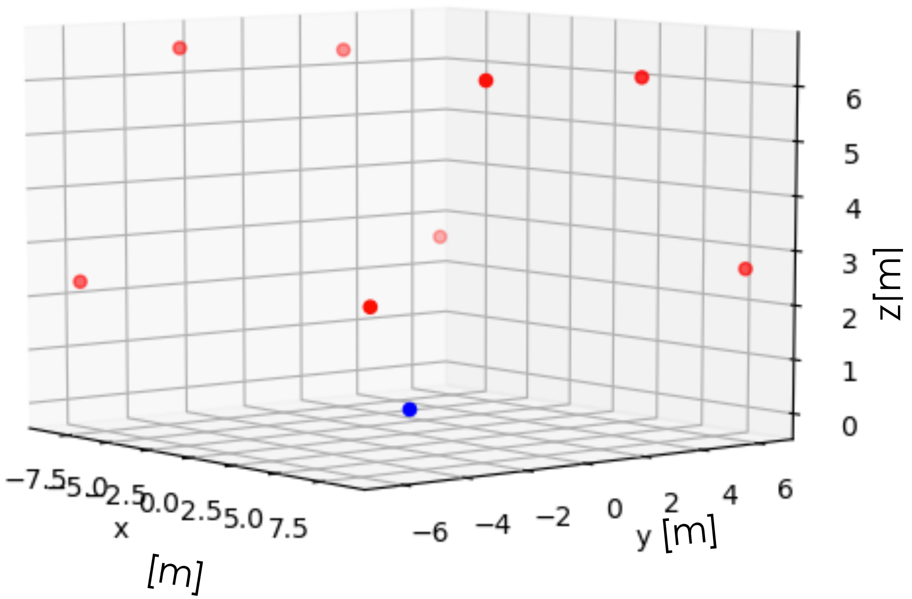
- Development of wind shield for microphones to improve external acoustic measurements and microphone correlations for infrasound NN suppression

- **LIDAR technique** is promising **for coherent cancellation of infrasound NN**, but it **does not have the required sensitivity yet**. It seems instead **already possible to apply this technique to cancel wind-driven NN** due to temperature and humidity fields

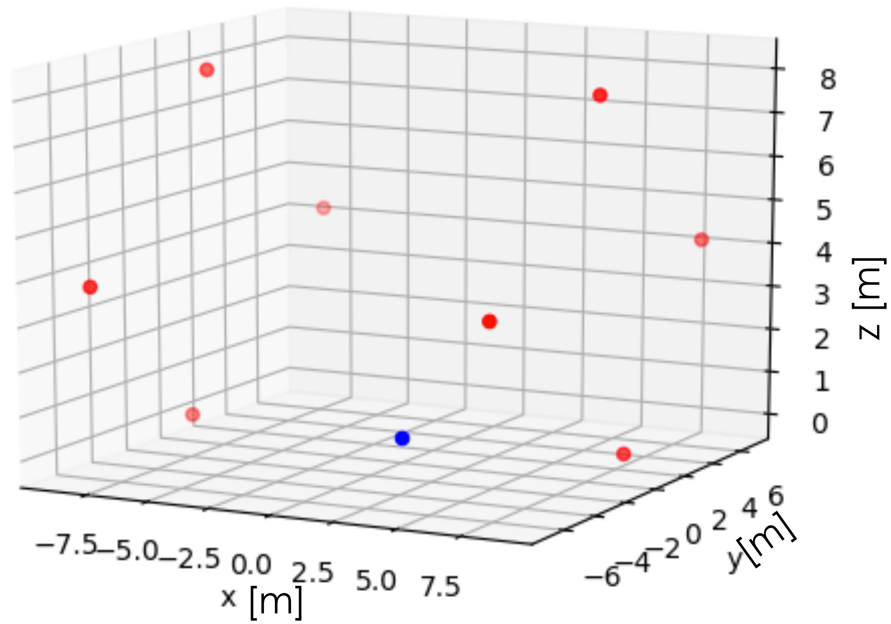
Atmospheric NN : cancellation strategies

3D optimized array @ 10 Hz

SNR 4, N=8

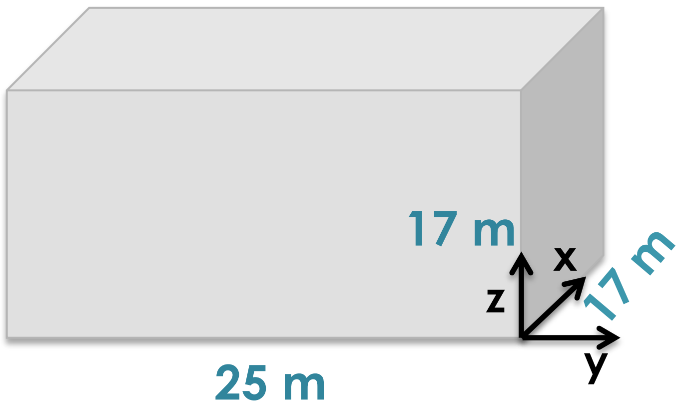


SNR 15, N=8

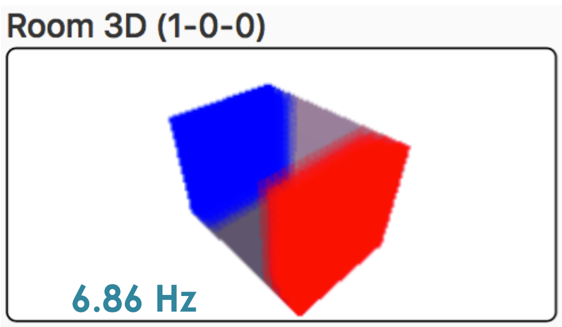


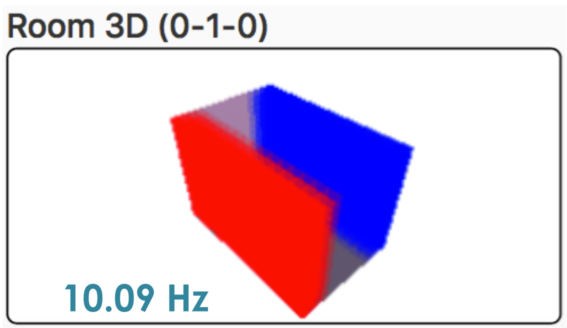
*J.Harms, Terrestrial Gravity Fluctuations

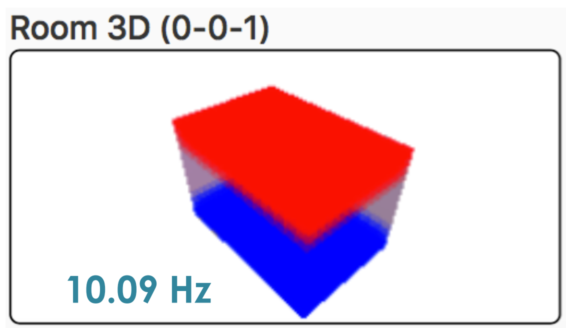
Building modes



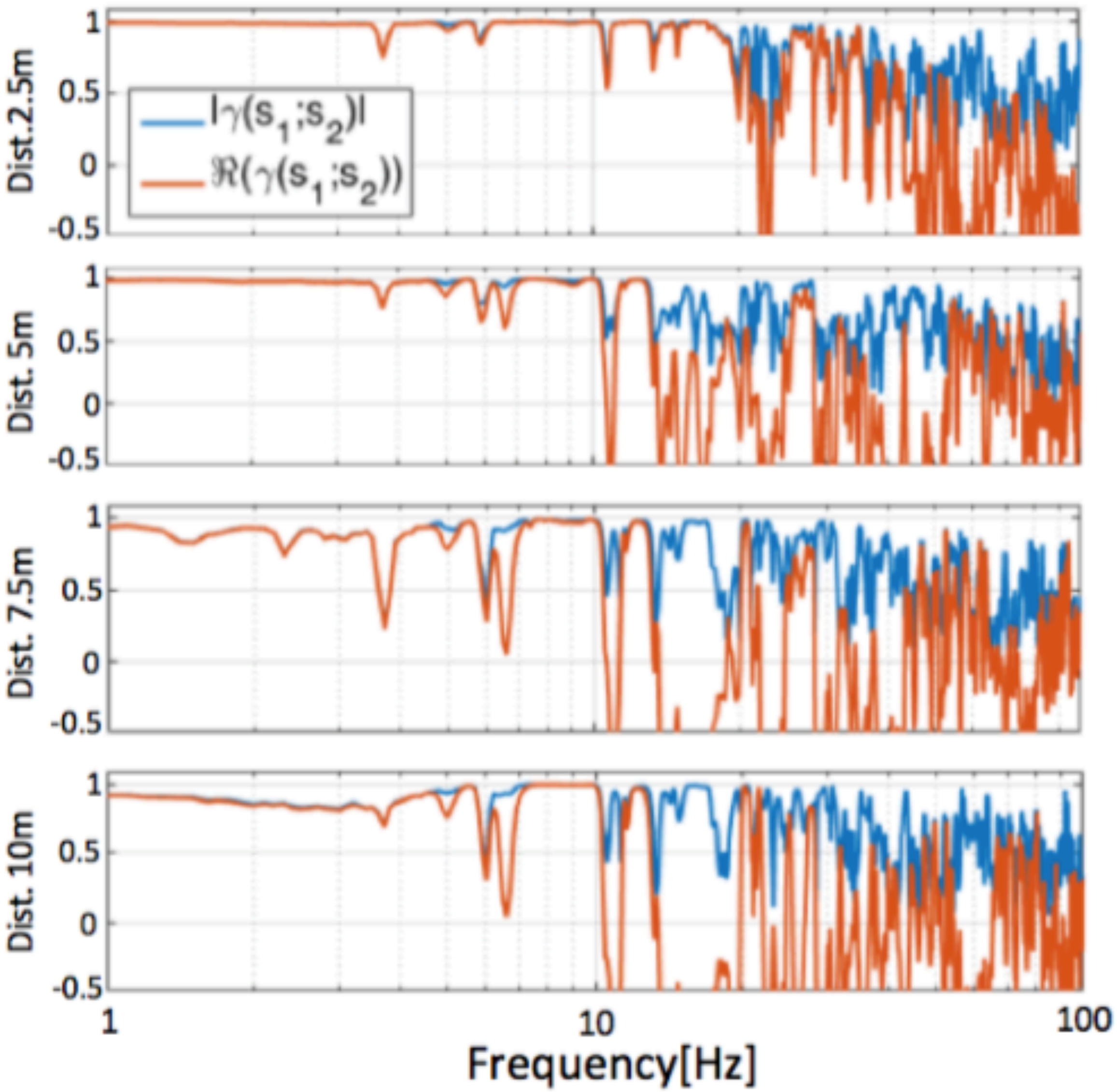
NEB
simplified geometry







Correlation measurements - AdV site (inside NEB)

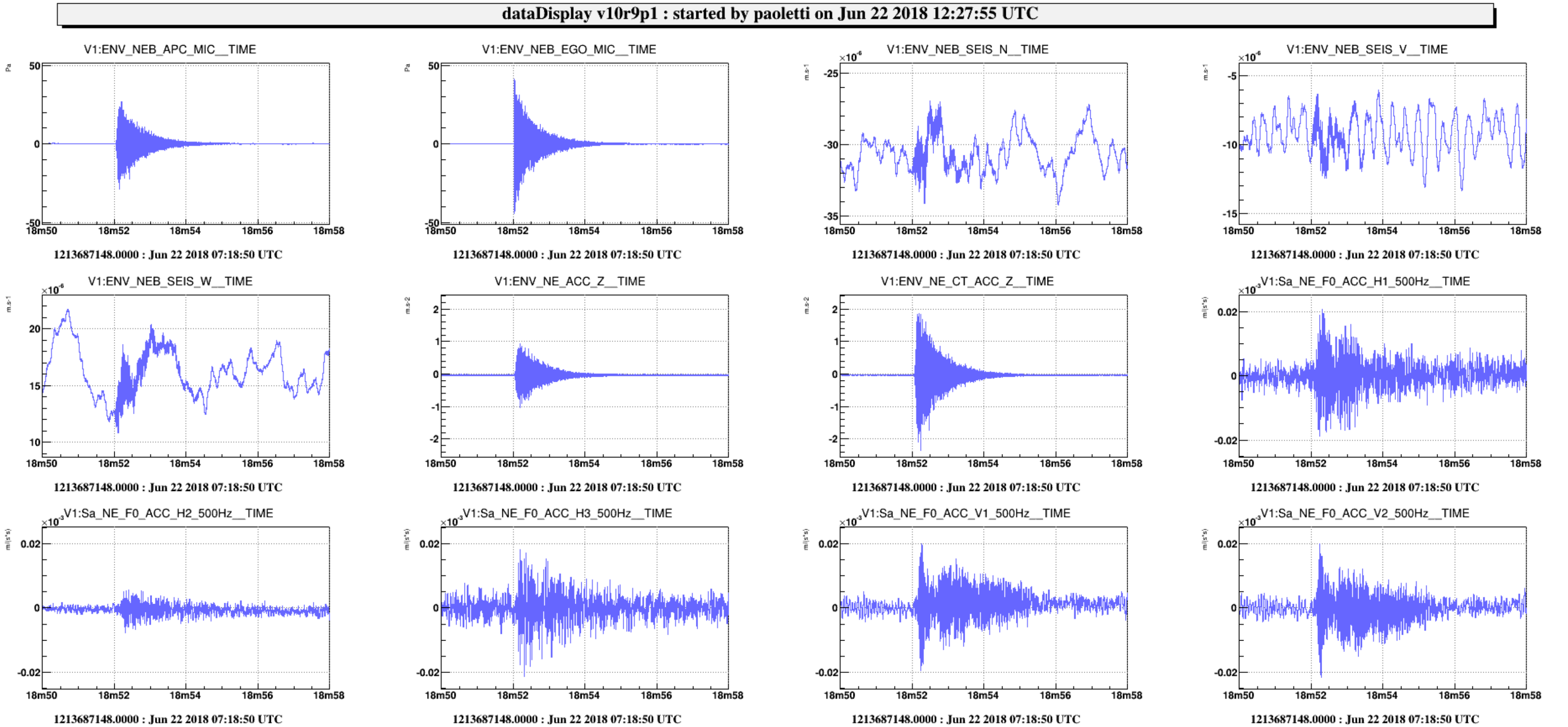


Sound correlation analysis inside the AdV NEB, without windshield. Absolute value and real value of complex coherence.

* D.Fiorucci, J.Harms, M. Barsuglia, I. Fiori, F.Paoletti, PRD 97, 062003 (2018)

NEB measurements

Reverberation Time : T_{60}

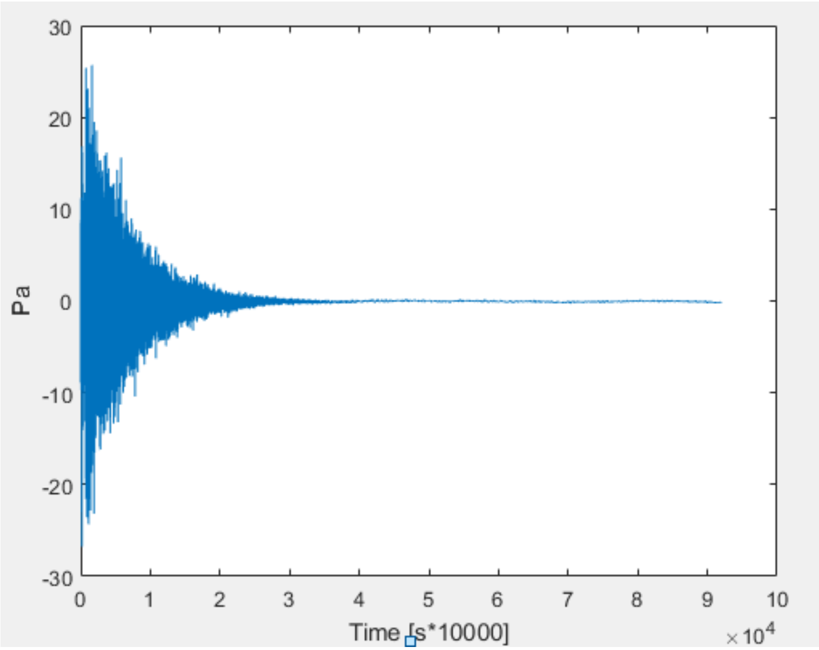


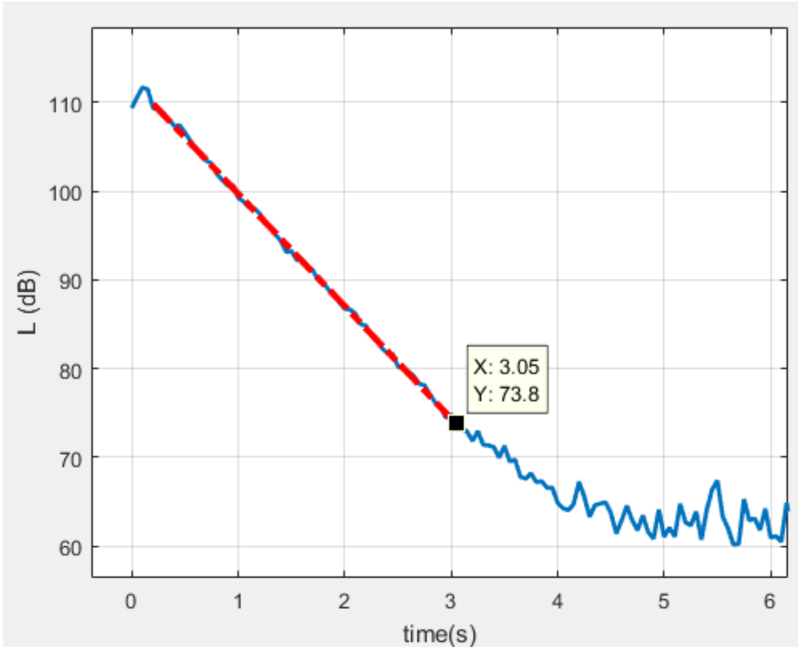
F. Paoletti

NEB measurements

Reverberation Time : T_{60}

T_{60} : 4.74 s - > F_s ~ 51.1 Hz

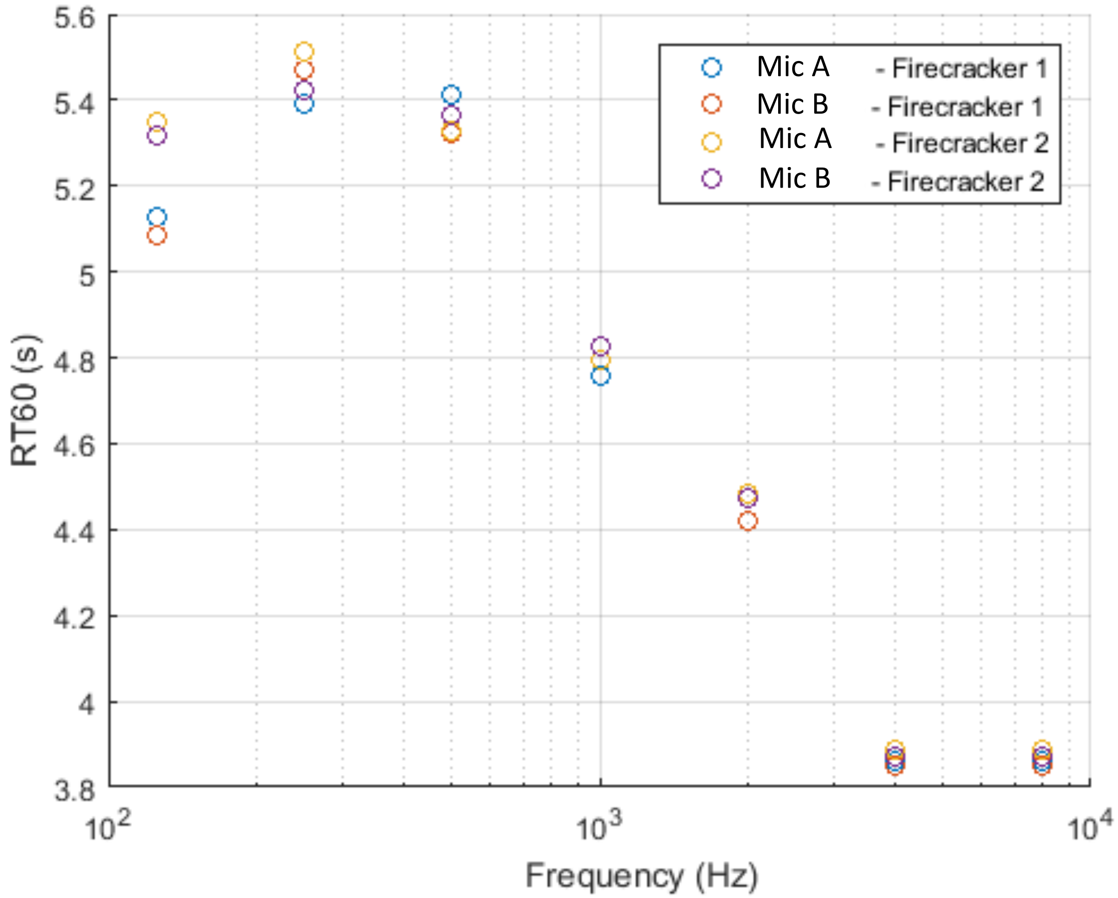




I. Fiori

NEB measurements

Reverberation Time : T_{60}



$< T_{60} > \sim$ 4.7 s

$F_s \sim$ 51 Hz

M. Falxa

RT60(s)		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Firecracker 1	MicA	5.1290	5.3936	5.4100	4.7556	4.4855	3.8582	3.8582
	MicB	5.0876	5.4713	5.3246	4.7940	4.4190	3.8506	3.8506
Firecracker 2	MicA	5.3489	5.5116	5.3302	4.7965	4.4838	3.8893	3.8893
	MicB	5.3189	5.4229	5.3636	4.8283	4.4719	3.8693	3.8693

Atmospheric NN : cancellation strategies

Suppression factor : $1/\sqrt{R(\omega)}$

$$R(\omega) = 1 - \frac{\vec{C}_{\rm SN}^{\rm T}(\omega) \cdot (\mathbf{C}_{\rm SS}(\omega))^{-1} \cdot \vec{C}_{\rm SN}(\omega)}{C_{\rm NN}(\omega)}$$

3D array:

$$C_{SS}^{ij} = 2S(\delta p, \omega)\left(j_0(kd_{1,ij}) + j_0(kd_{2,ij}) + \frac{\delta_{ij}}{SNR_i^2}\right)$$

$$C_{SN}^{i} = 8\pi \frac{S(\delta p, \omega)}{k} \frac{G\rho_0}{\gamma p_0} \frac{x_i}{d_i} j_1(kd_i)$$

$$C_{\rm NN}(\omega) = \frac{16\pi^2}{3} \frac{S(\delta p, \omega)}{k^2} \left(\frac{G\rho_0}{\gamma p_0}\right)^2$$

3D formulas gives 2D ones in Ref. * for the right choice of $d_{1,ij}$, $d_{2,ij}$, d_i

*J.Harms, Terrestrial Gravity Fluctuations

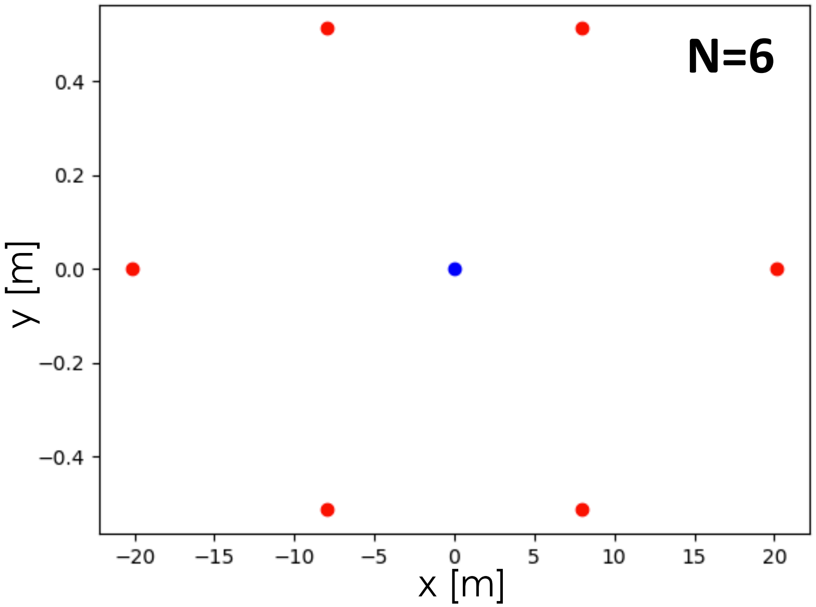
Infrasound NN : coherent noise cancellation

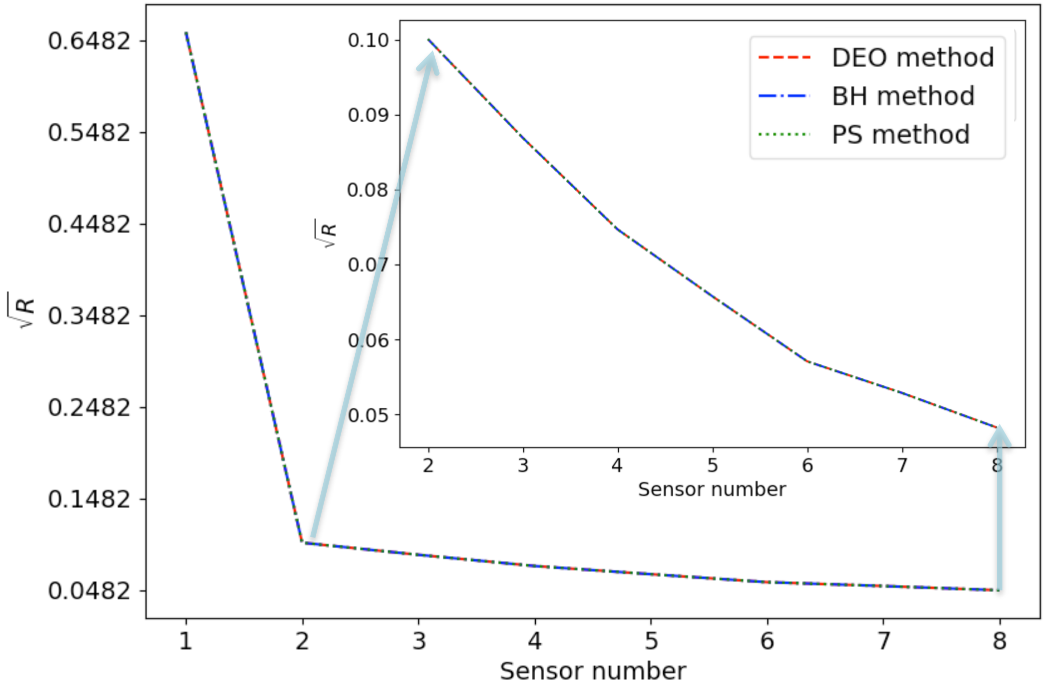
2D optimized array @ 10 Hz

SNR 15

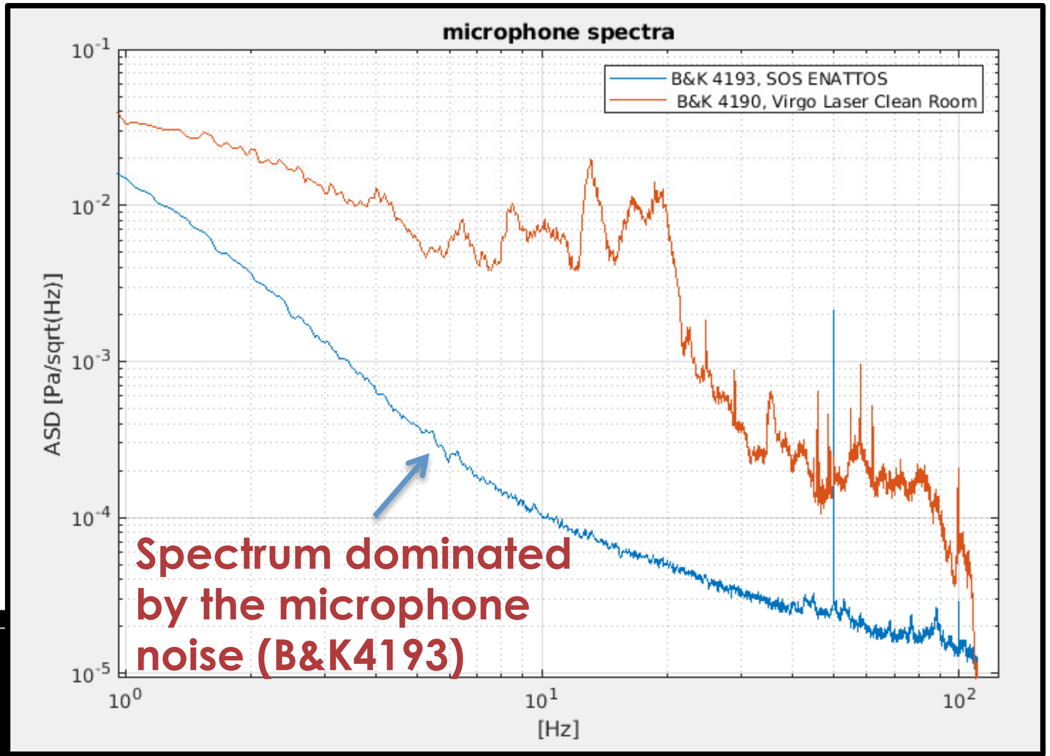
Suppression factor : $1/\sqrt{R(\omega)}$

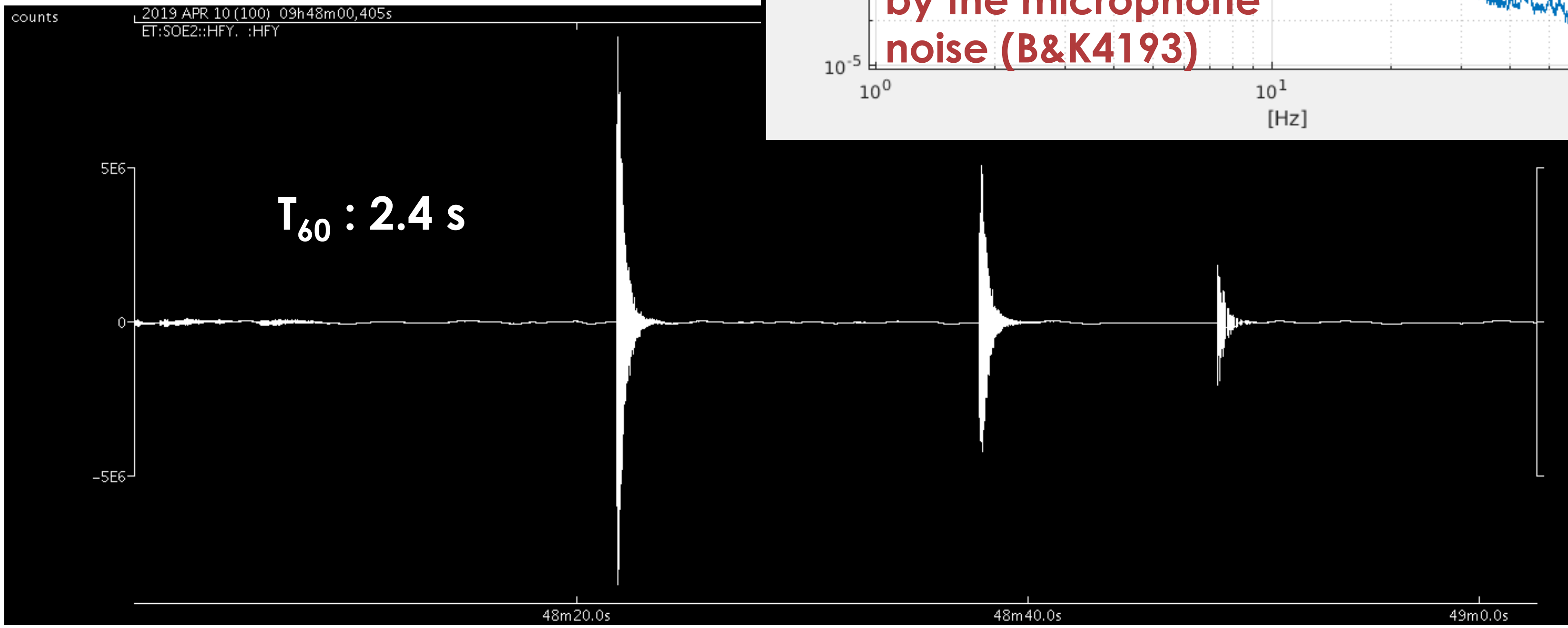
$$R(\omega) = 1 - \frac{\vec{C}_{\rm SN}^{\rm T}(\omega) \cdot (\mathbf{C}_{\rm SS}(\omega))^{-1} \cdot \vec{C}_{\rm SN}(\omega)}{C_{\rm NN}(\omega)}$$





Sos Enattos mine - first acoustic measurements





F. Paoletti, I. Fiori, N. Singh

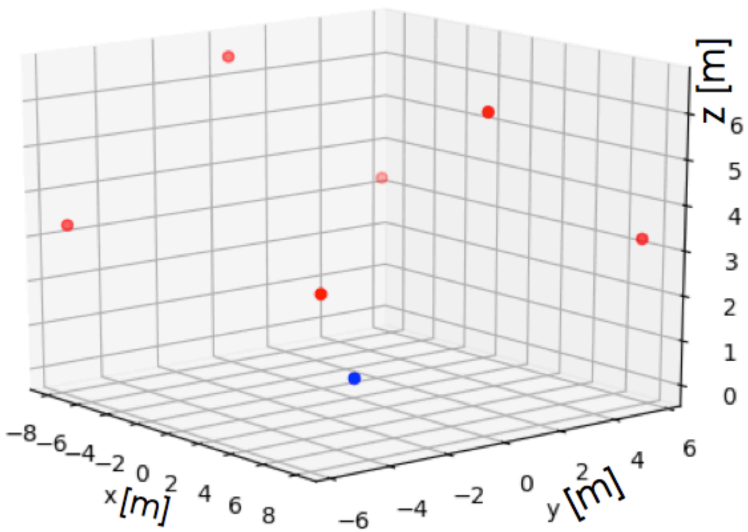
Infrasound NN : coherent noise cancellation

3D optimized array @ 10 Hz

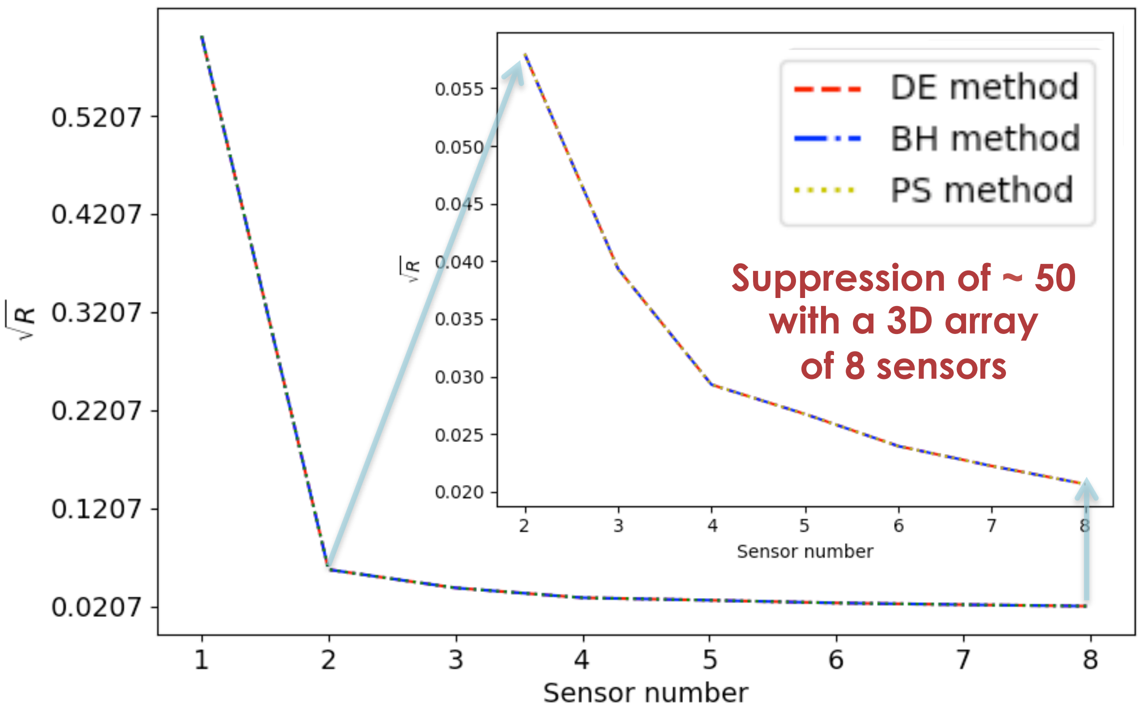
SNR 15

Suppression factor : $1/\sqrt{R(\omega)}$

$$R(\omega) = 1 - \frac{\vec{C}_{\mathrm{SN}}^{\mathrm{T}}(\omega) \cdot (\mathbf{C}_{\mathrm{SS}}(\omega))^{-1} \cdot \vec{C}_{\mathrm{SN}}(\omega)}{C_{\mathrm{NN}}(\omega)}$$



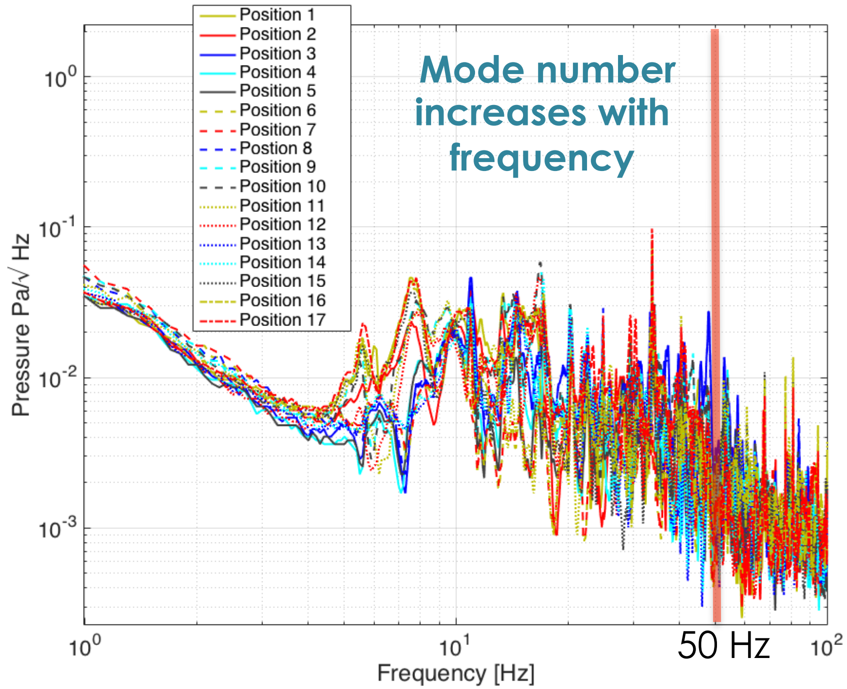
N=6



Acoustic characterization of the AdV buildings

NEB measurements: not taken at the same time!

*



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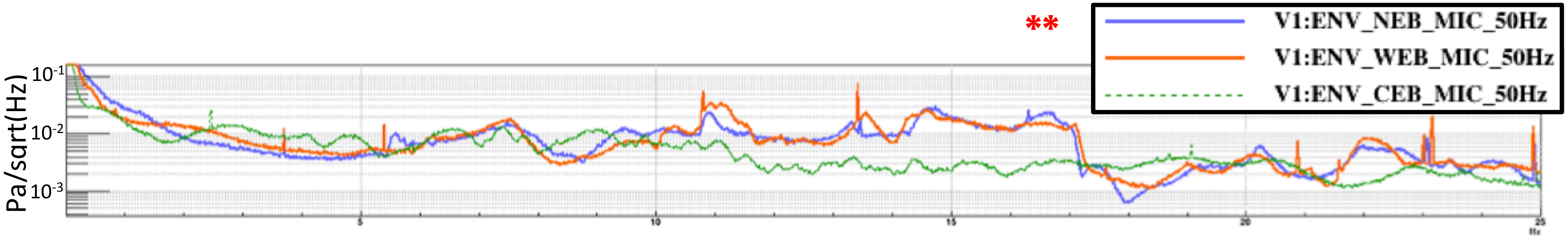
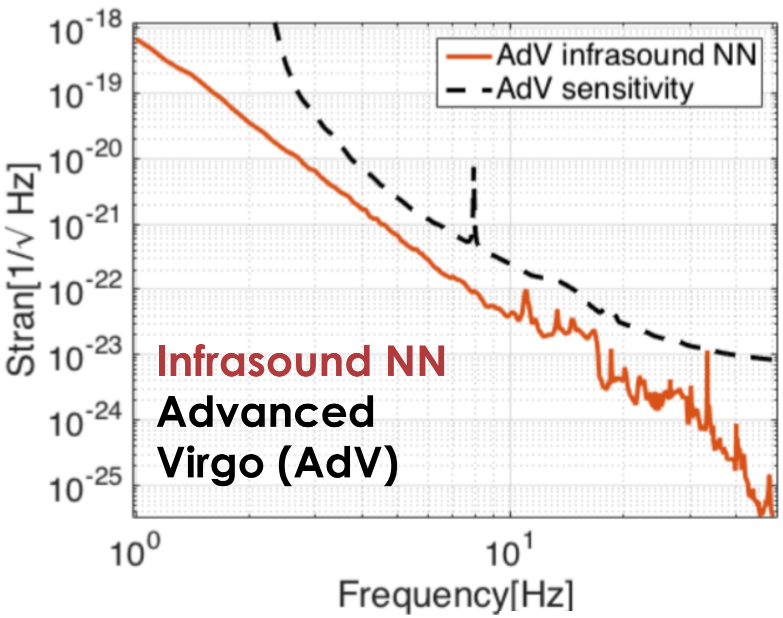


* M. Falxa et al. Acoustic characterization of Advanced Virgo buildings

** F. Paoletti

Impact of atmospheric NN on gravitational wave detectors-I



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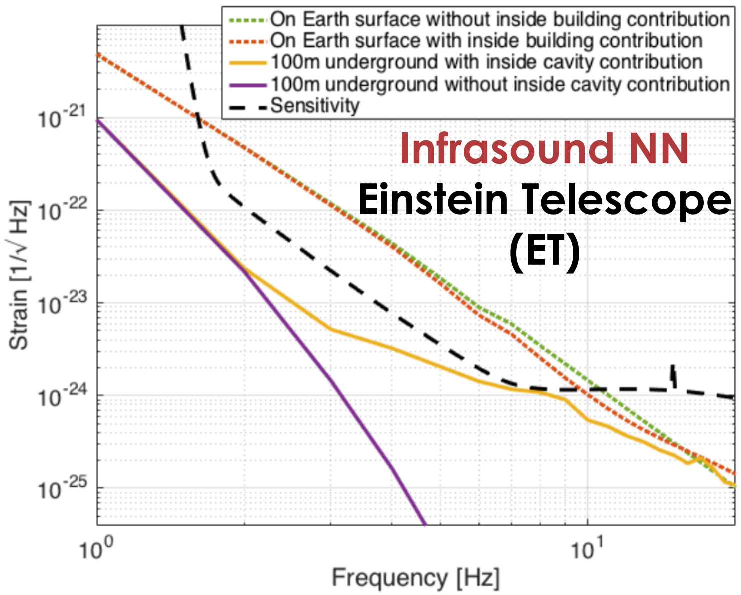

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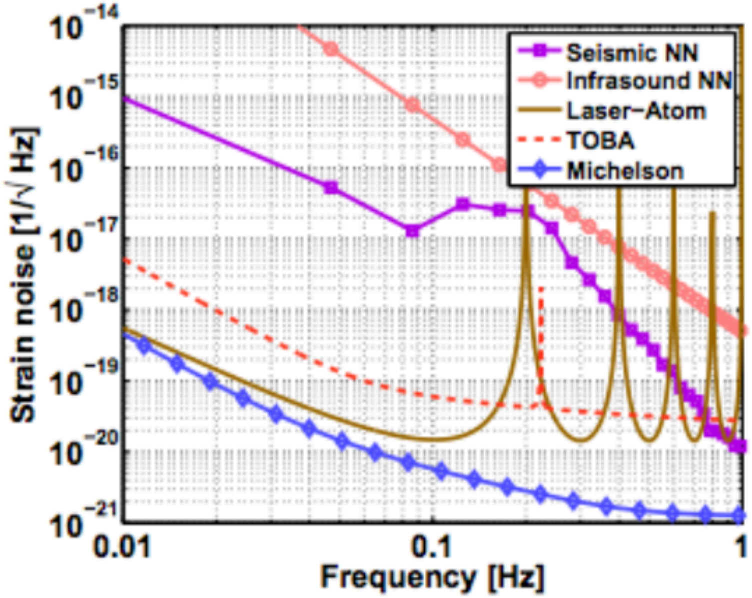

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Low frequency detectors

Infrasound NN expected to be higher than seismc NN below ~ 1 Hz

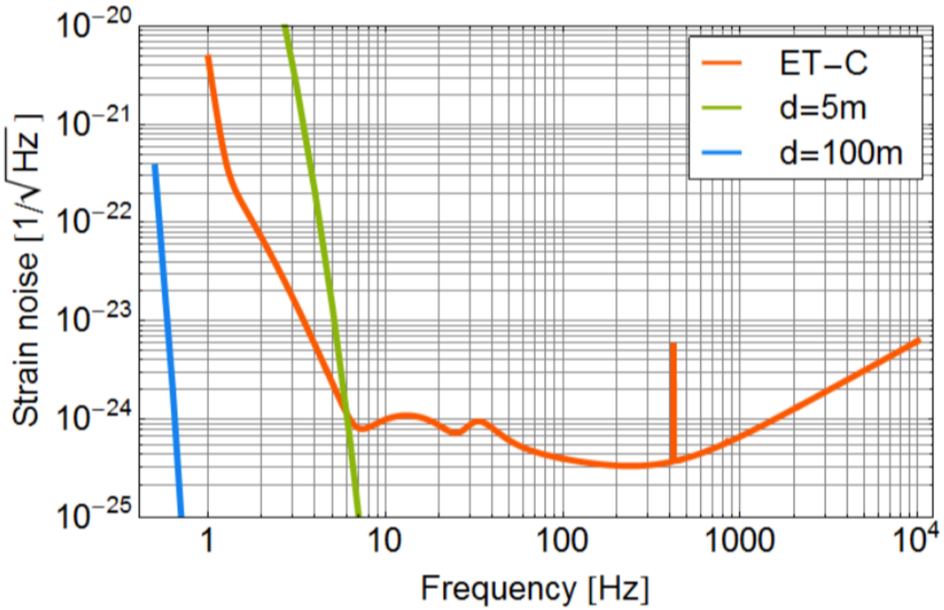
* D.Fiorucci et al. PRD 97, 062003 (2018)
** J. Harms et al. PRD 88 (2013) no.12, 122003

Impact of atmospheric NN on gravitational wave detectors-II

Wind-advected temperature fluctuation NN

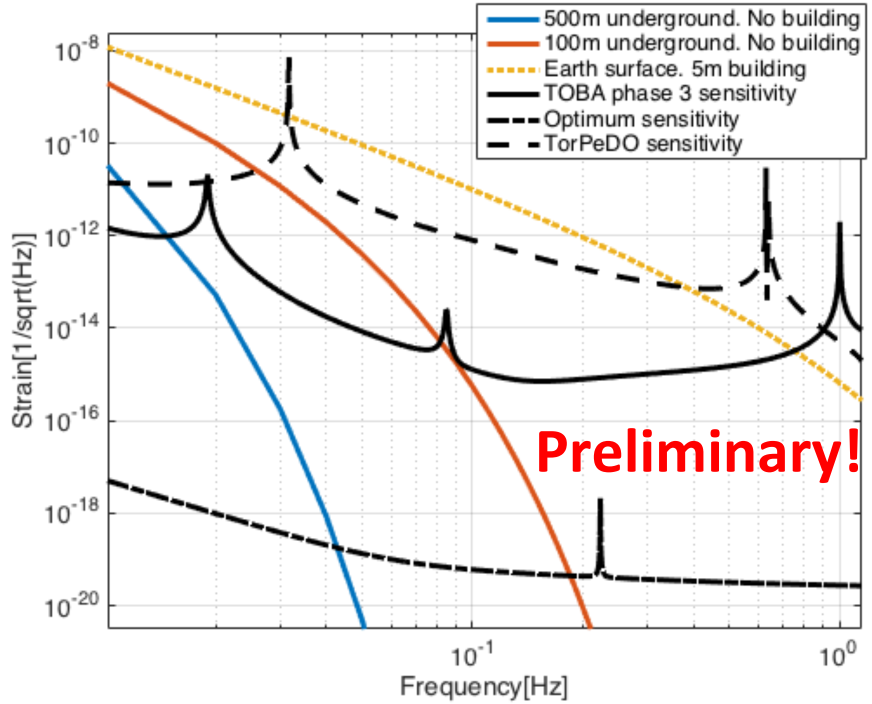
ET ◆

Uniform airflow 20 m/s



Torsion bar antennas

Uniform airflow , v=10 m/s, along one of the detector axis



Temperature fluctuation NN to be considered for detectors at the Earth surface

◆ **Credit: Jan Harms**