Thèse de doctorat,
université du Maine
Spécialité acoustique

Characterization of the acoustic emission of vehicles by equivalent point sources

F. Golay

Advisory committee:

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G. Dutilleux	LRS
L. Simon	LAUM

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Ressources, territoires et habitats
Énergie et climat
Développement durable
Infrastructures, transports et mer
Prévention des risques

Présent pour l'avenir

Introduction: urban noise

Introduction: urban noise

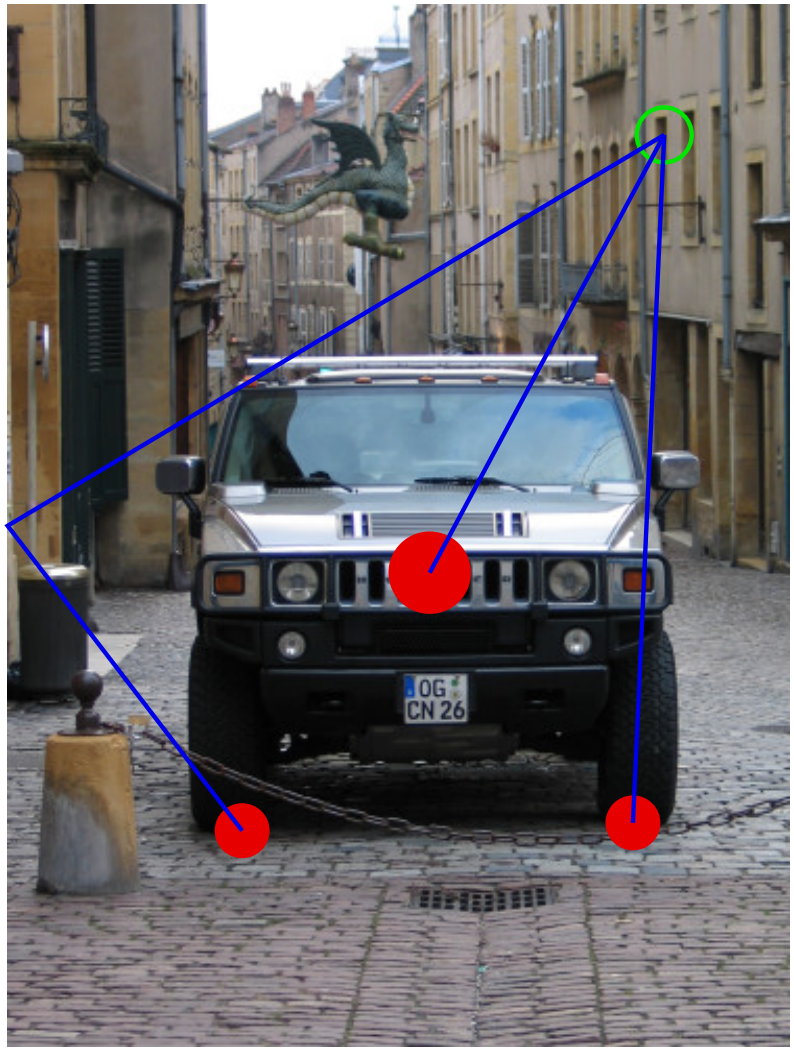
Reception

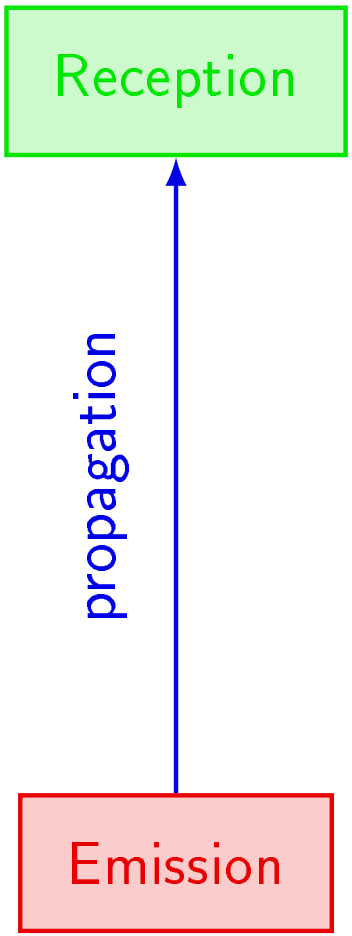
Introduction: urban noise

Reception

Emission

Introduction: urban noise





Introduction: research on emission

- modeling in France: *[Guide du Bruit, 1972]*, *[NMPB, 2008]* *[Dutilleux, AAuA, 2010]*

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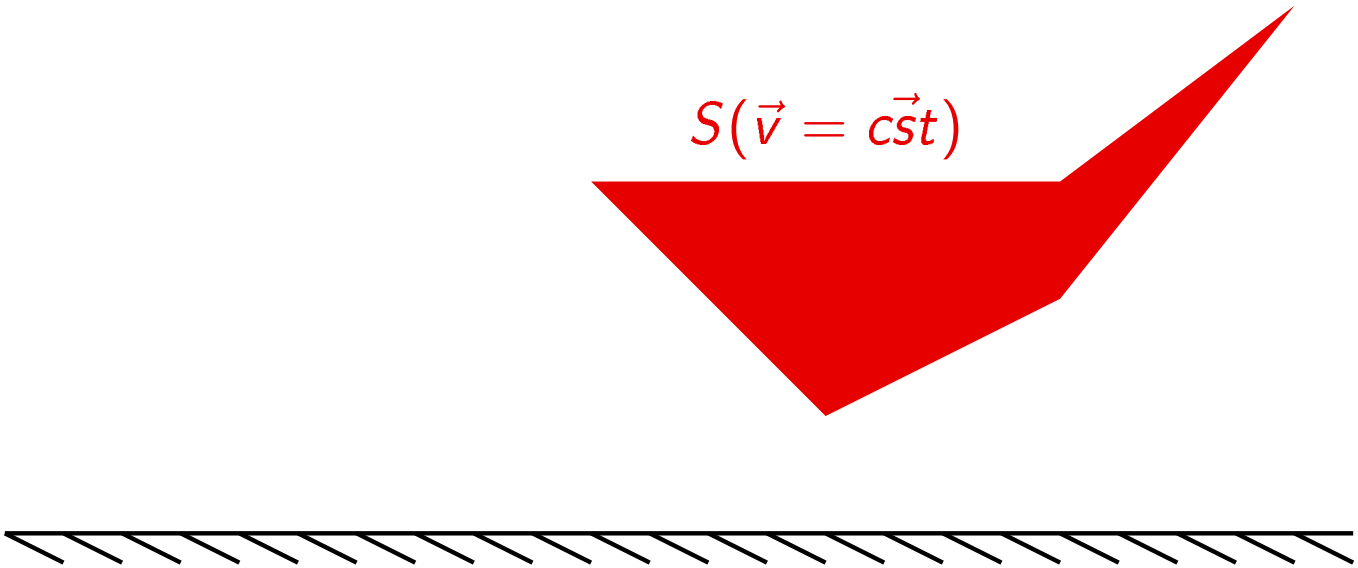
- need of additional indicators to L_{Aeq} in urban context (near field $\neq$ far field)

Introduction: problem statement



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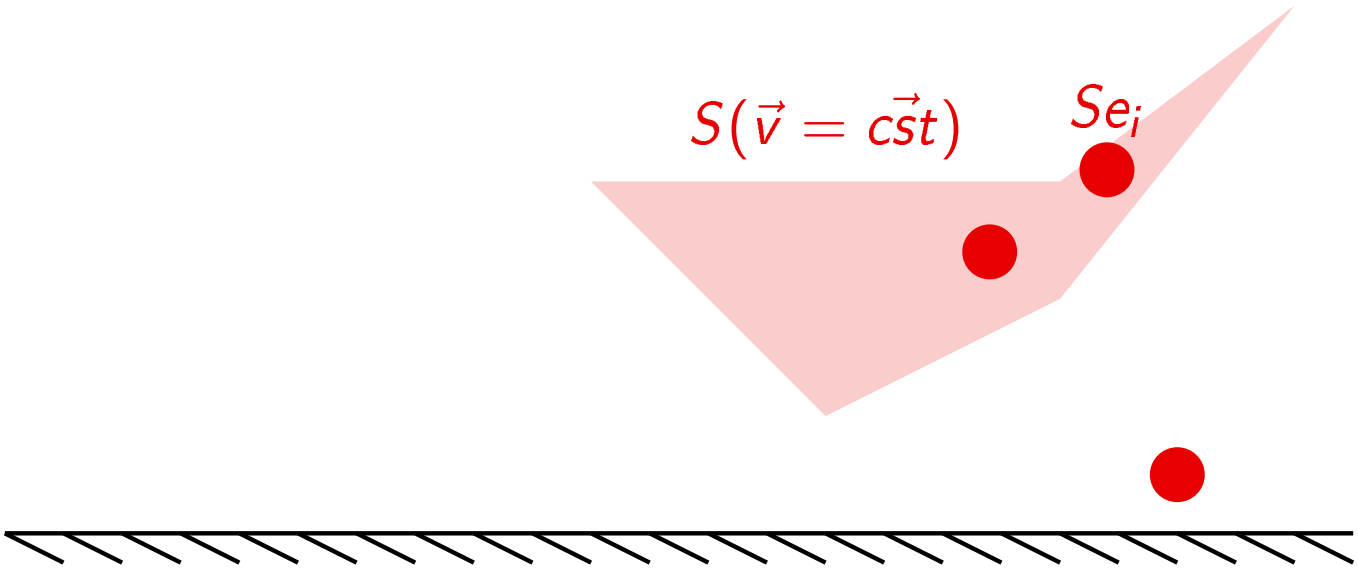

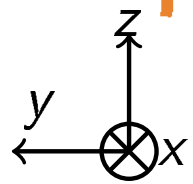

Emission
- N_{Se}
- $(x_{Se}, y_{Se}, z_{Se})_i$
- $|A_i|^2$

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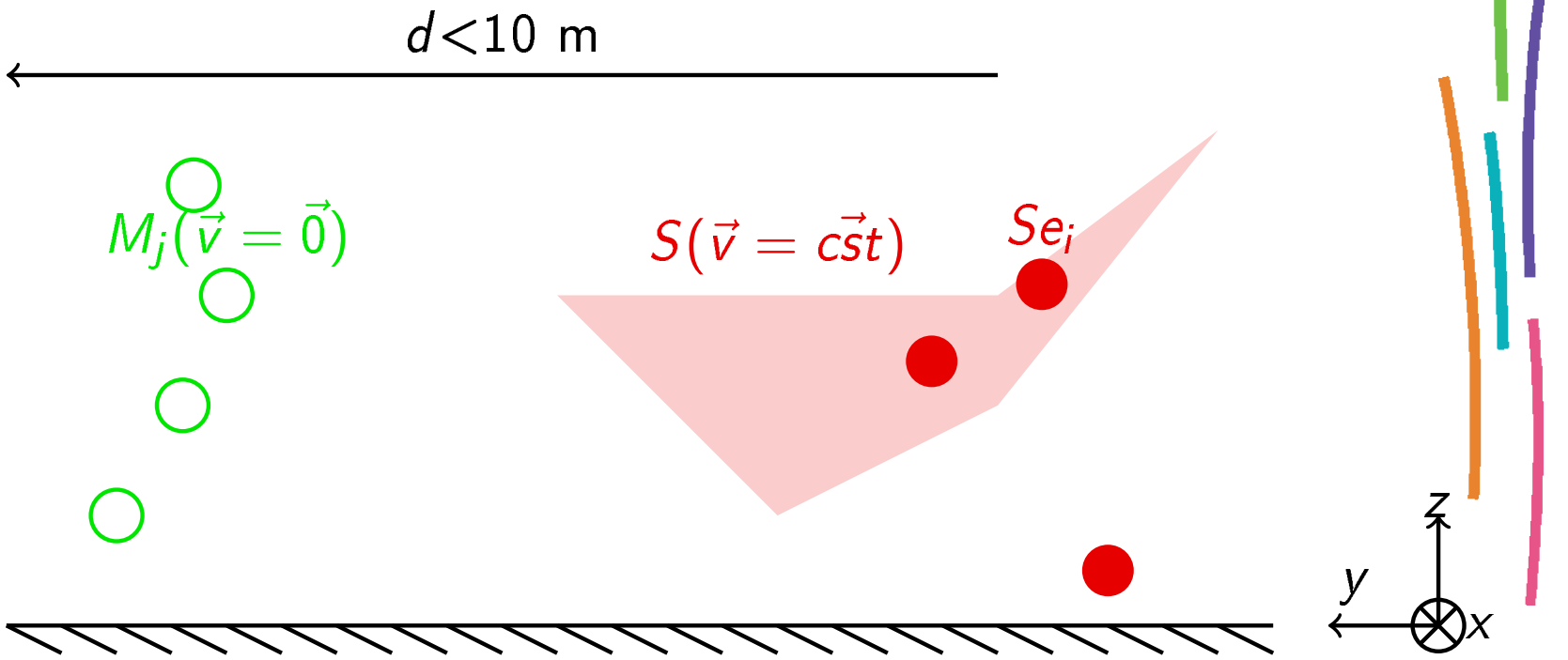

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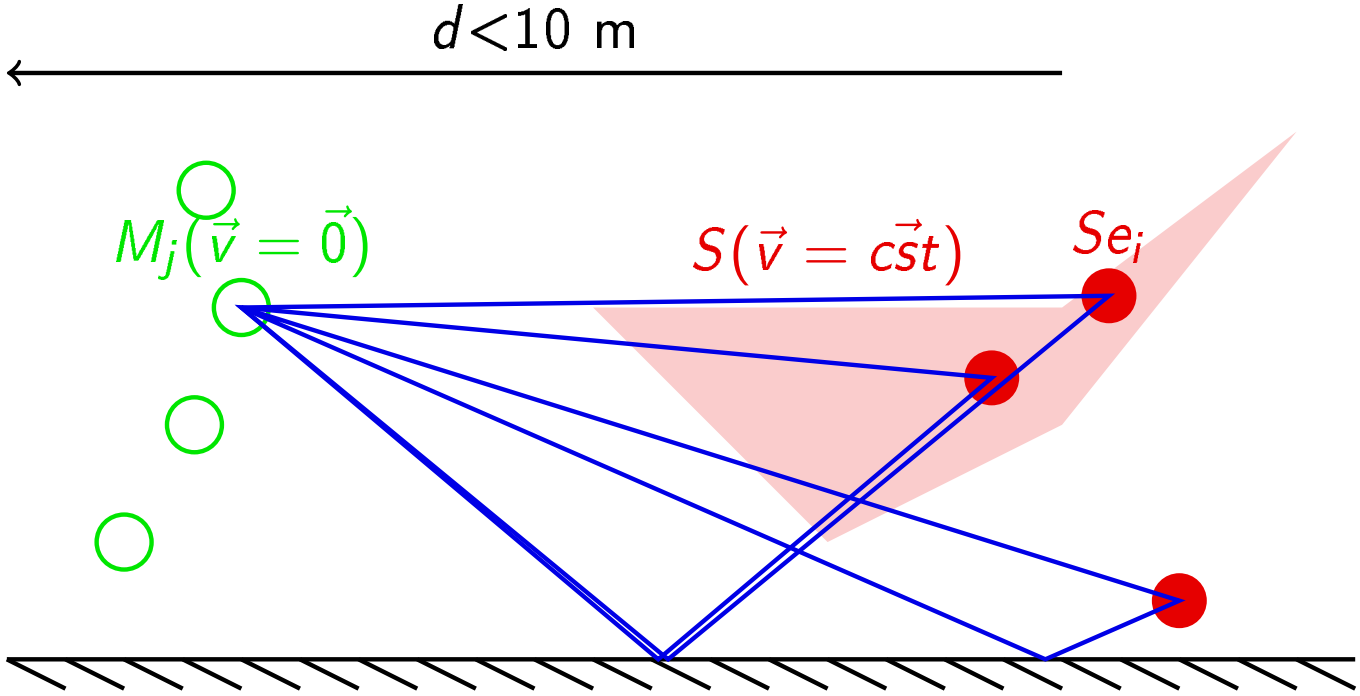

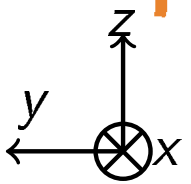

propagation

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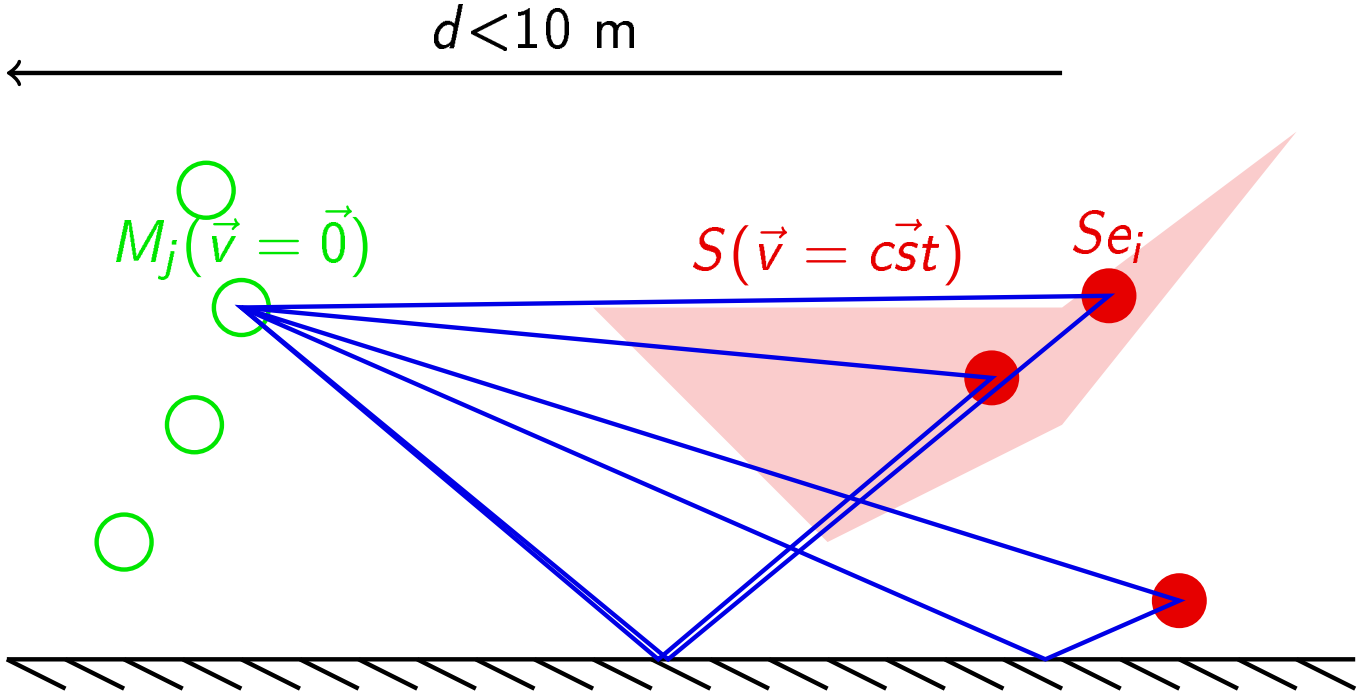

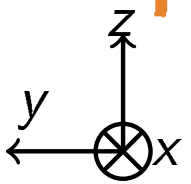

PSD_j → propagation^{-1} →

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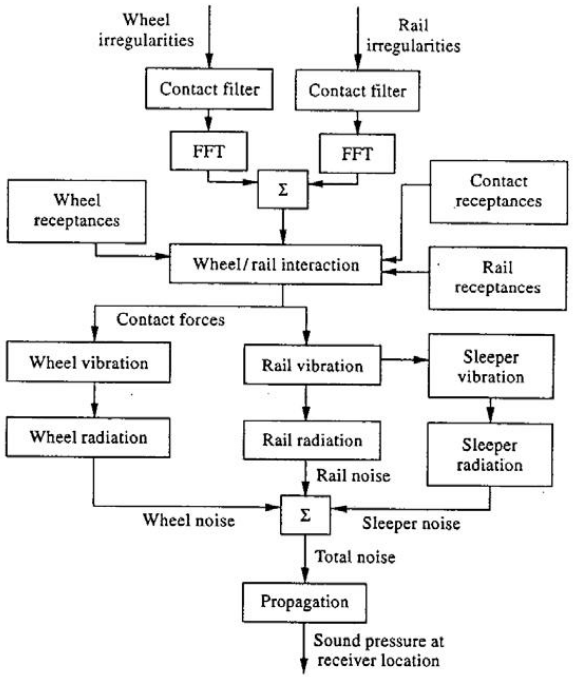

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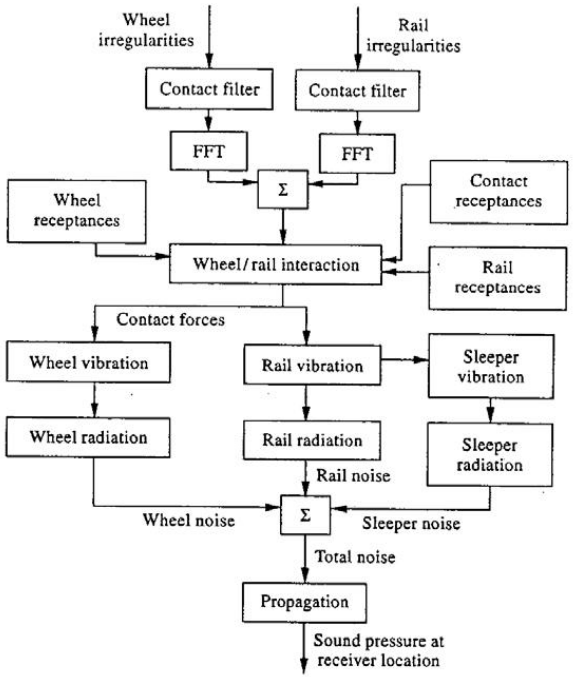

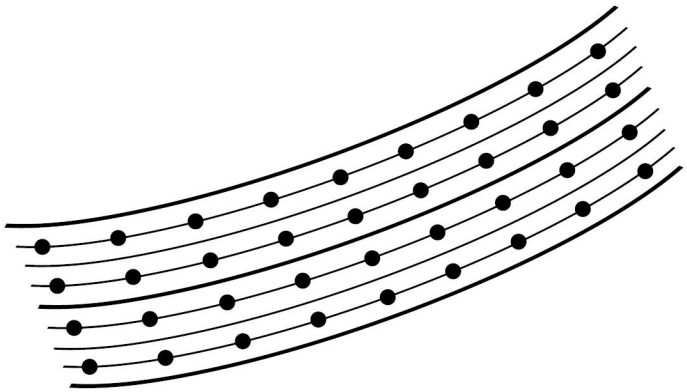

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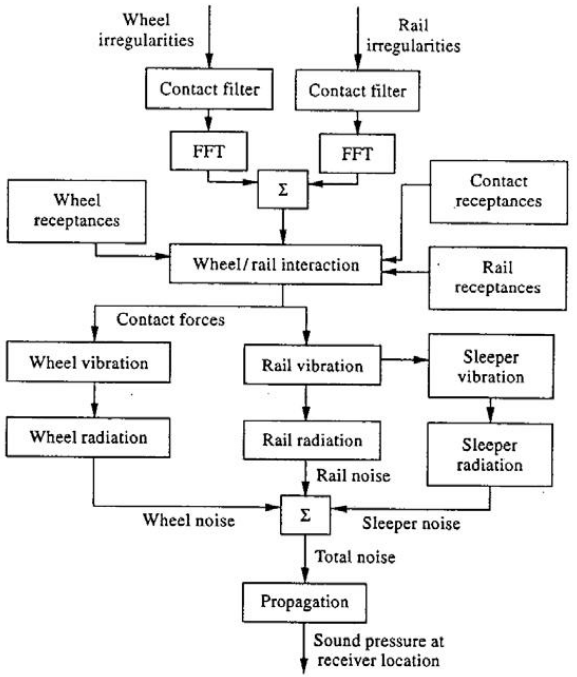

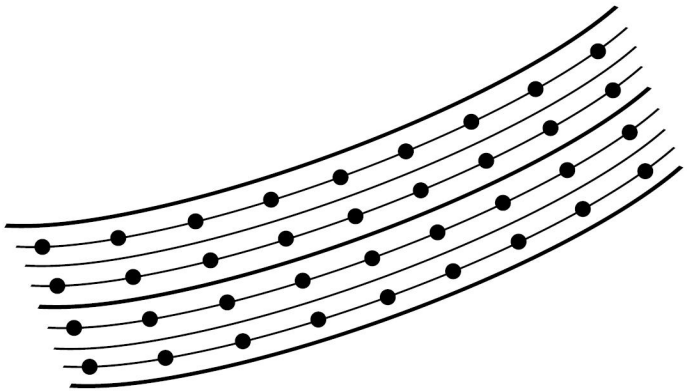

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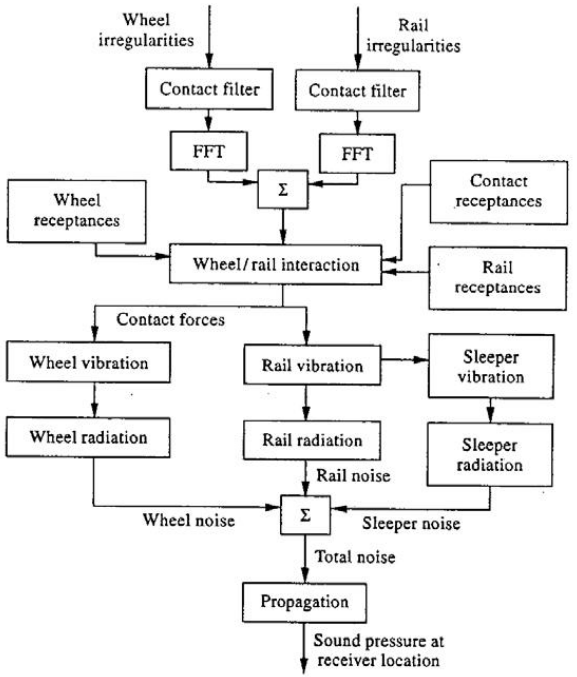

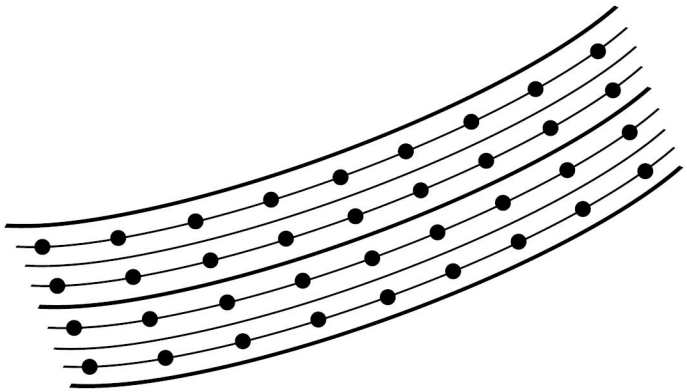

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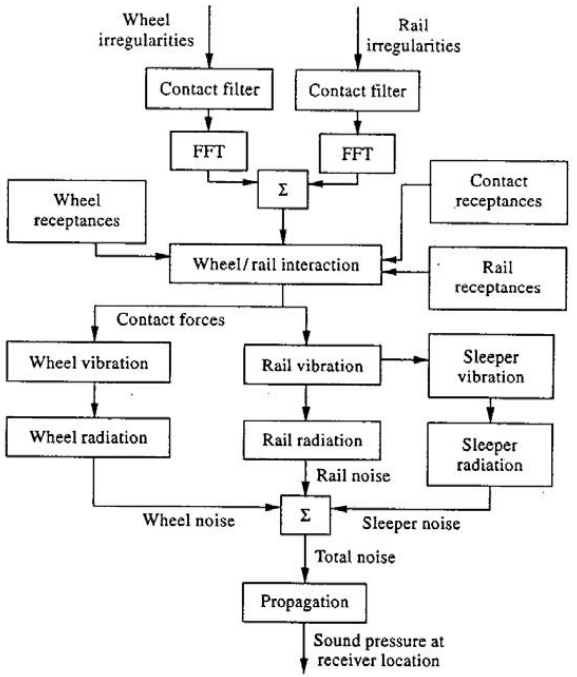
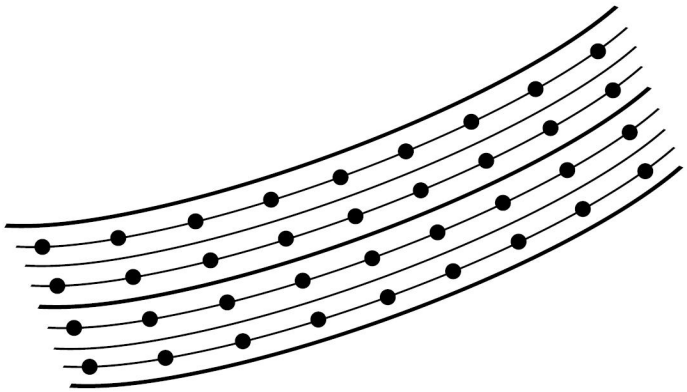
- numerous engineering models with different characteristics





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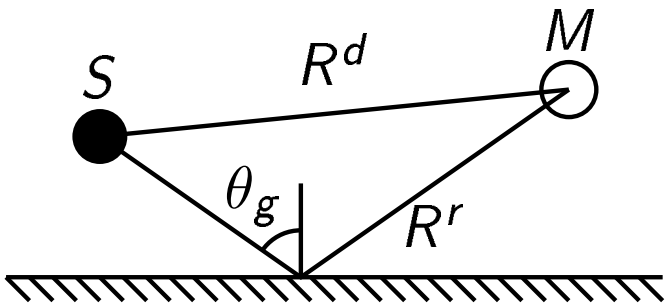

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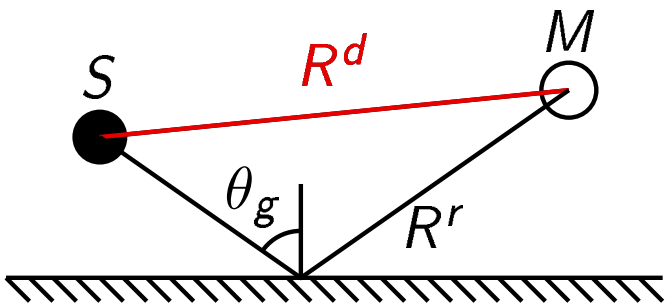

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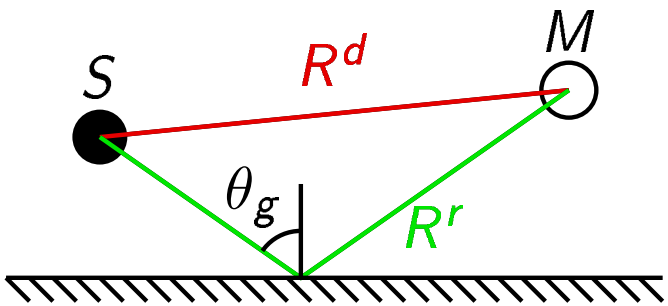

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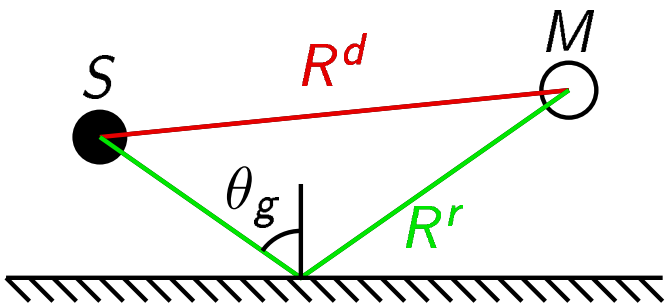

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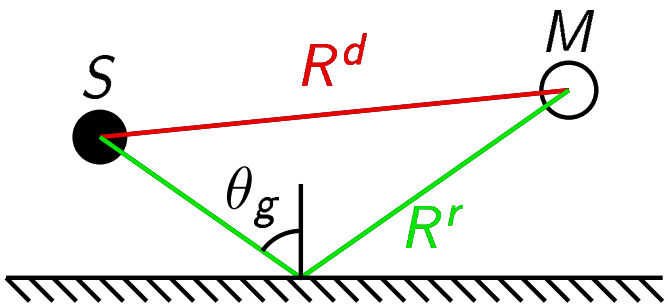
- ground impedance: Delany-Bazley-Miki's model
- meteorological effects neglected



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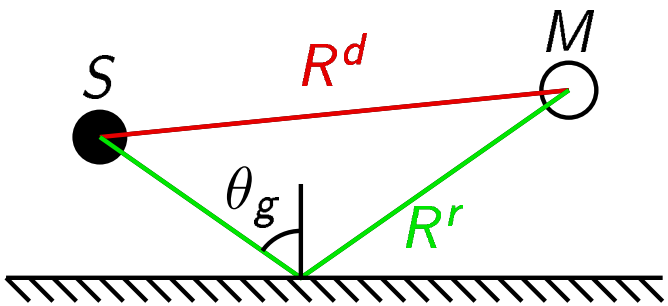

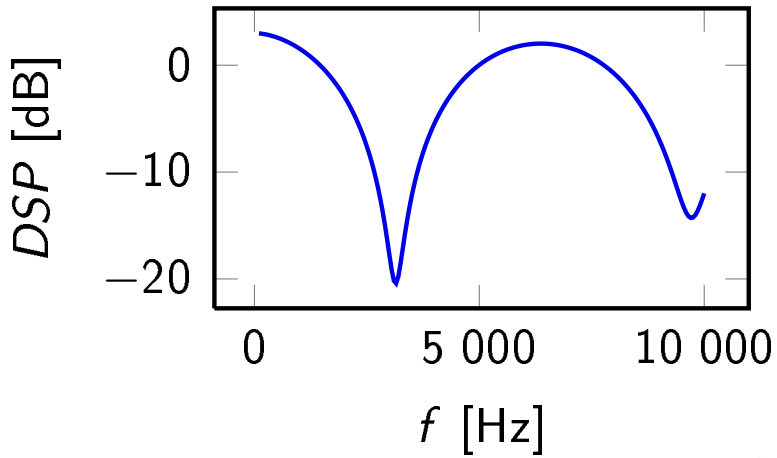

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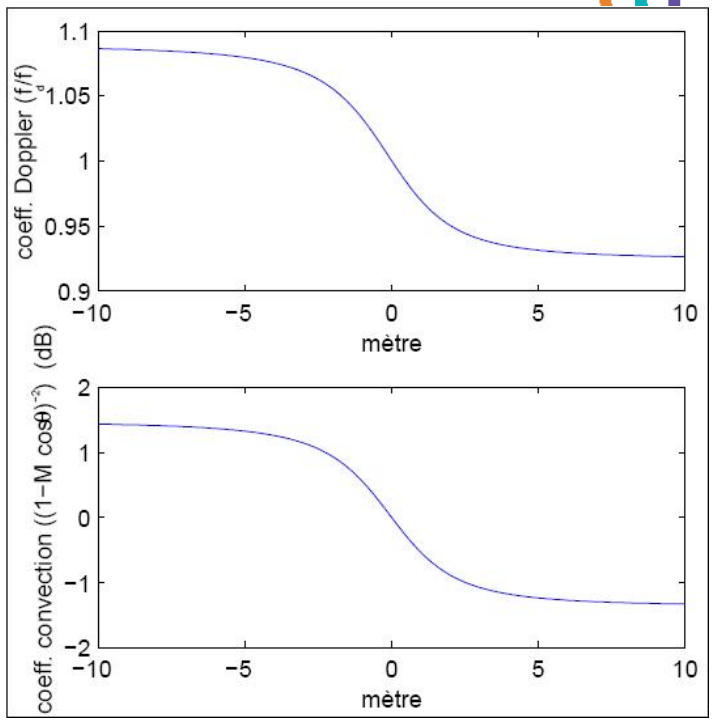

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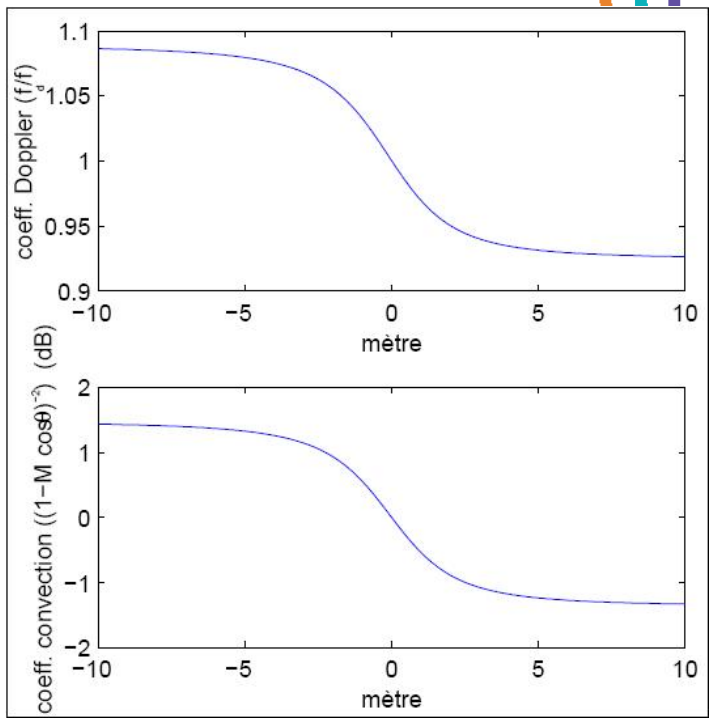
- *Doppler Weyl Van der Pol equation [Buret et al., 2006]*



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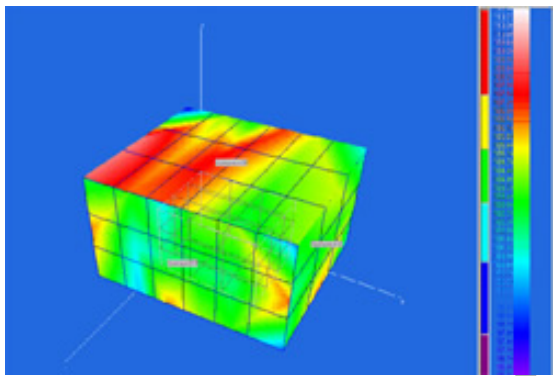

Measurements methods: reference

- acoustic arrays
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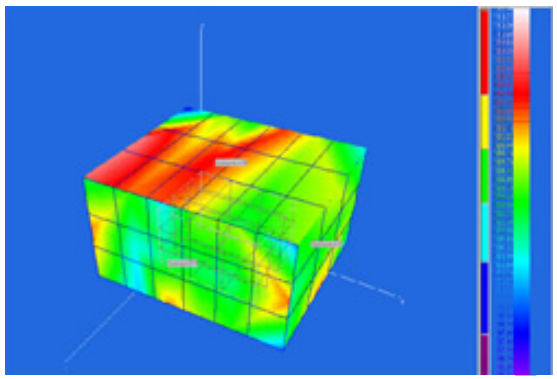
$\Rightarrow$ Not suitable for everyday out measurements:

- a lot of microphones
  - data acquisition
  - post-processing
- phase calibration
- is phase relevant outdoors near a real source?



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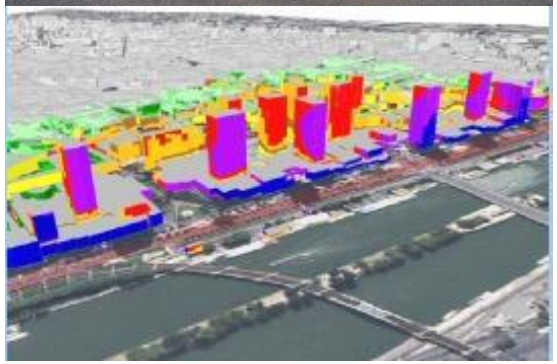

$\Rightarrow$ none is adapted for a dynamic indicator

State of the art: conclusion

- emission models: numerous with different parameters
- propagation models:
  - assume harmonic point source
  - no simple expression of the pressure produced by a moving source
- existing measurement methods:
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  - often deal only with one equivalent source
- need for a new method
  - easy measurement
  - easy post-processing
  - adapted to dynamic indicators

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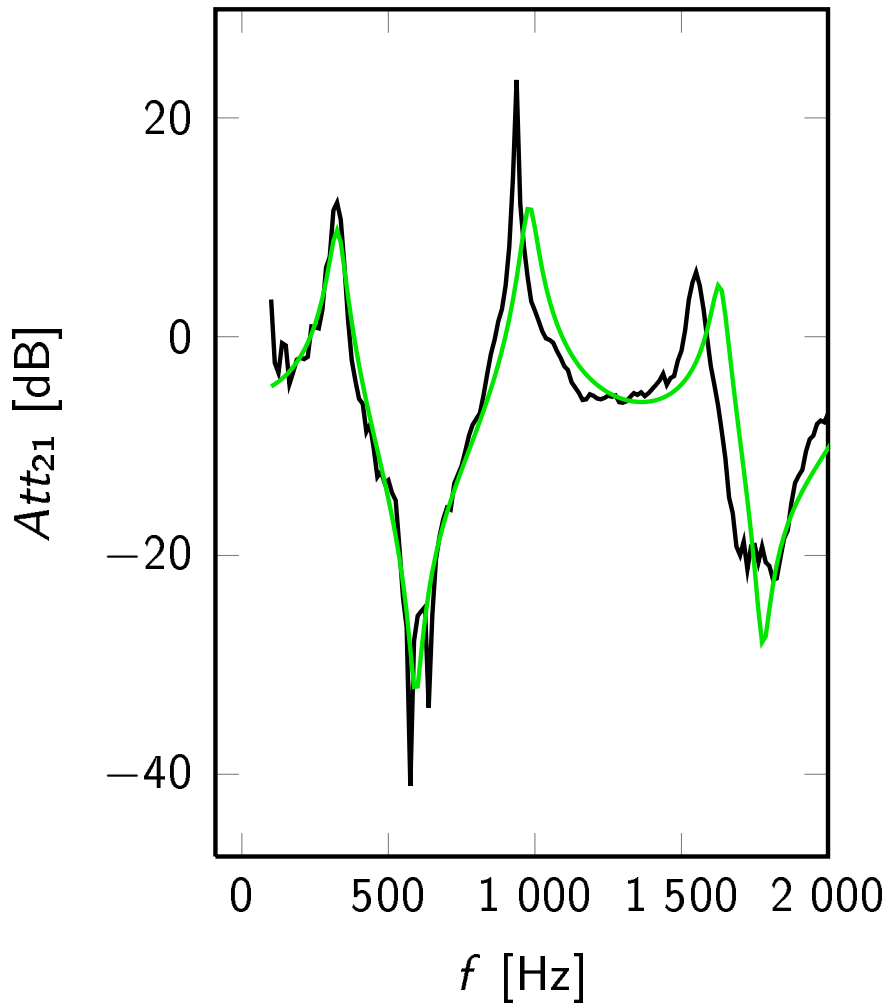
Broadband sources: measurement problems

Remarks from measurements

- differences between measurement and model
- localized at the interferences minima



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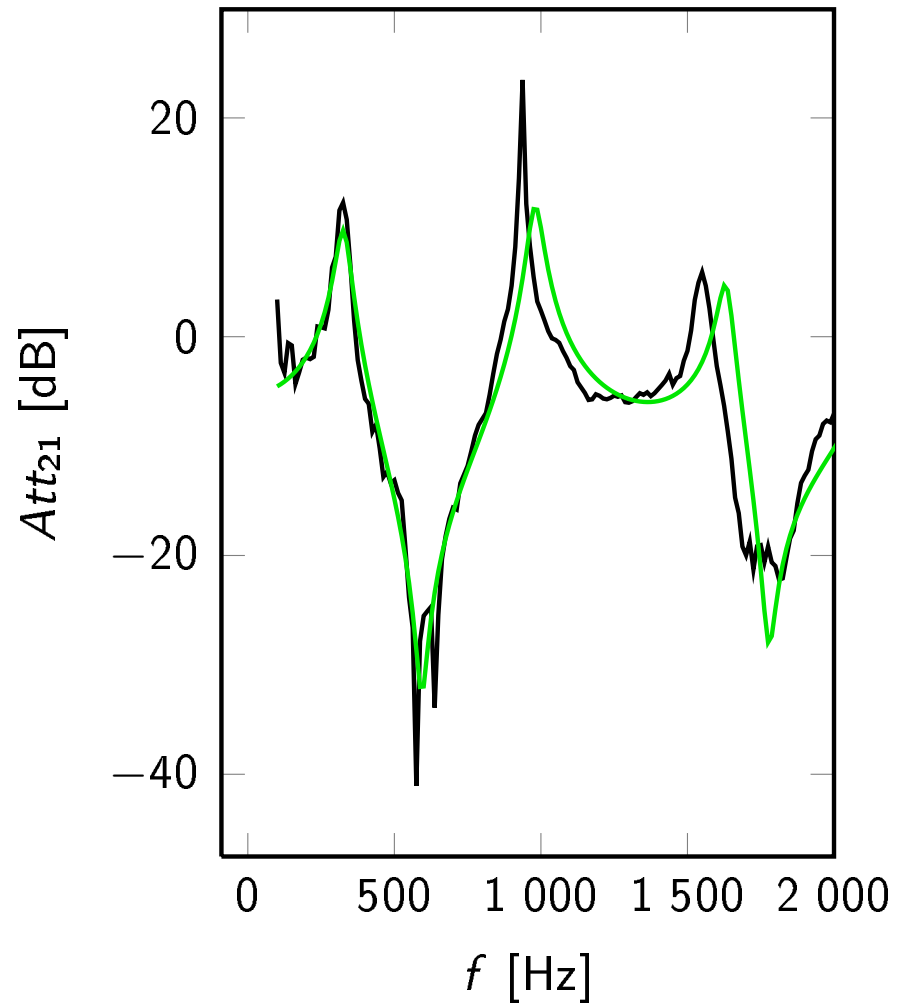

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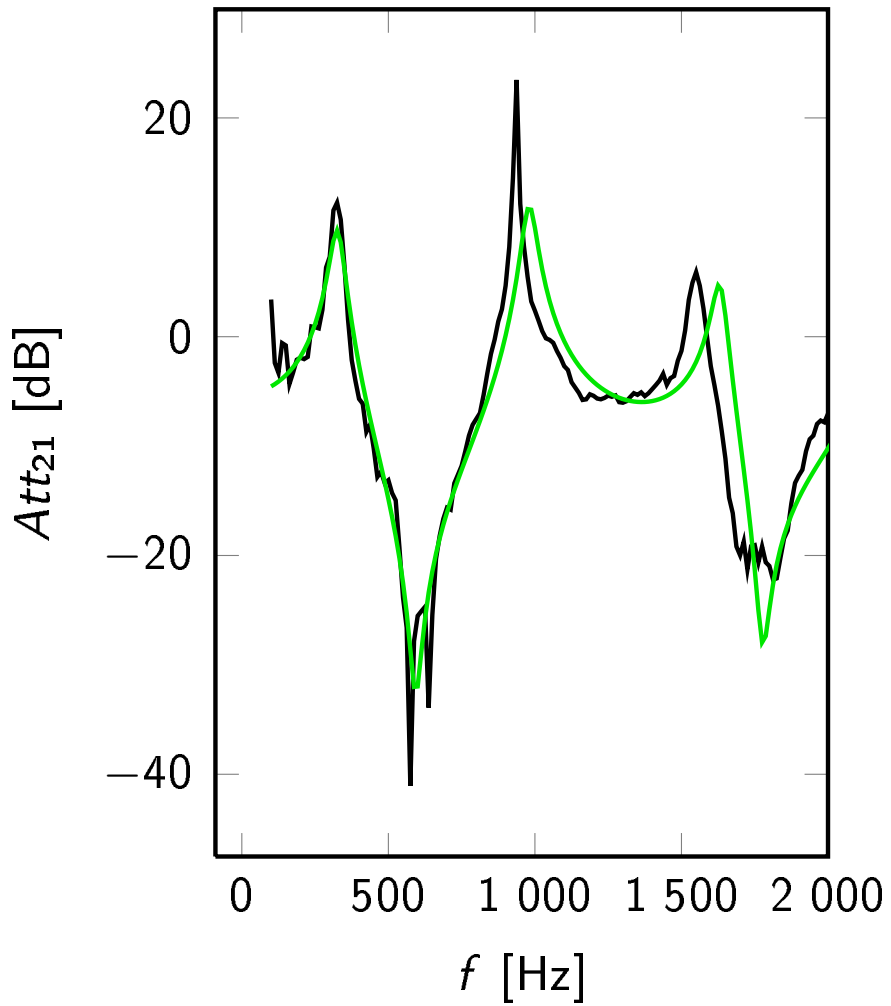

Broadband noise: theory

$$PSD(f) = \frac{1}{2}\left(\left|P^d(f)\right|^2 + |P^r(f)|^2 + 2\,\tau_{coh}\,\mathrm{Re}(P^d\,\overline{P^r})\right)$$

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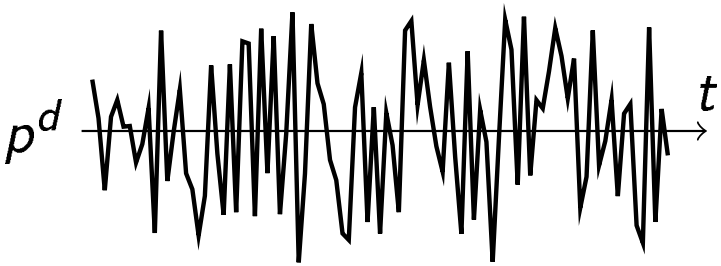

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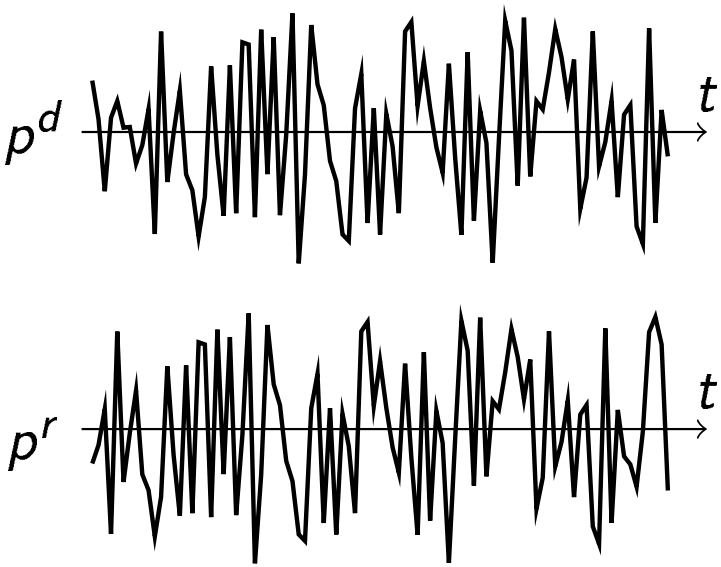

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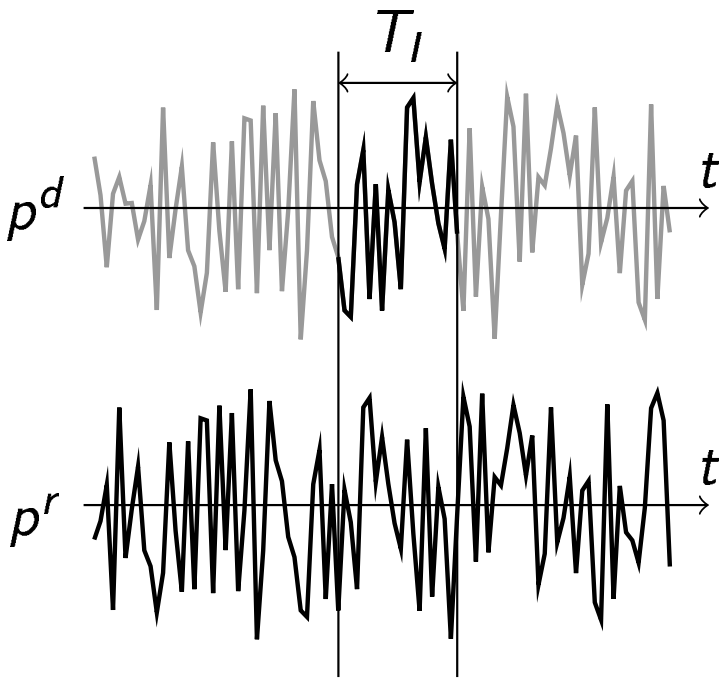

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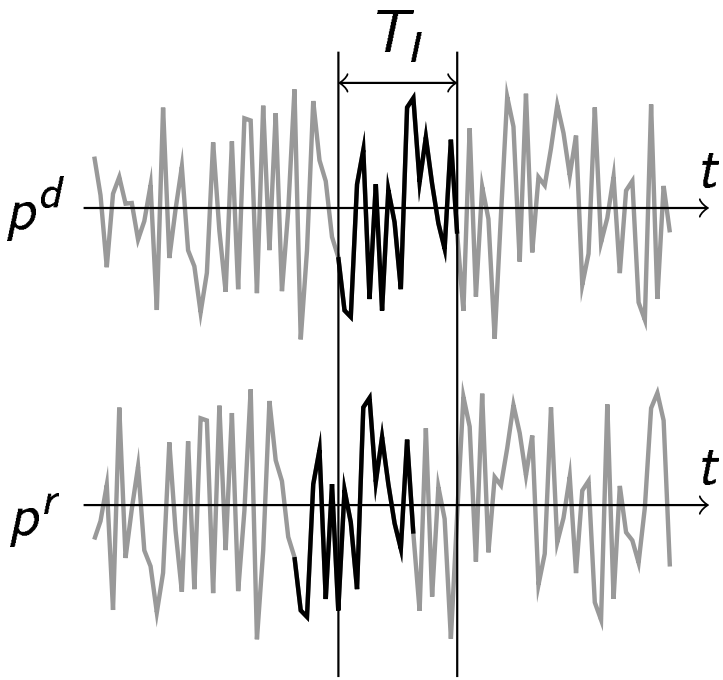

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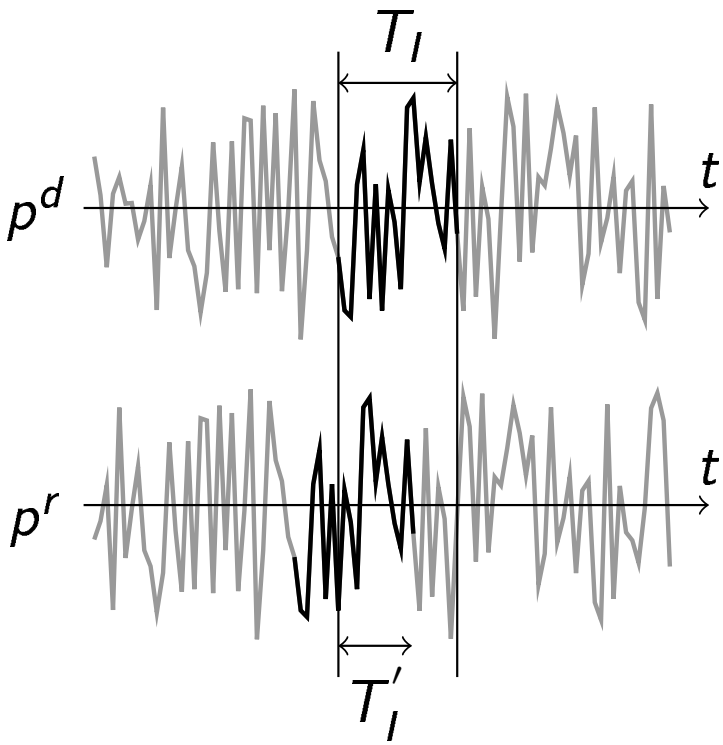


Broadband noise: theory

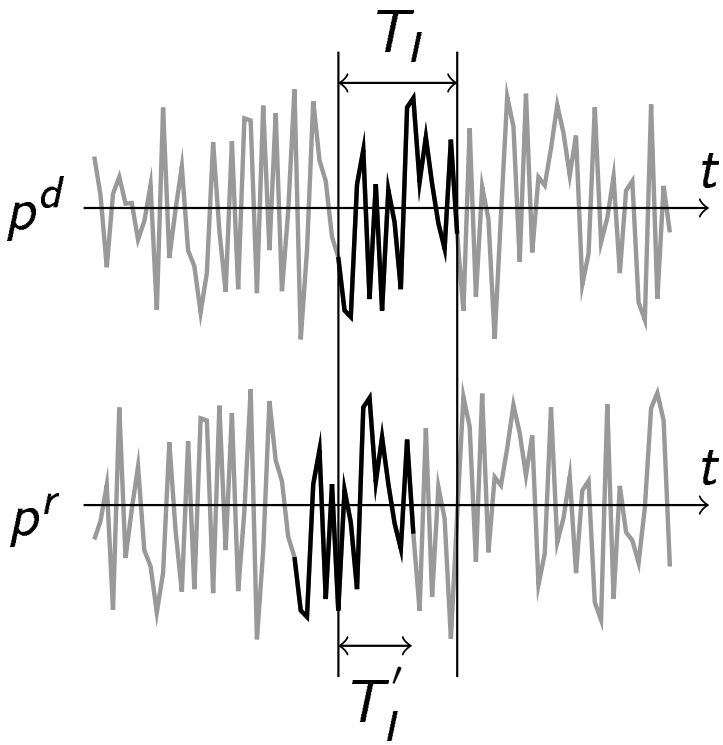
$$PSD(f) = \frac{1}{2}\left(\left|P^d(f)\right|^2 + |P^r(f)|^2 + 2\,\tau_{coh}\,\mathrm{Re}(P^d\,\overline{P^r})\right)$$

with

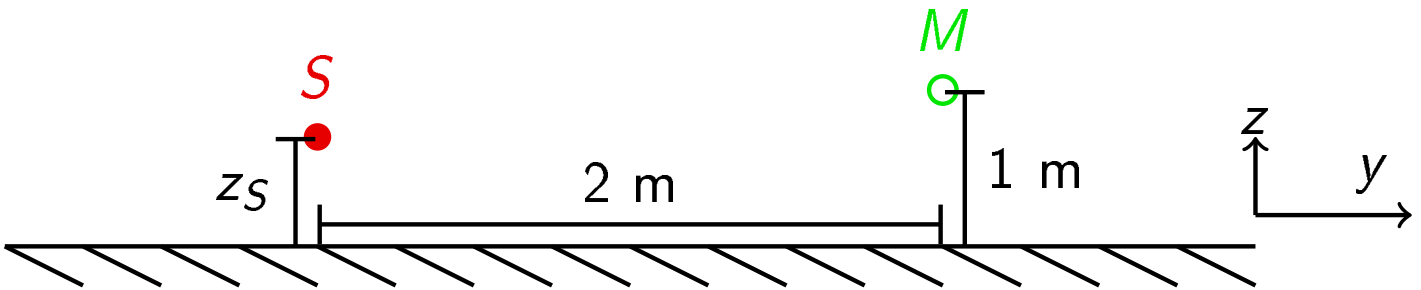
$$\tau_{coh} = \begin{cases} 0 \text{ if } (R^r - R^d)/c > T_l \\ 1 \text{ if } R^r \approx R^d \\ \dfrac{T_l'}{T_l} \text{ otherwise.} \end{cases}$$

and

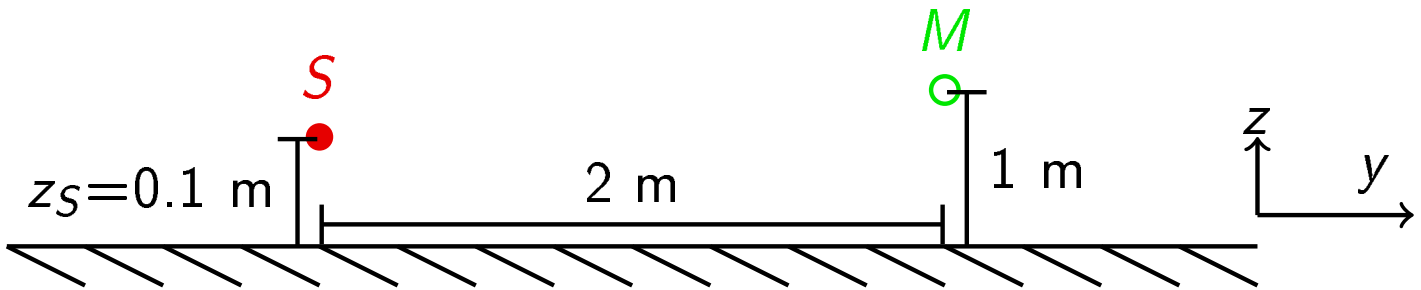
$$T_l' = T_l - \frac{R^r - R^d}{c}$$

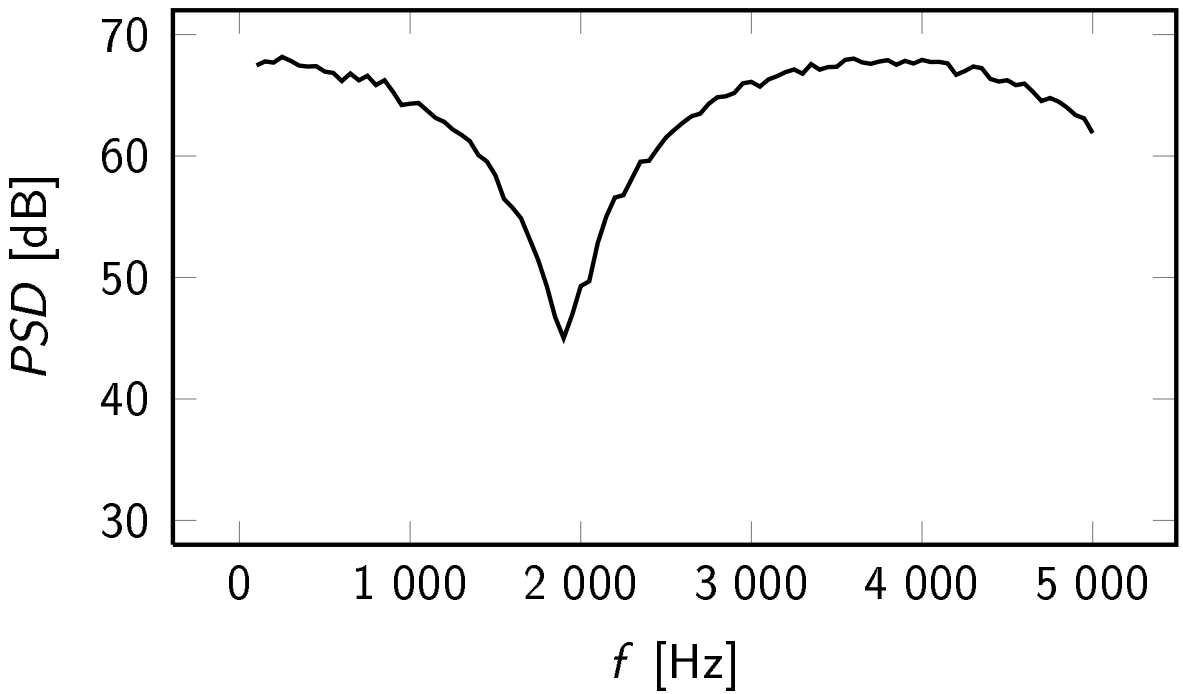


Broadband noise: simulations

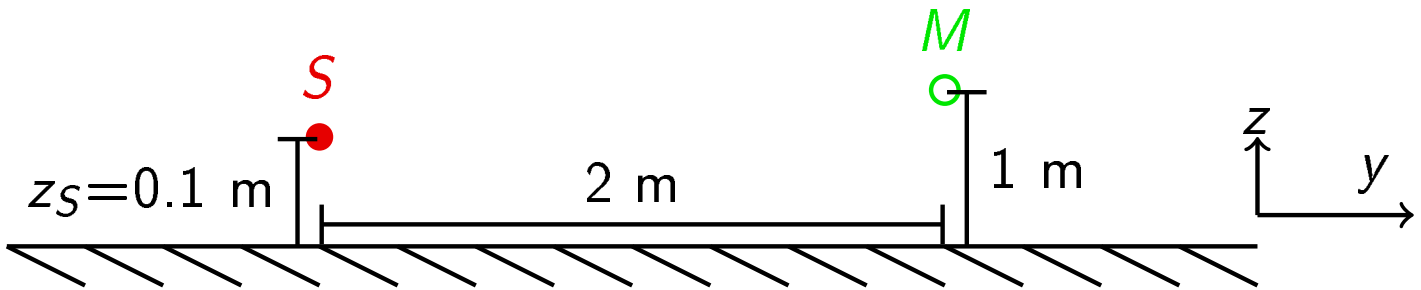


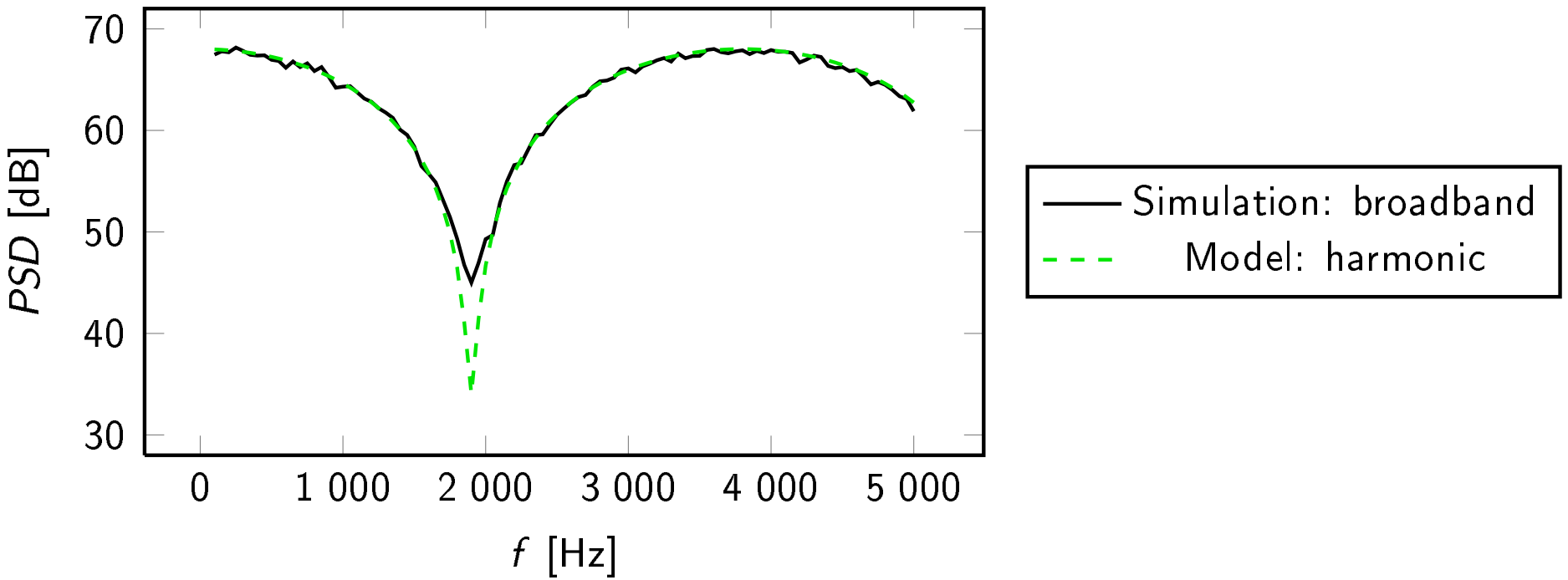
Broadband noise: simulations





Broadband noise: simulations





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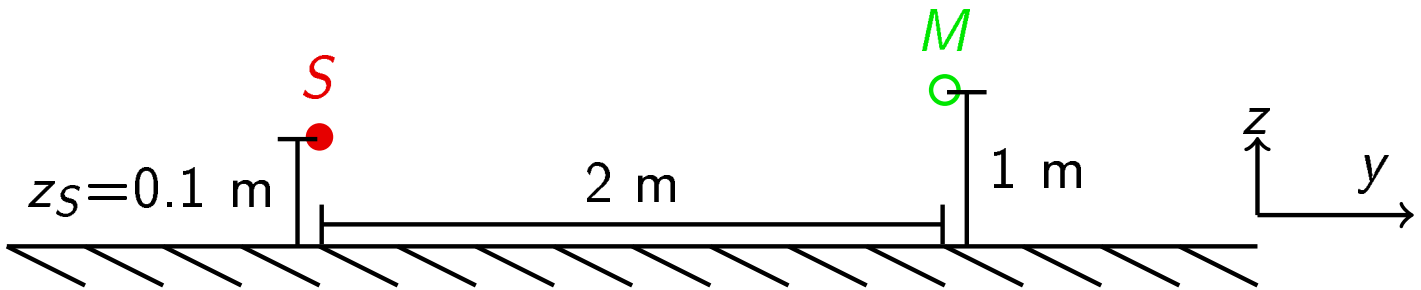

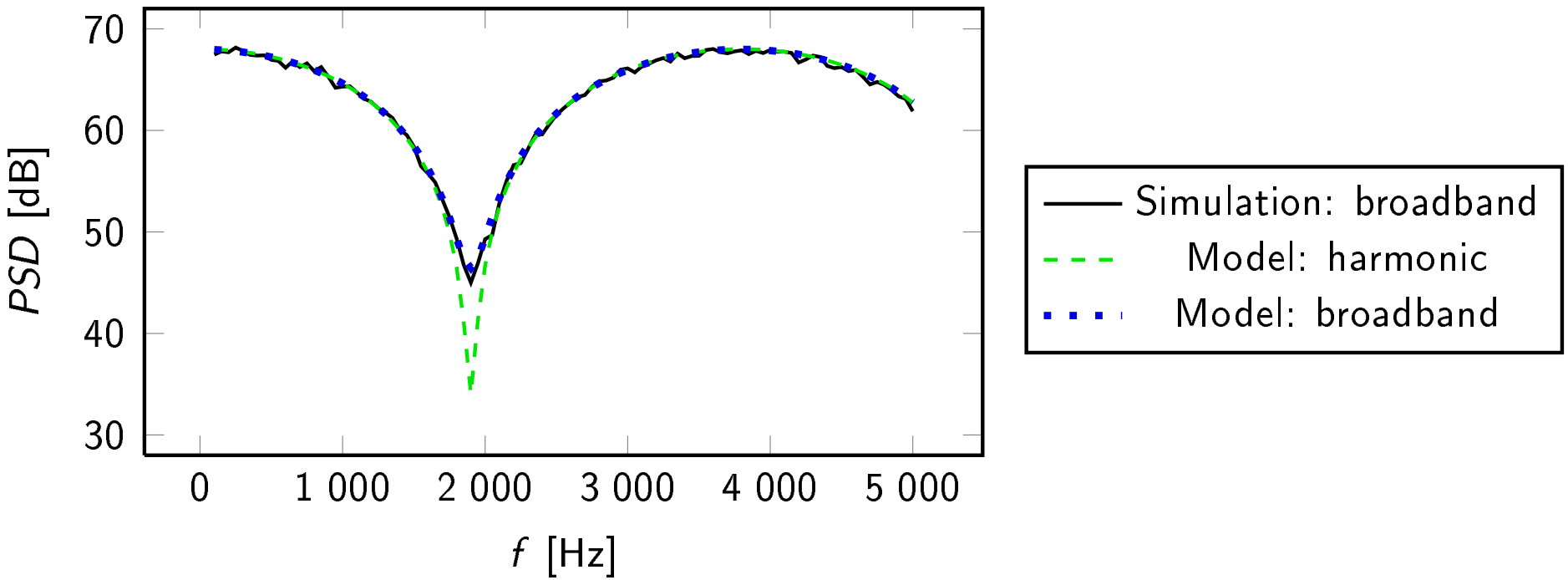

Moving source: layout

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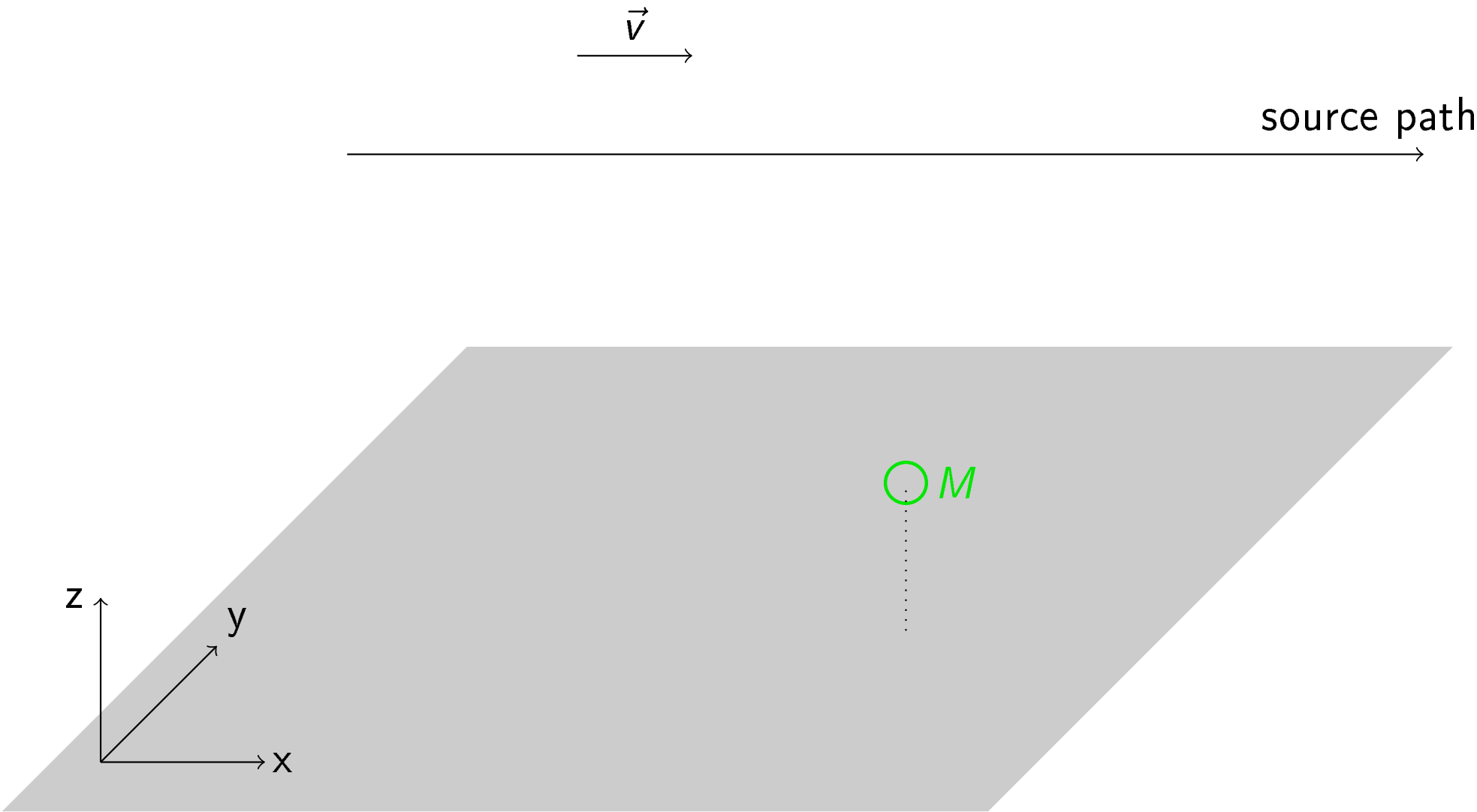

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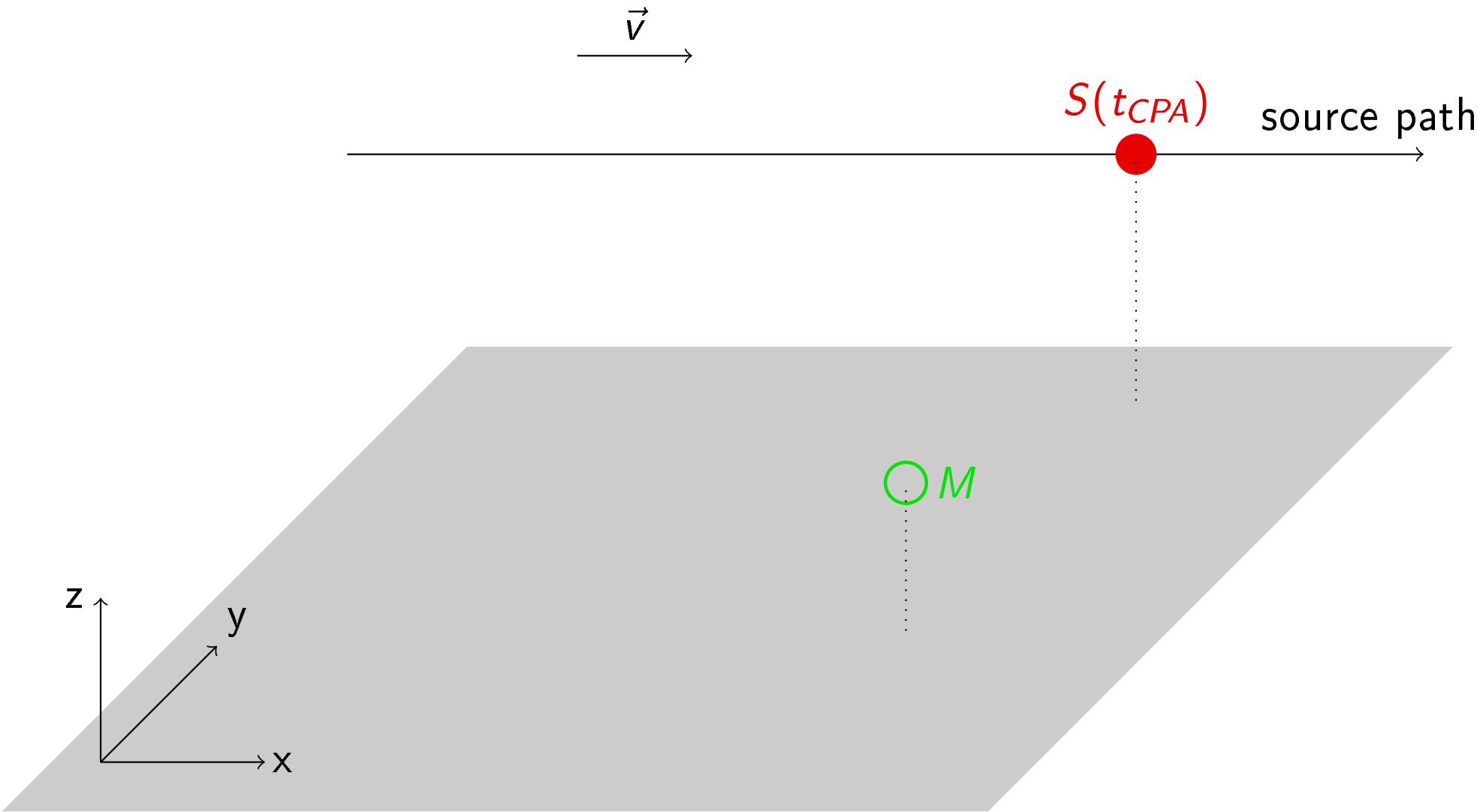

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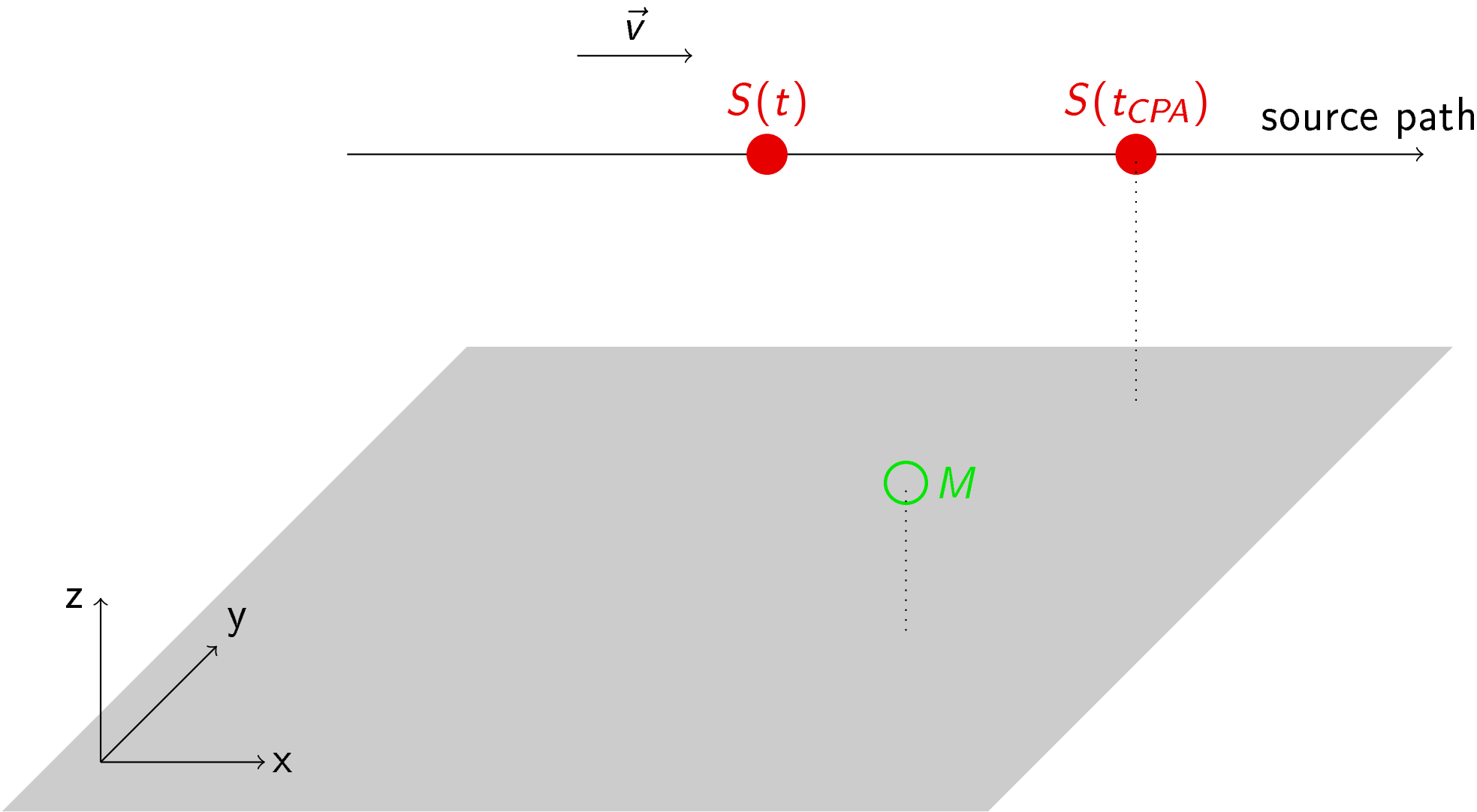

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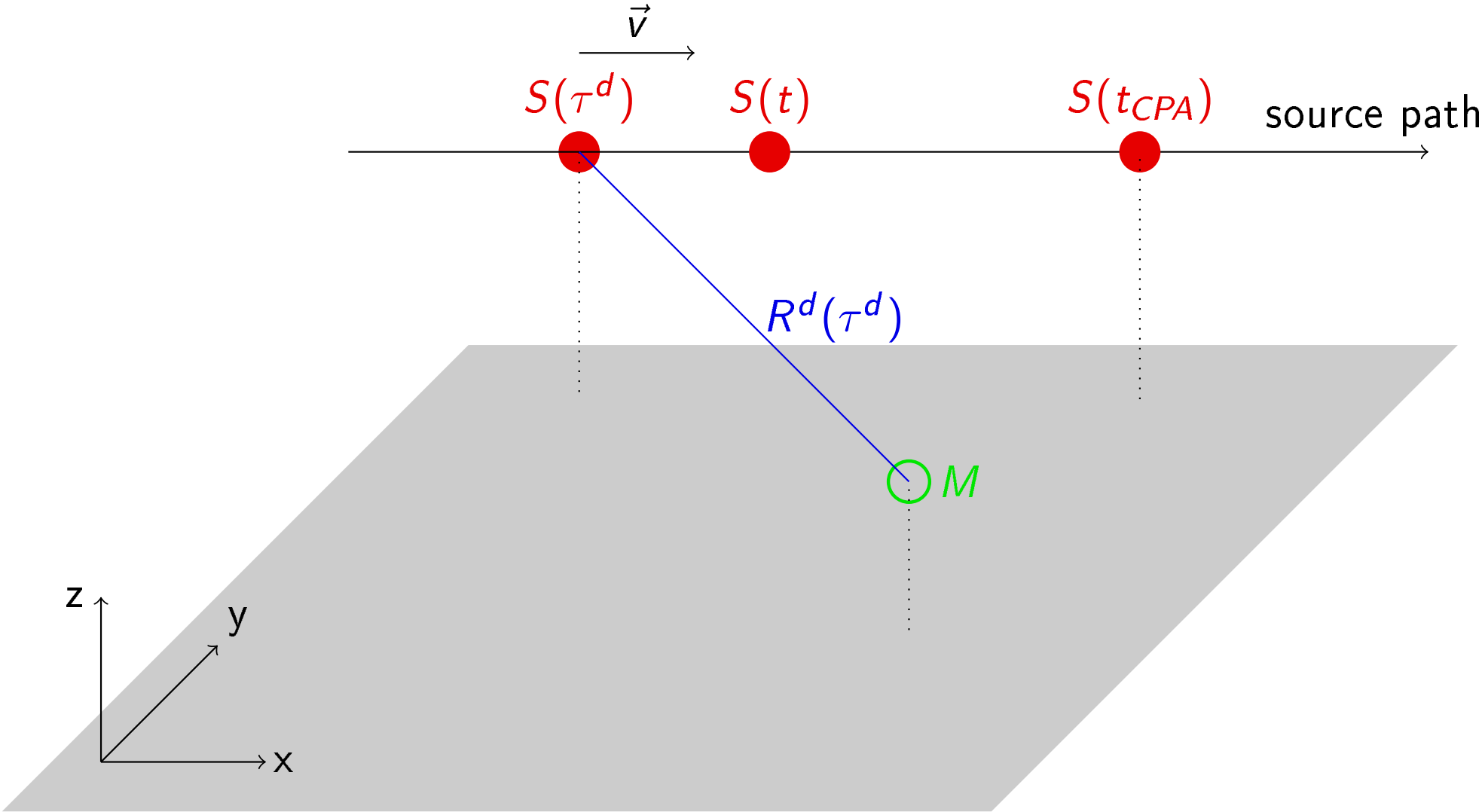

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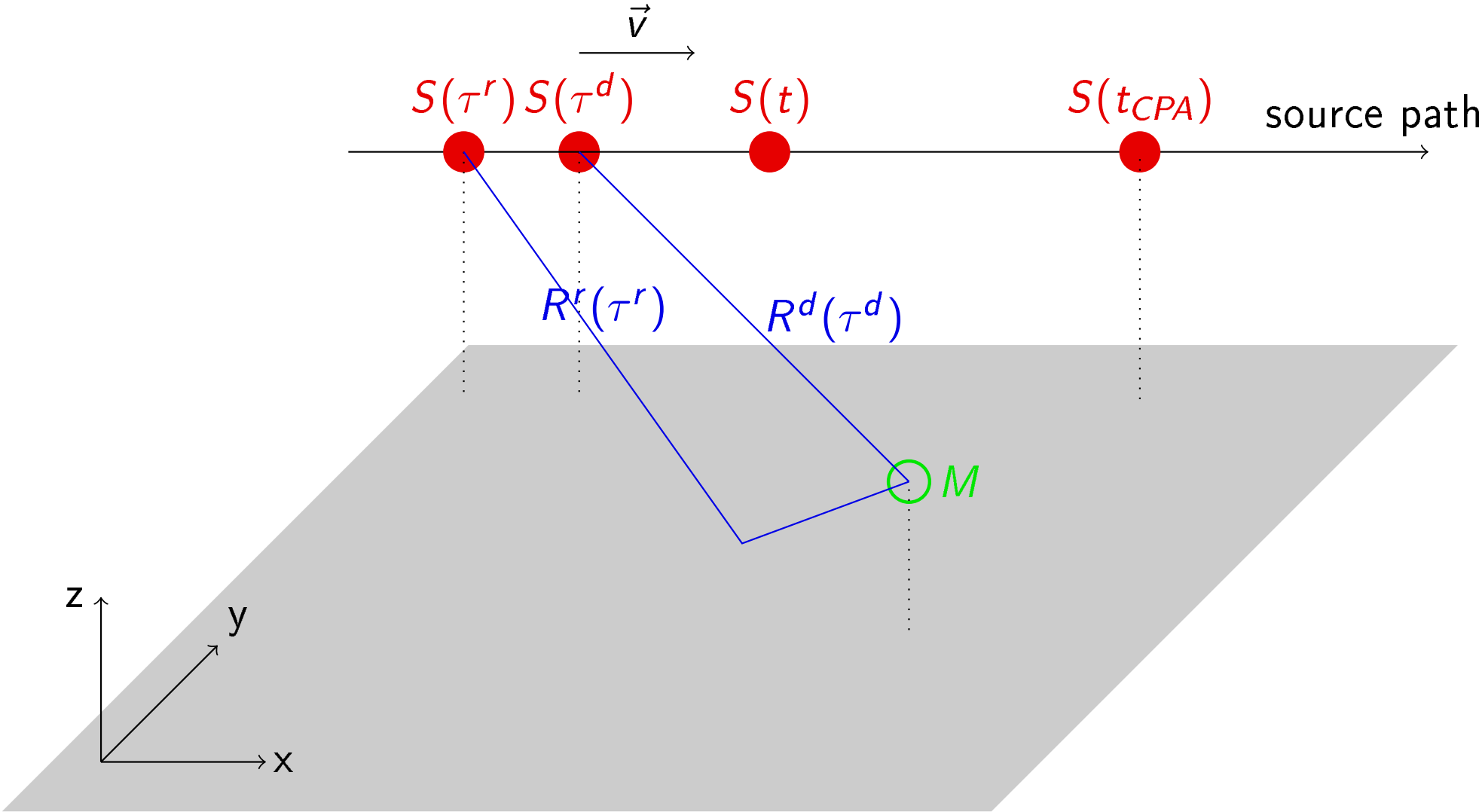

Moving source: existing model

- Temporal Model for one Moving Source (MTSM), *Doppler Weyl van der Pol equation*

$$p(t) = \frac{-\jmath\omega A}{4\pi} \times \left(C^d \frac{e^{\jmath\kappa R^d}}{R^d} + C^r \; Q(w^r) \; \frac{e^{\jmath\kappa R^r}}{R^r} \right)$$

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Moving source: simplified model

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- a lot of variables are function of time

Moving source: simplified model

$$p_l = \frac{-\jmath\omega A}{4\pi} \times \left(C^d \frac{e^{\jmath\kappa R^d}}{R^d} + C^r \; Q(w^r) \; \frac{e^{\jmath\kappa R^r}}{R^r} \right)$$

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Moving source: simplified model

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$$p_l(t) \approx \frac{-\jmath \; \omega \; A}{4\pi} \times \left\{ \tilde{C}_l^d \frac{e^{\jmath(\mu_l^d t + \nu_l^d)}}{R_l^d} + \tilde{C}_l^r \; Q_l \; \frac{e^{\jmath(\mu_l^r t + \nu_l^r)}}{R_l^r} \right\}$$

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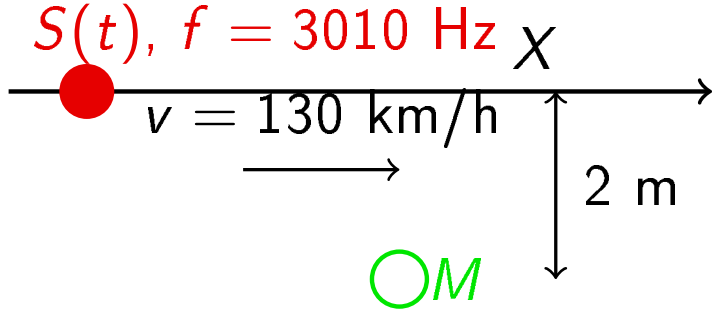
Moving source: numerical results of a worst case



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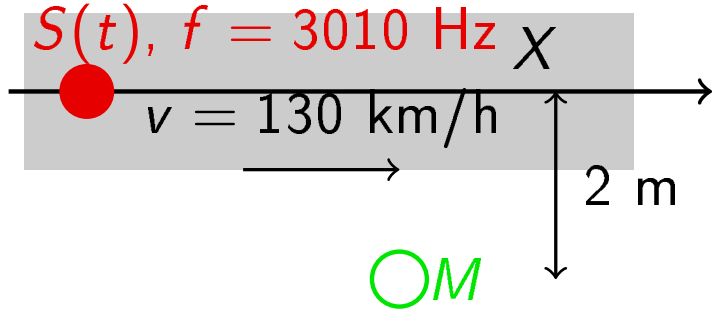

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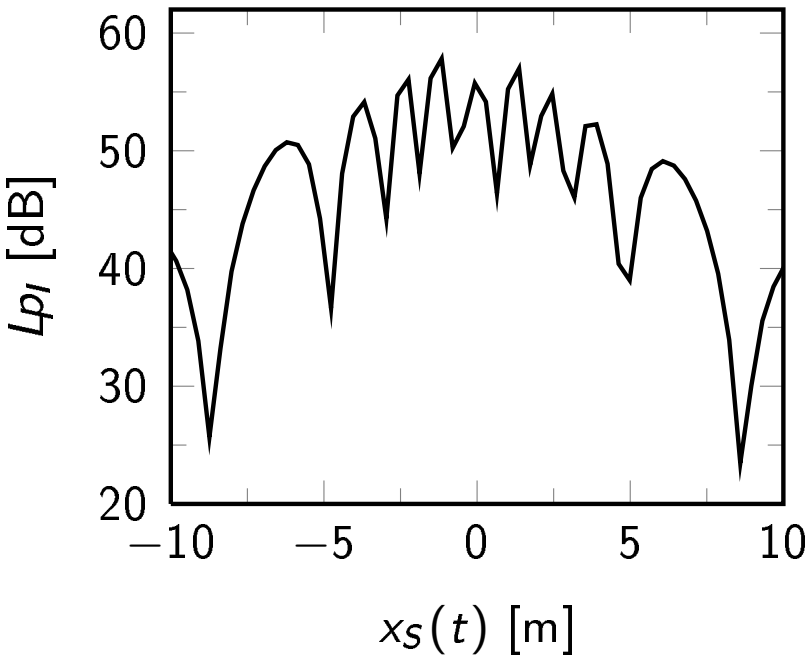

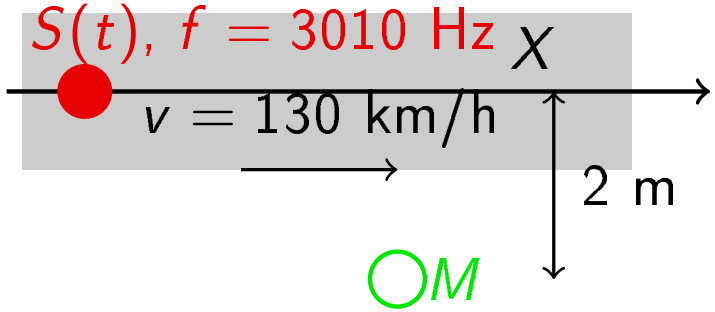

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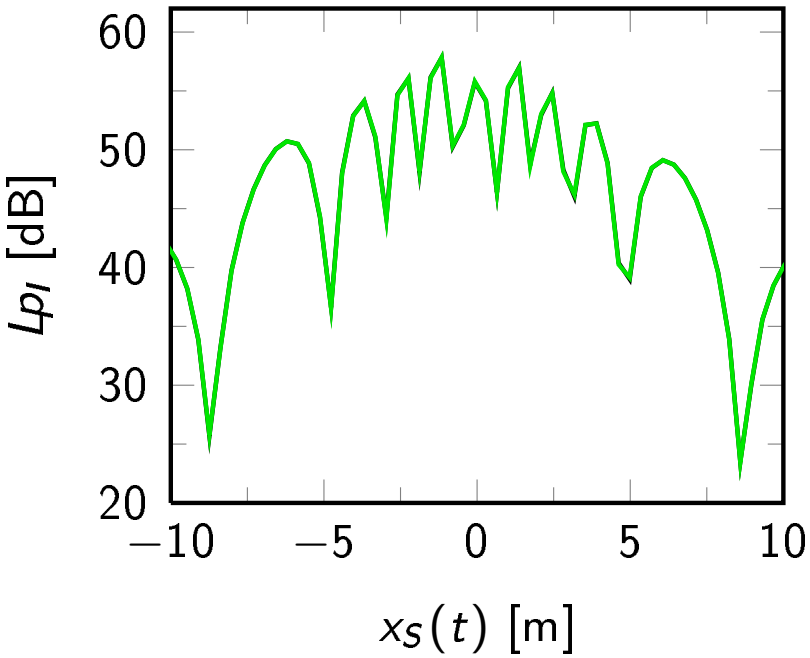

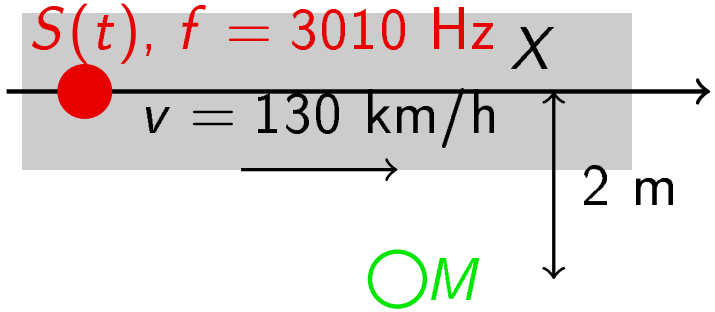

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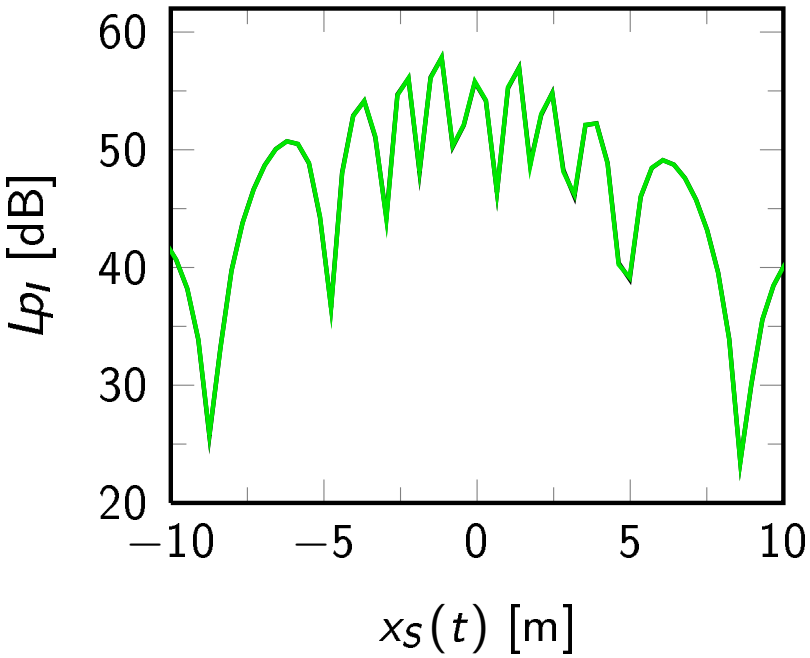

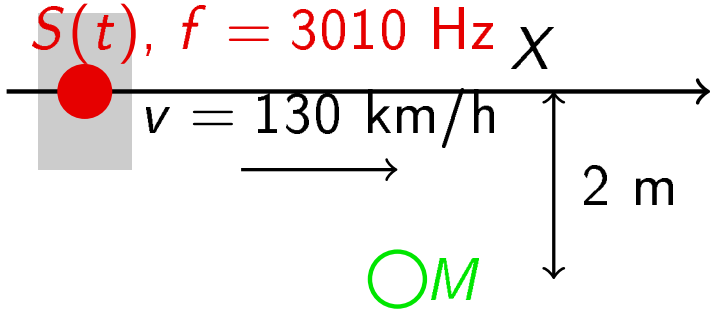

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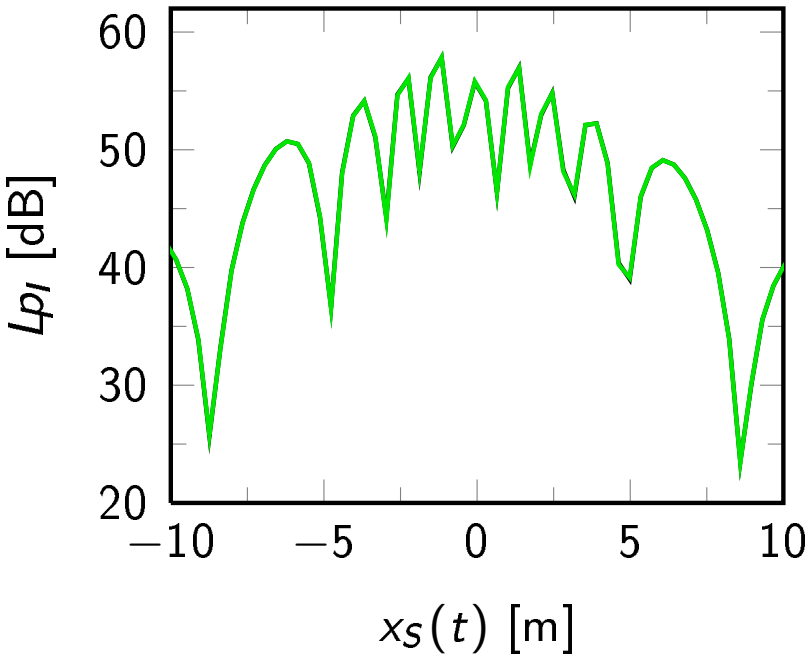
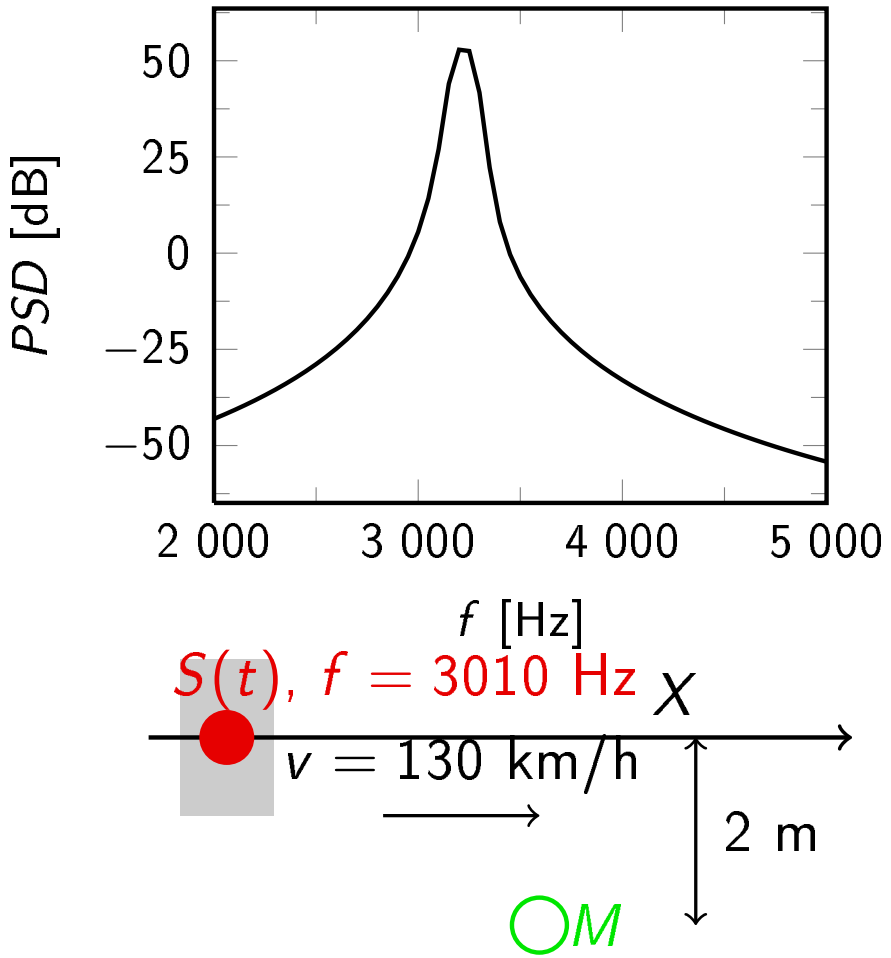
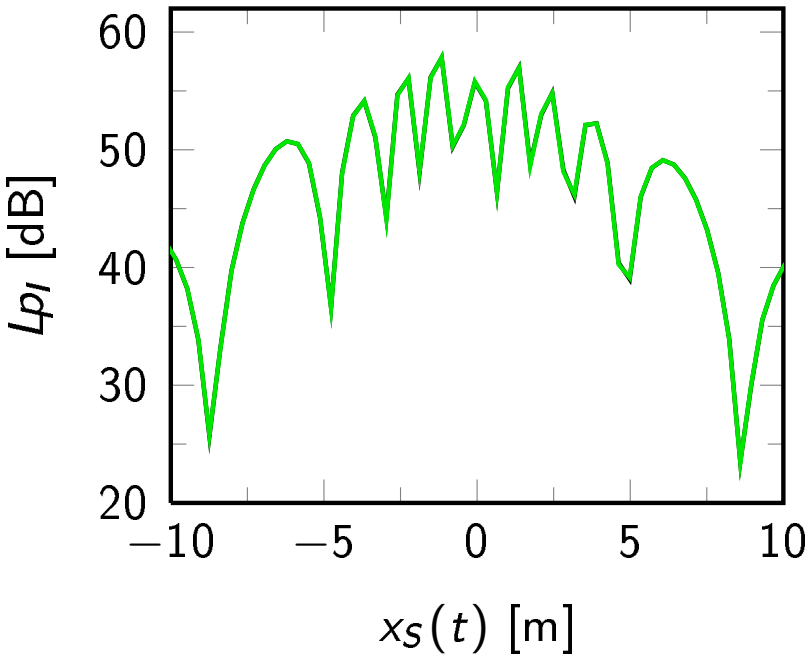
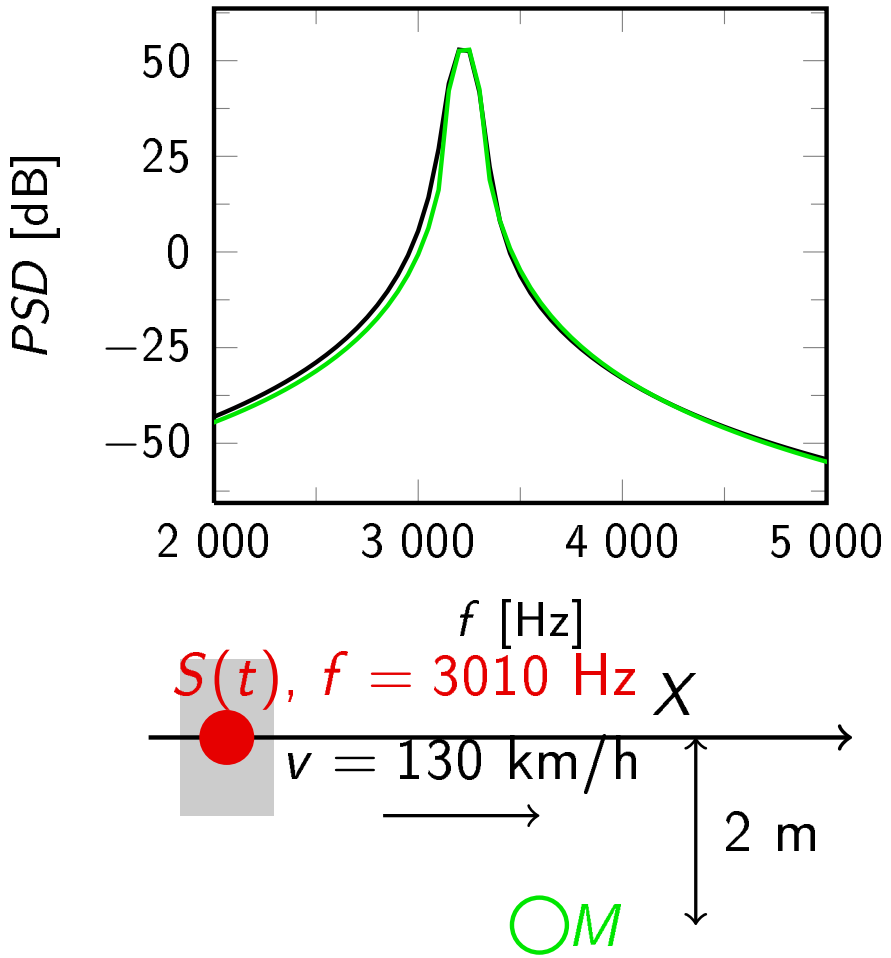




Model
Simplified model

Moving source: numerical results of a worst case





Model
Simplified model

Model improvements

- Broadband source
  - heuristic approach
  - numerical validation

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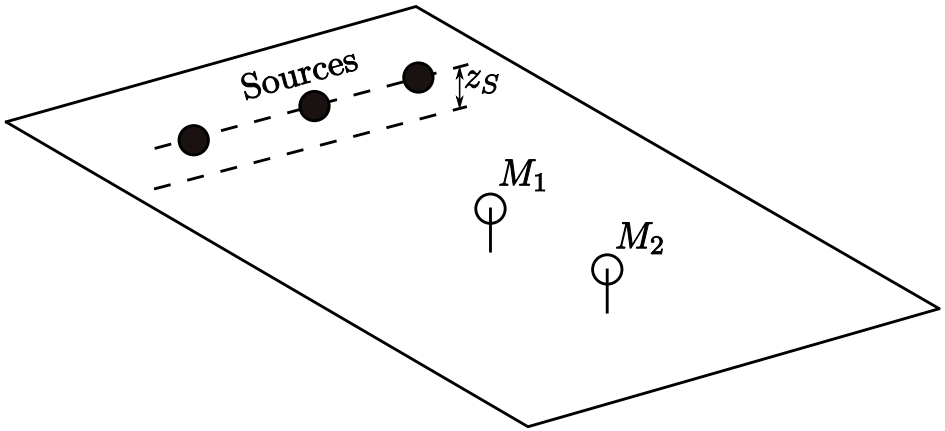
Table of contents

Fixed source height: statement of the problem



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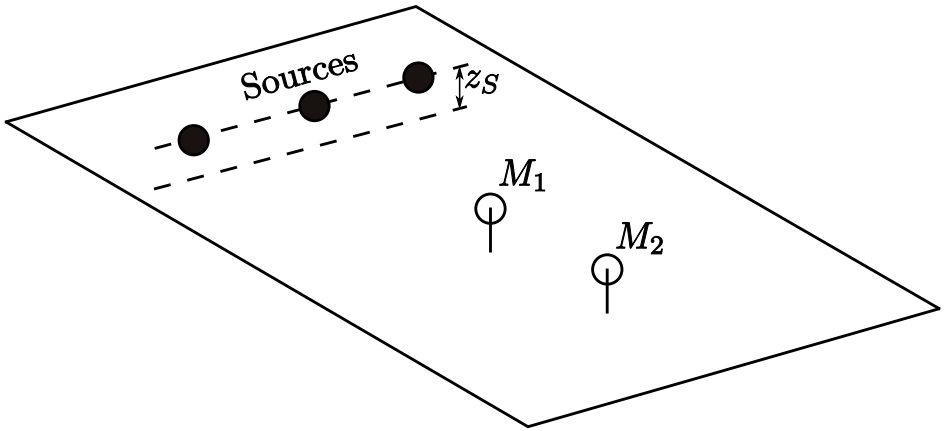

PSD_j → propagation^{-1} → Emission
- N_{Se}
- $(x_{Se}, y_{Se}, z_{Se})_i$
- $|A_i|^2$

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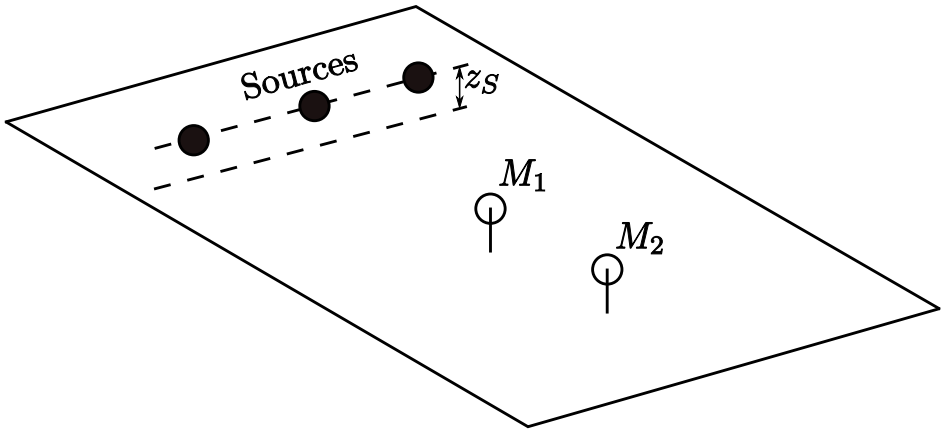

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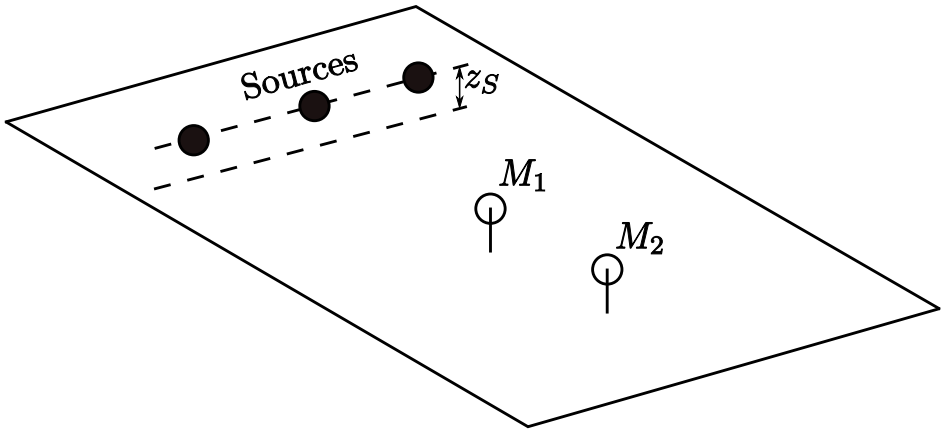

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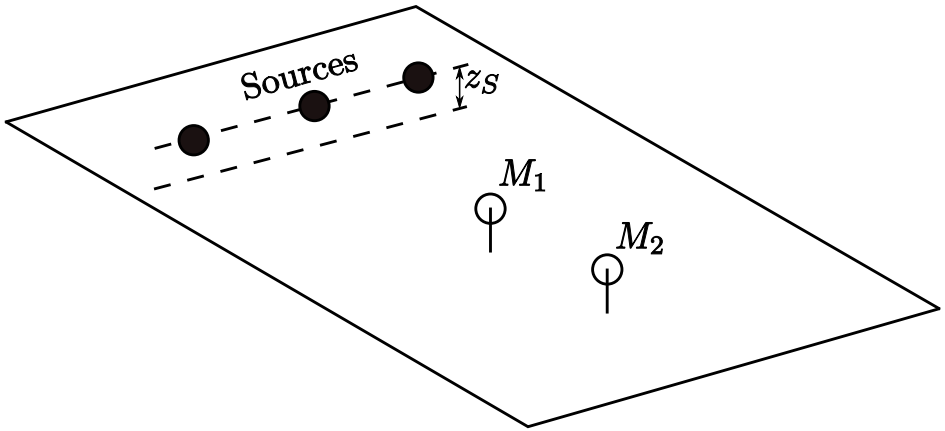

$\cancel{PSD_j} Att_{21}$ → propagation^{-1} → Emission

- $\cancel{N_{Se}}$
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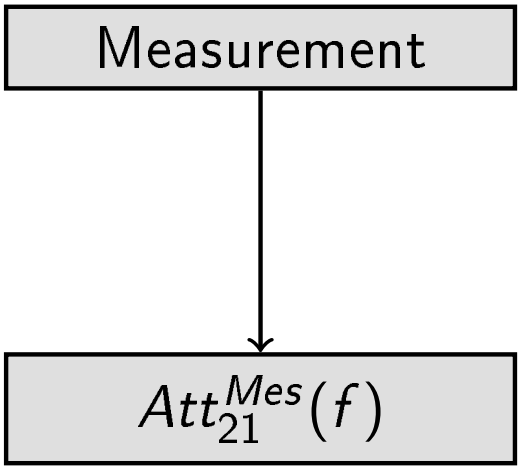
Fixed source height: synoptic



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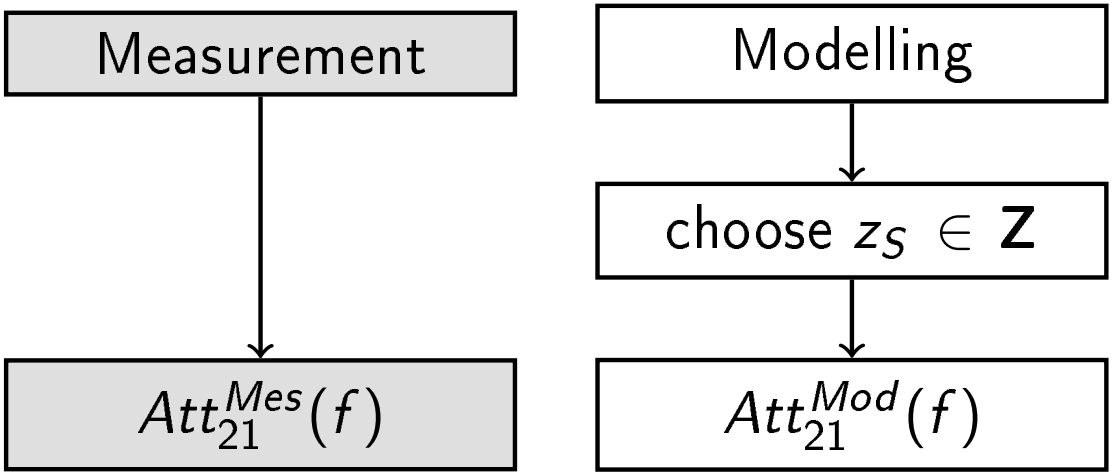

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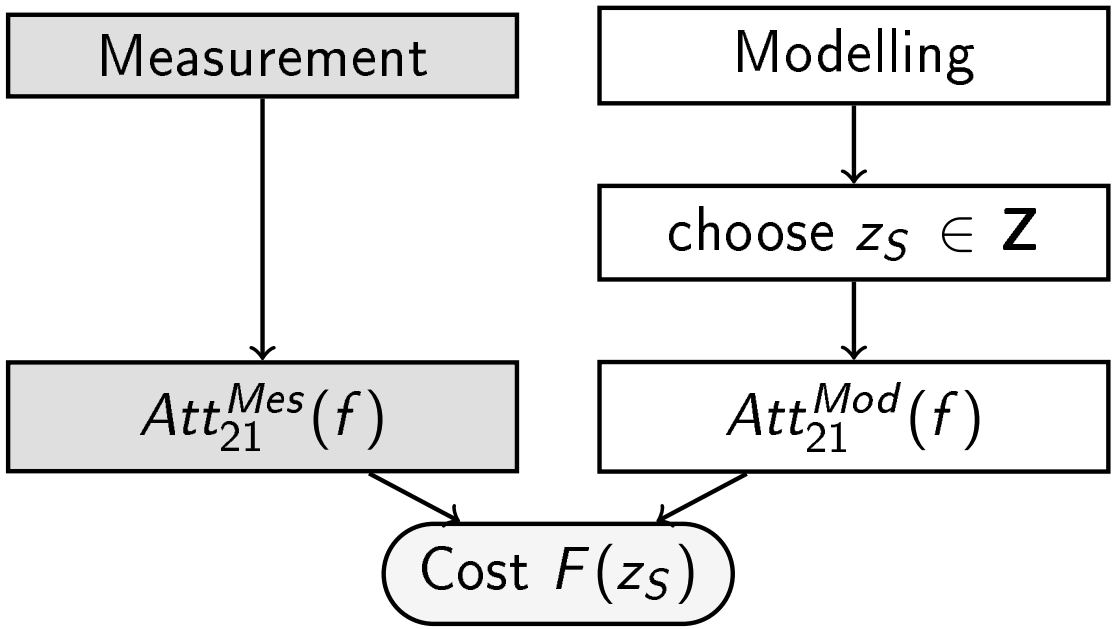

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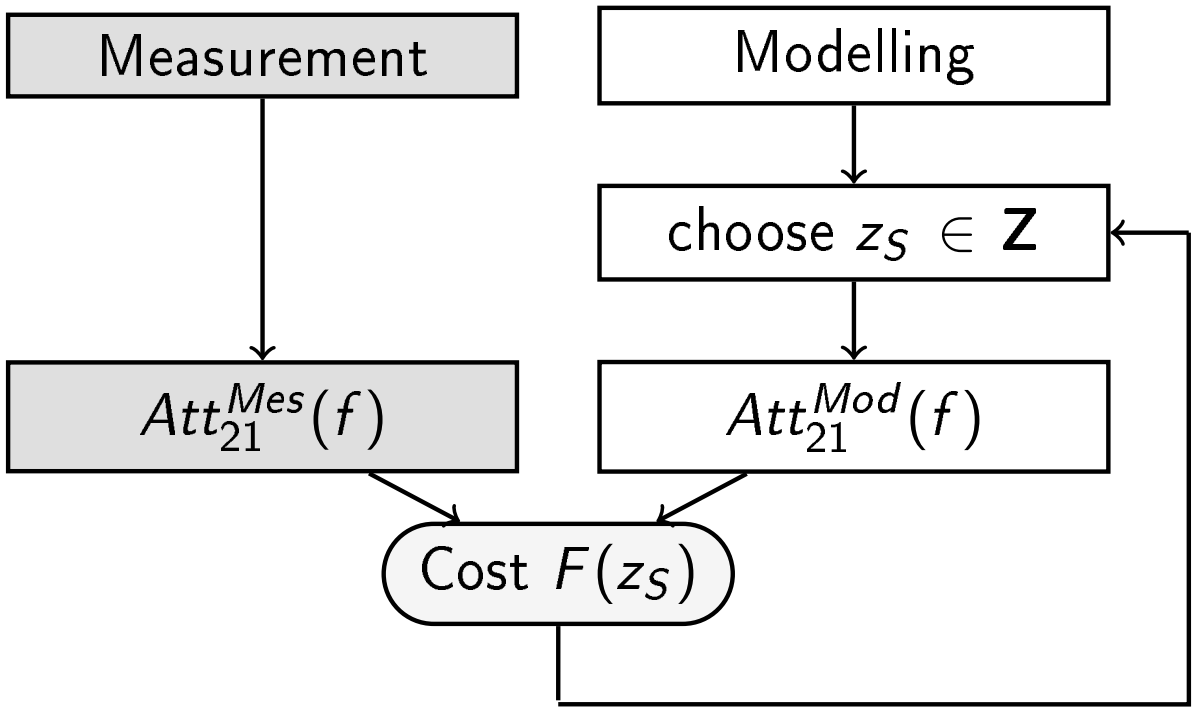

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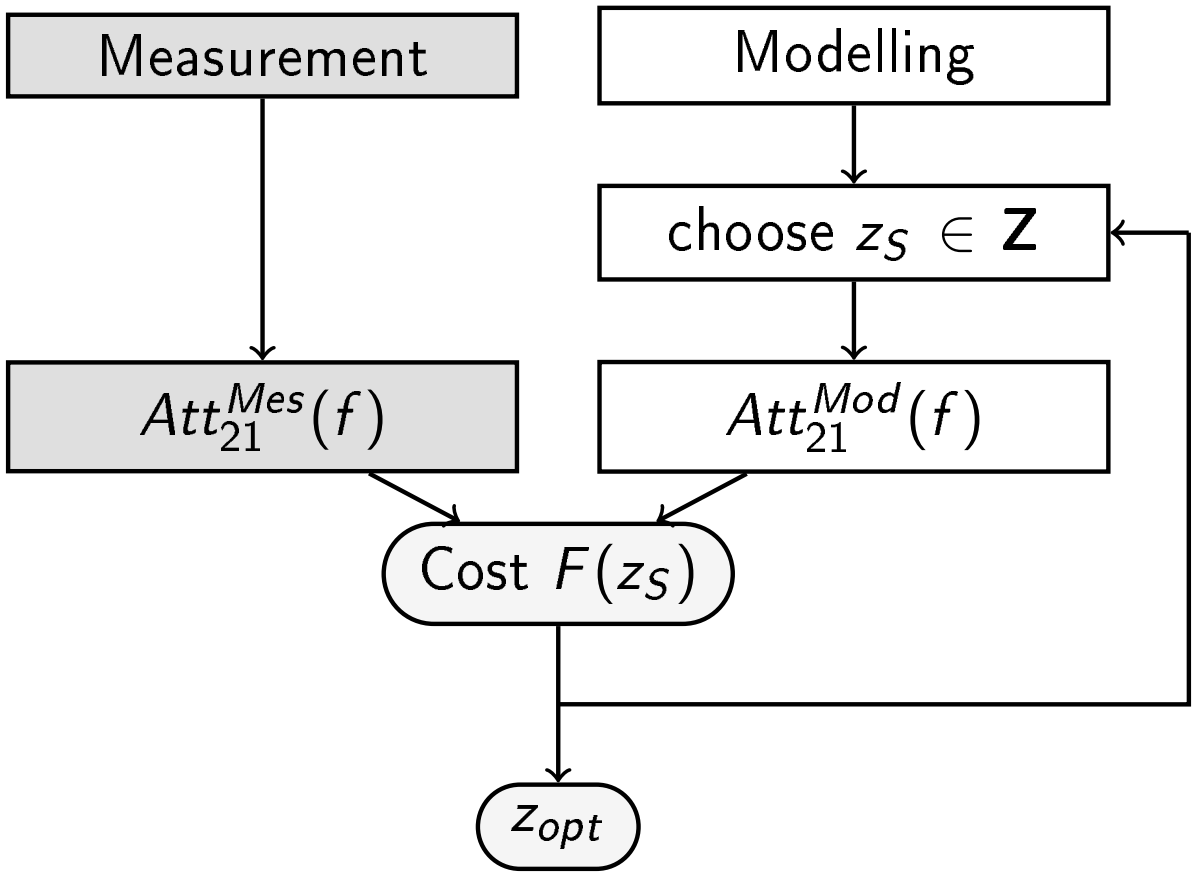
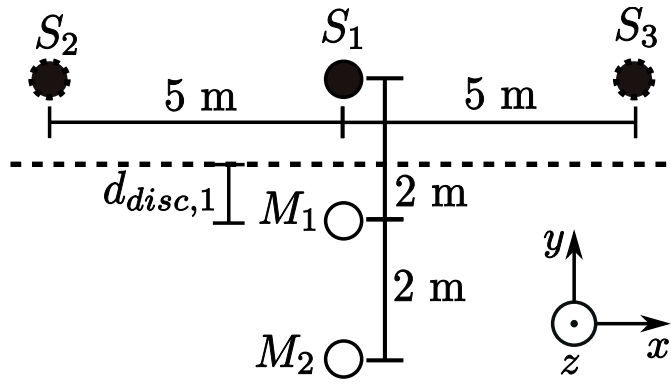


Fixed source height: measurement results (1/2)



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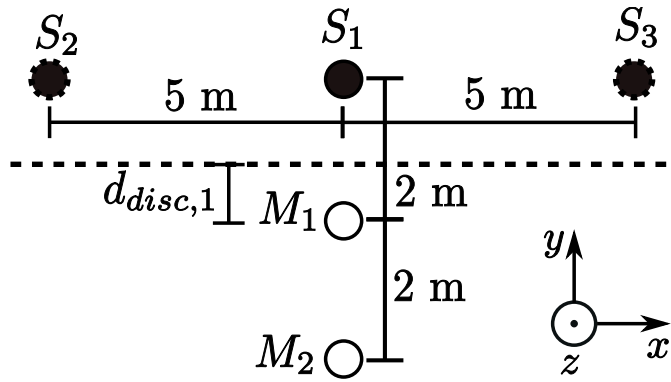

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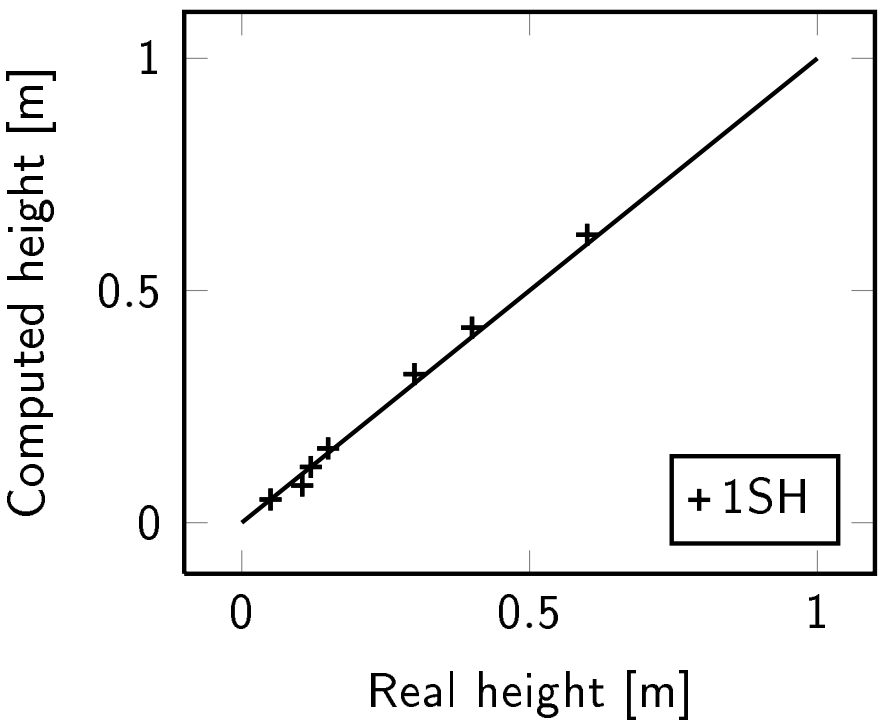

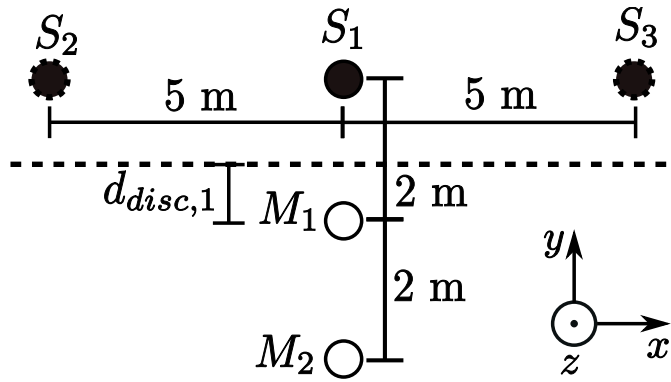

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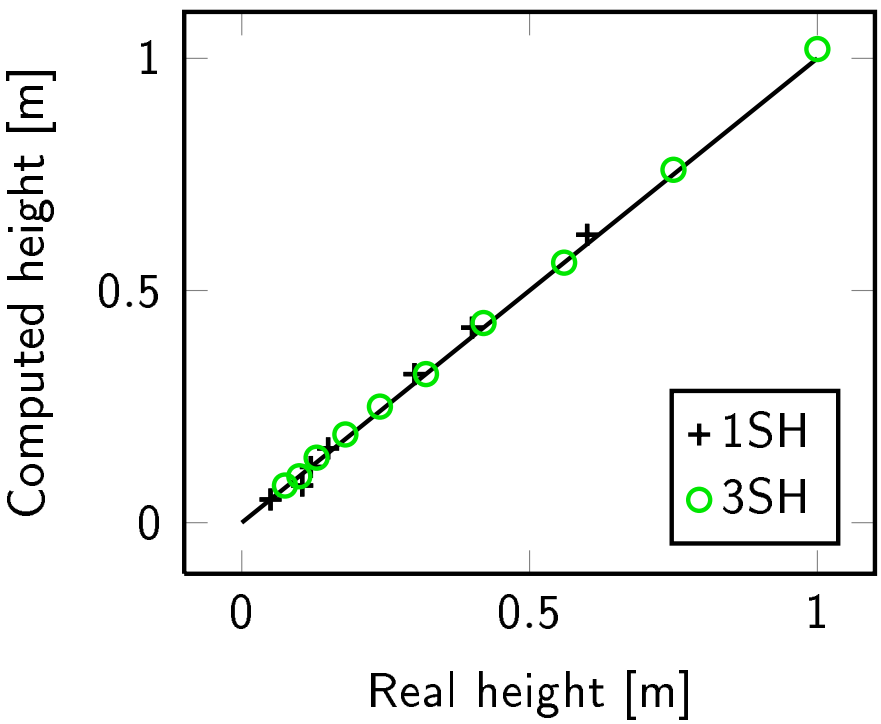

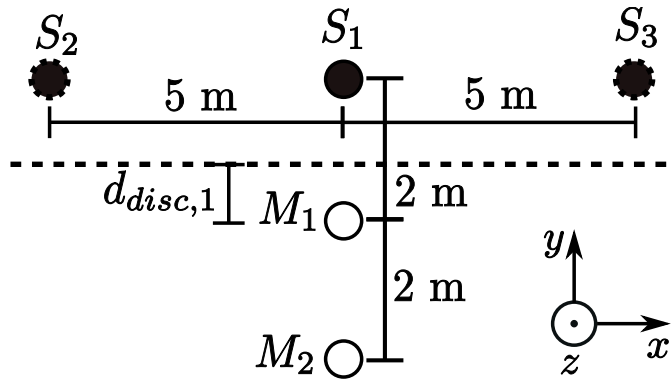

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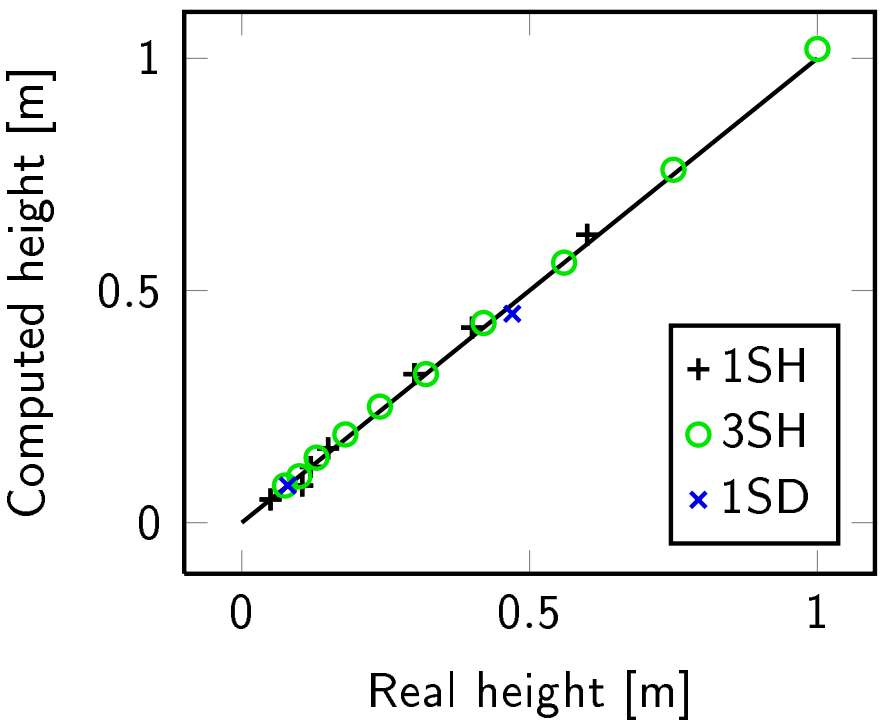
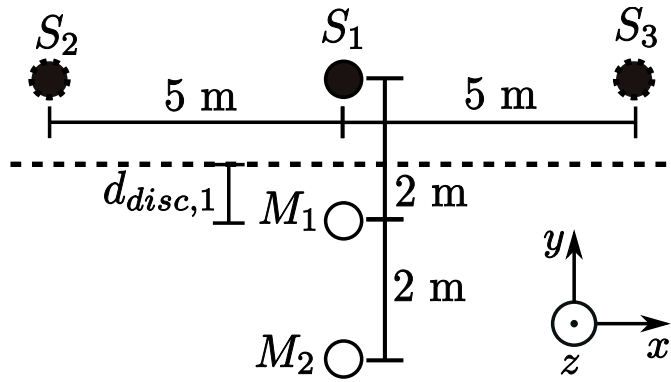
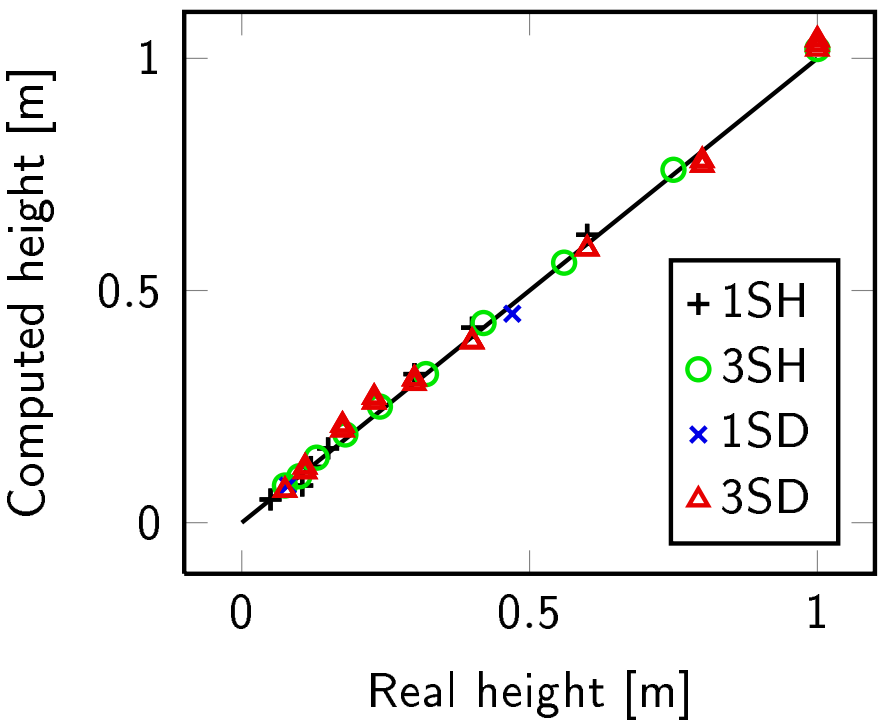
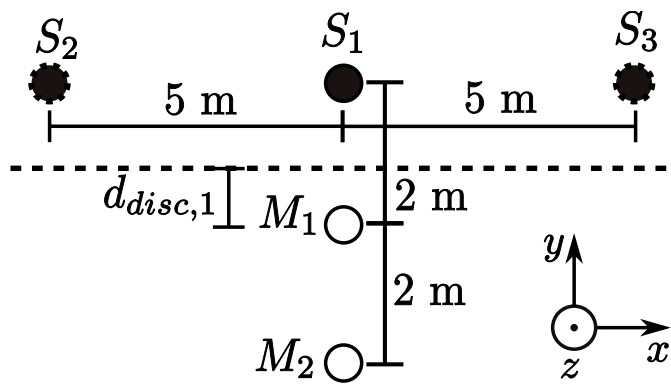


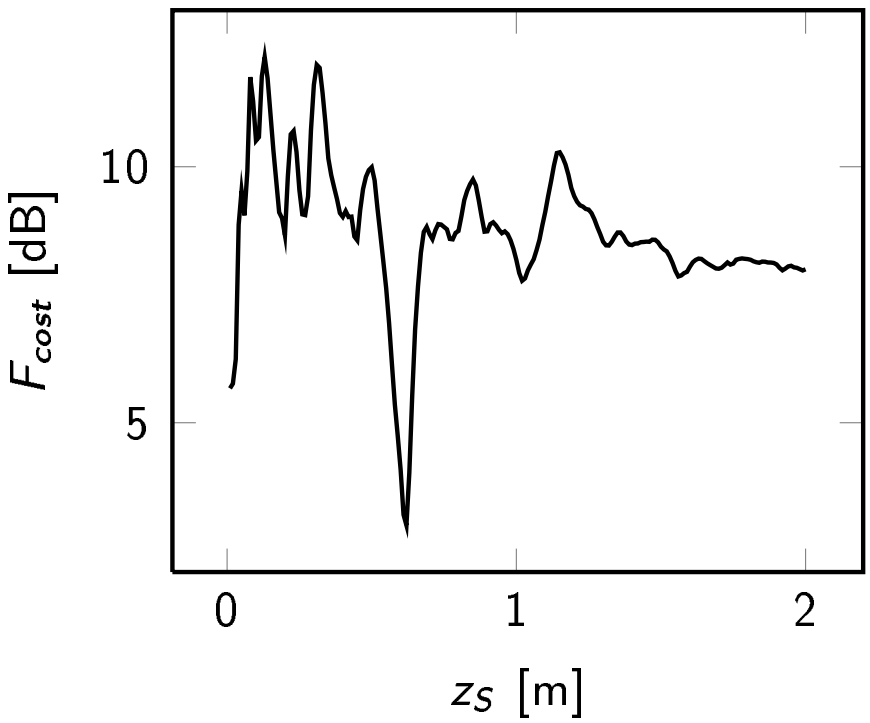


Fixed source height: measurement results (1/2)

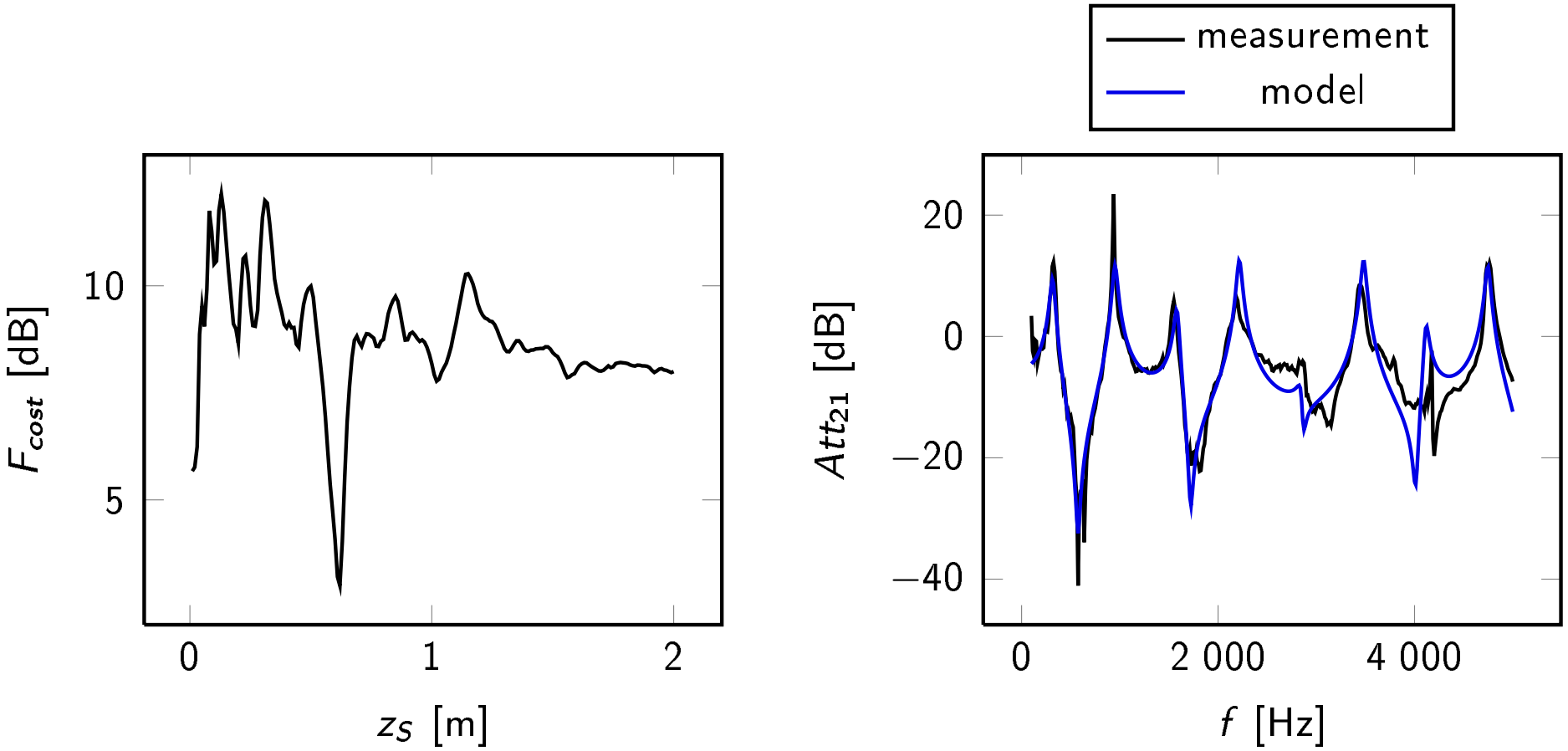




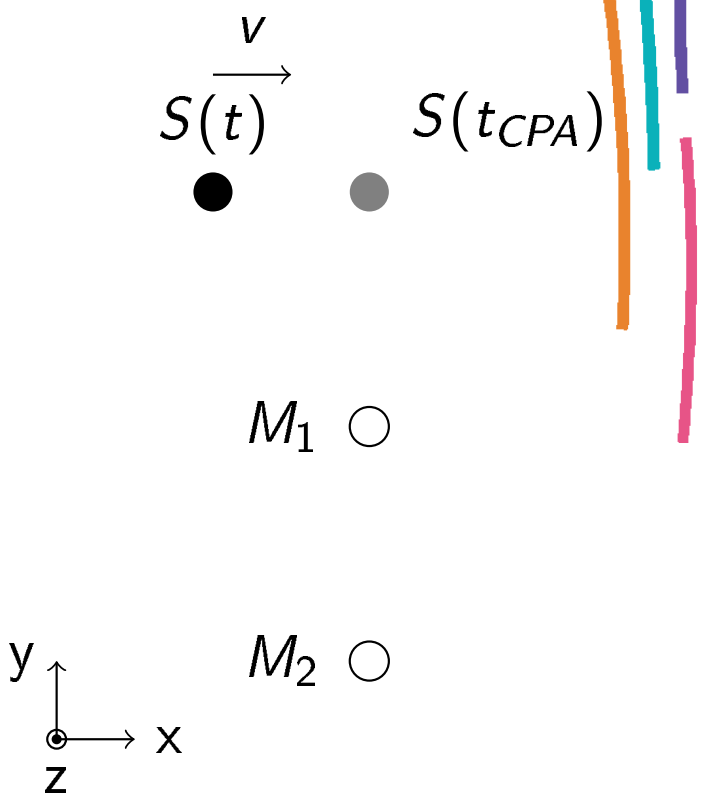
Fixed source height: measurement results for one point source (2/2)



Fixed source height: measurement results for one point source (2/2)



Moving source height: theory

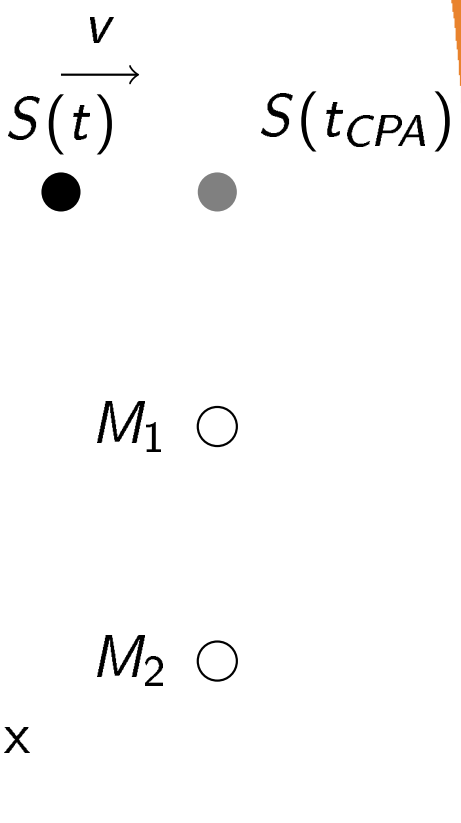


Moving source height: theory

Att_{21} →

Emission

- ~~N_{Se}~~
- ~~$(x_{Se}, y_{Se}, z_{Se})_i$~~
- ~~$|A_i|^2$~~

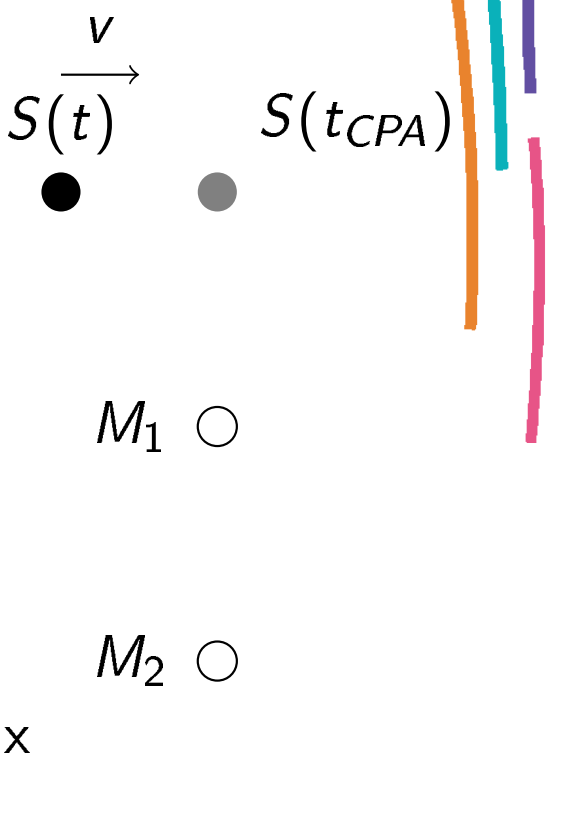


Moving source height: theory

$\underline{Att_{21}(t)}$

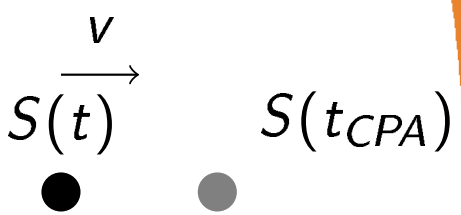
Emission

- ~~N_{Se}~~
- $(\underline{x_{Se}(t)}, \sout{y_{Se}}, z_{Se})_i$
- ~~$|A_i|^2$~~



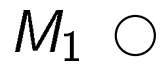
Moving source height: theory

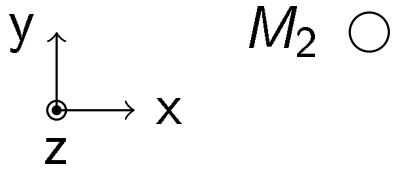
$\underline{Att_{21}(t)}$ → Emission
- ~~N_{Se}~~
- $(\underline{x_{Se}(t)}, \sout{y_{Se}}, z_{Se})_i$
- ~~$|A_i|^2$~~



Three models tested:

- fixed sources (near t_{CPA})



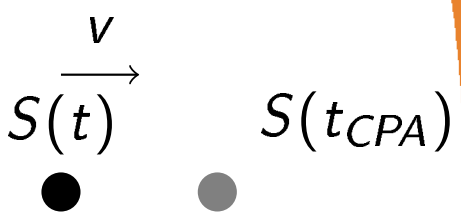


Moving source height: theory

$Att_{21}(t)$

Emission

- ~~N_{Se}~~
- $(x_{Se}(t), ~~y_{Se}~~, z_{Se})_{\vec{i}}$
- ~~$|A_i|^2$~~

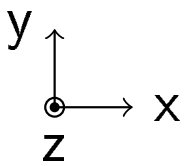


Three models tested:

- fixed sources (near t_{CPA})
- slow moving sources (without Doppler and convection effects)

M_1 ○

M_2 ○

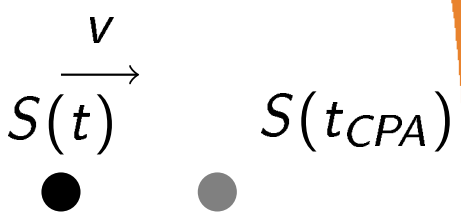


Moving source height: theory

$Att_{21}(t)$

Emission

- ~~N_{Se}~~
- $(x_{Se}(t), ~~y_{Se}~~, z_{Se})_i$
- ~~$|A_i|^2$~~

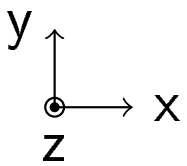


Three models tested:

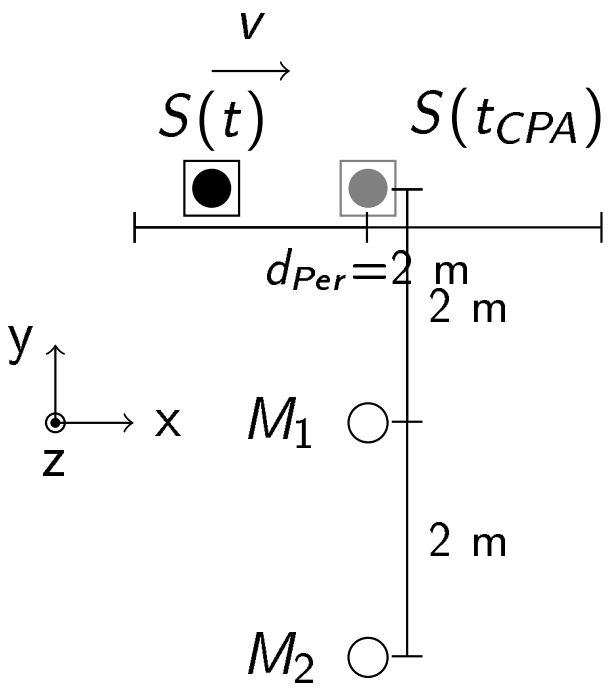
- fixed sources (near t_{CPA})
- slow moving sources (without Doppler and convection effects)
- moving sources, from simplified temporal model

M_1 ○

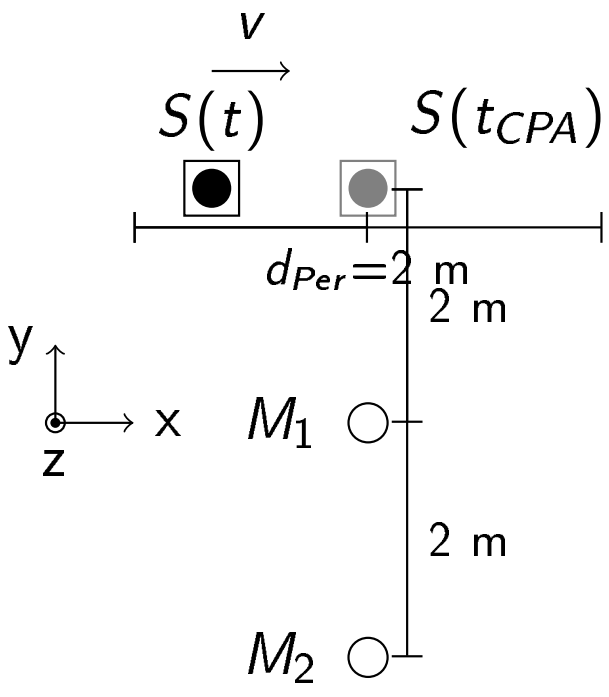
M_2 ○



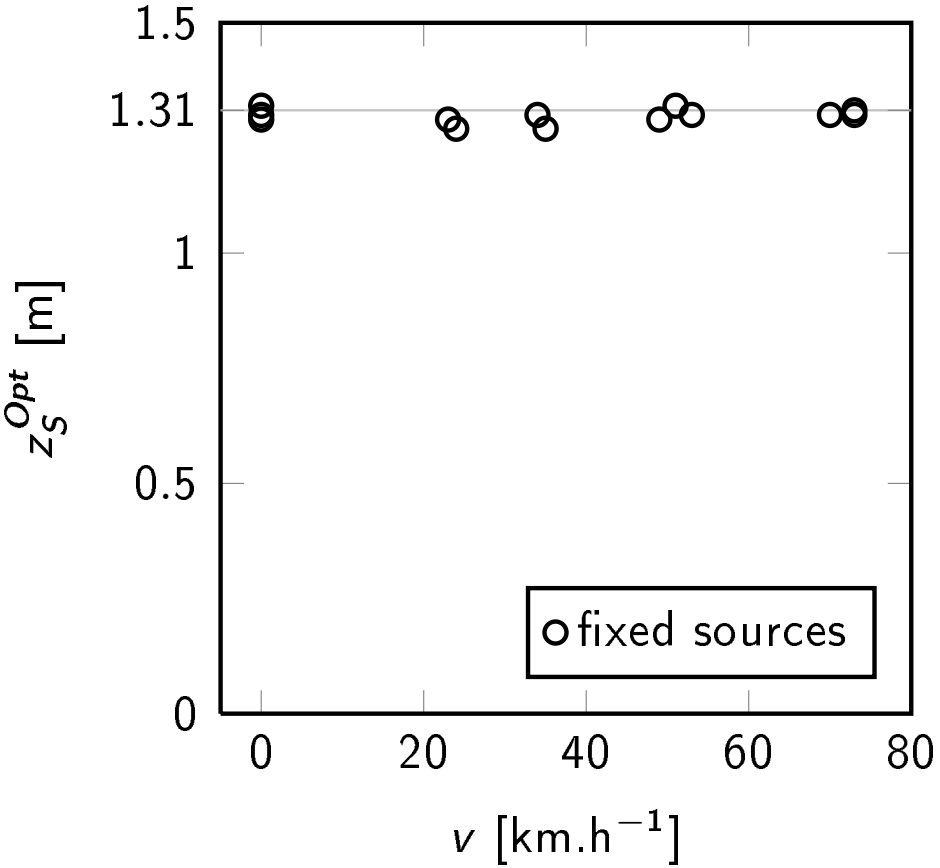
Moving source height: results

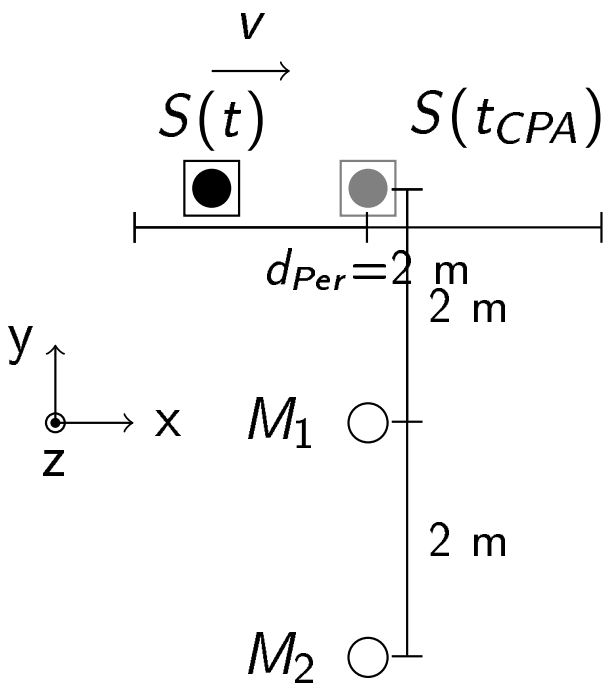


Moving source height: measurement results

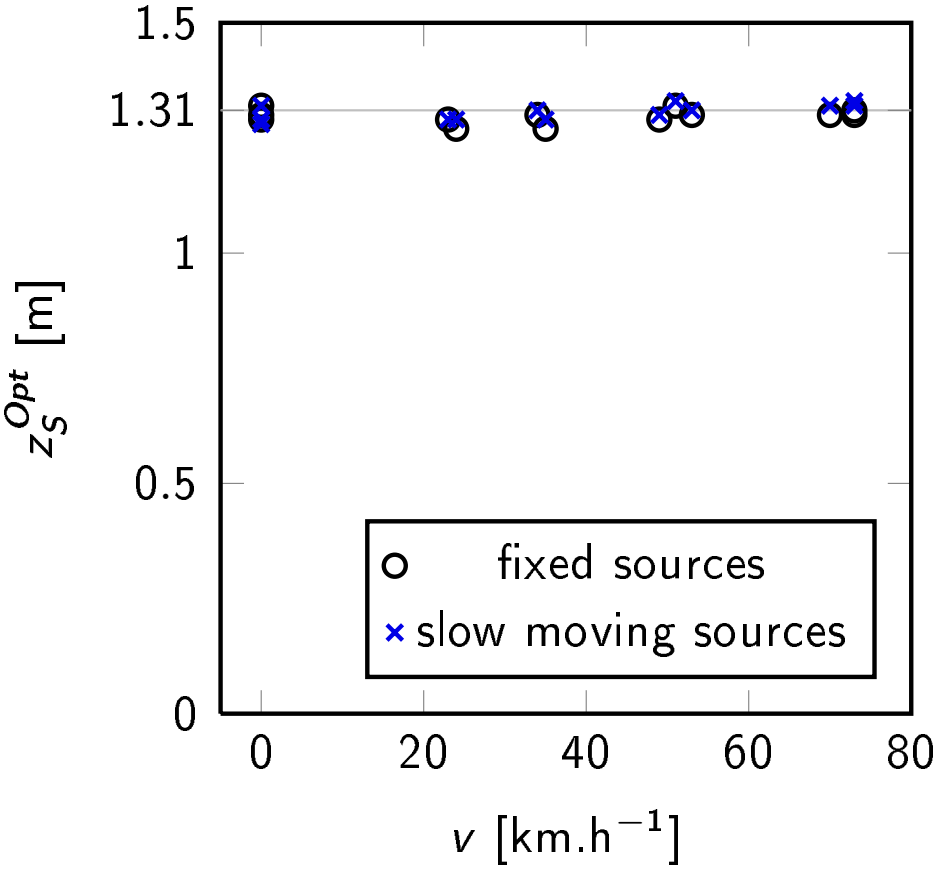


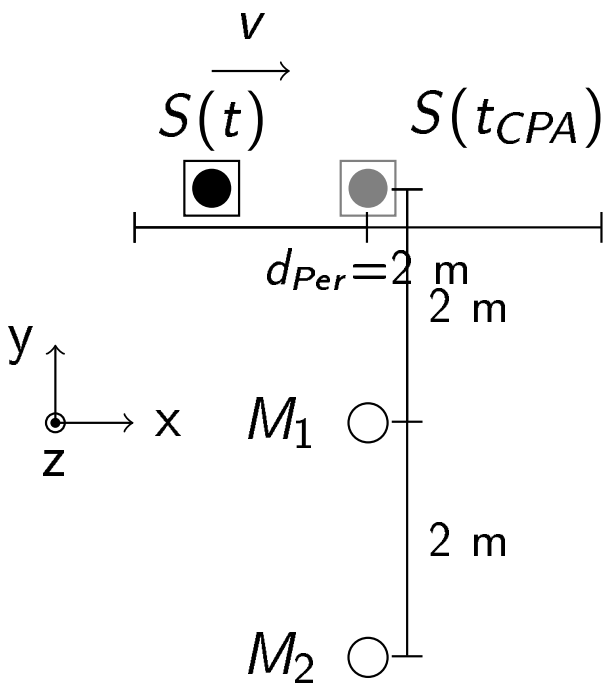
Moving source height: measurement results



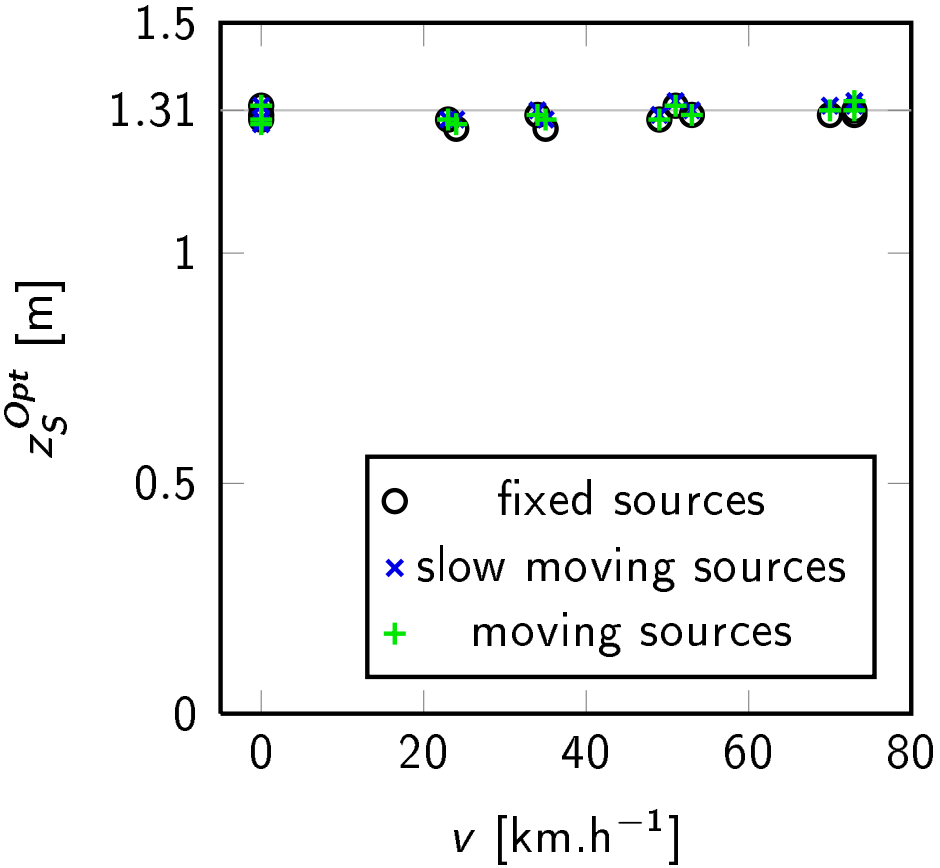


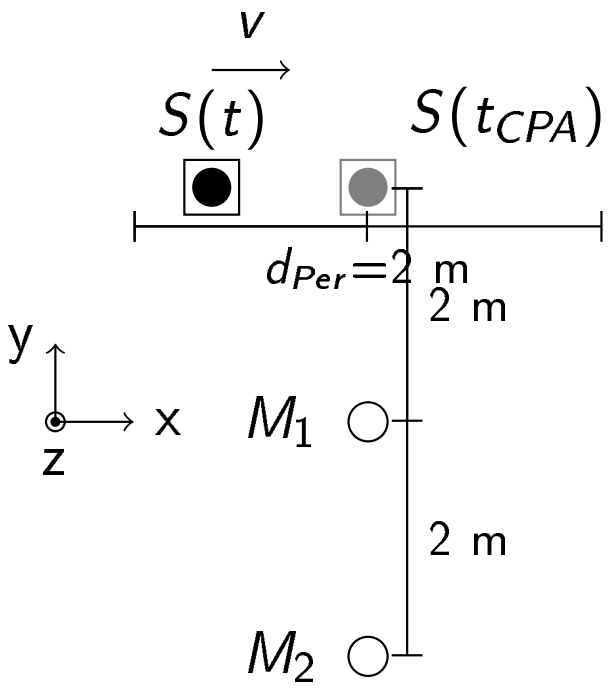
Moving source height: measurement results



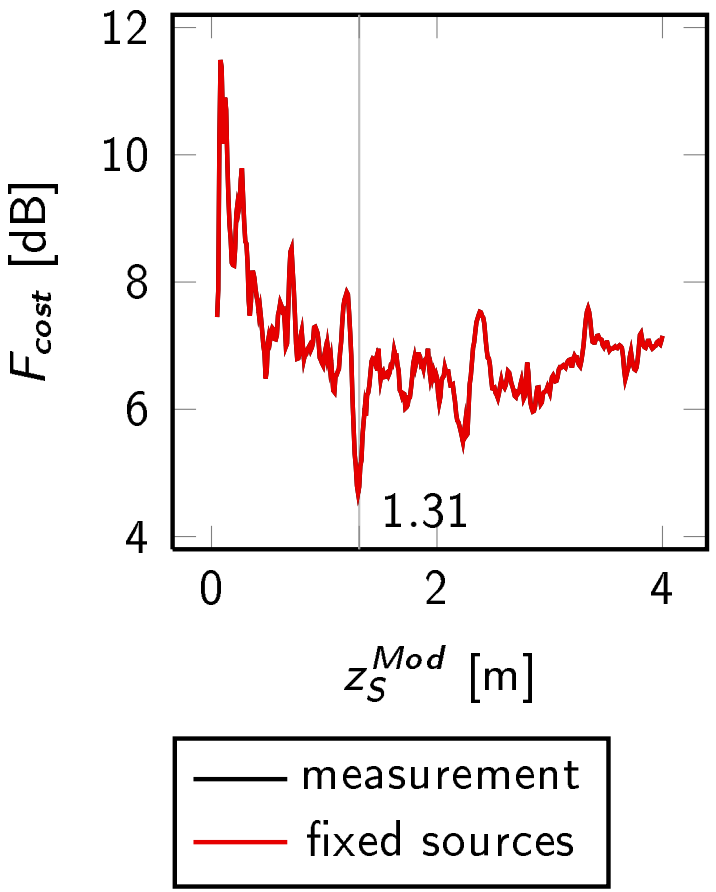


Moving source height: measurement results

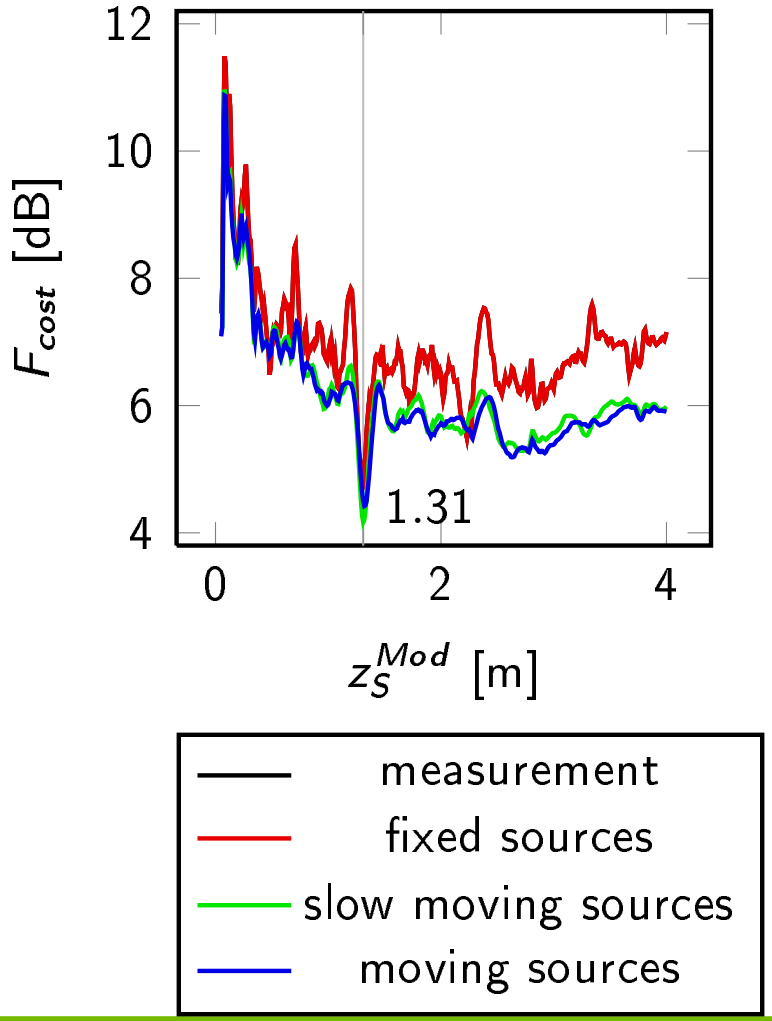




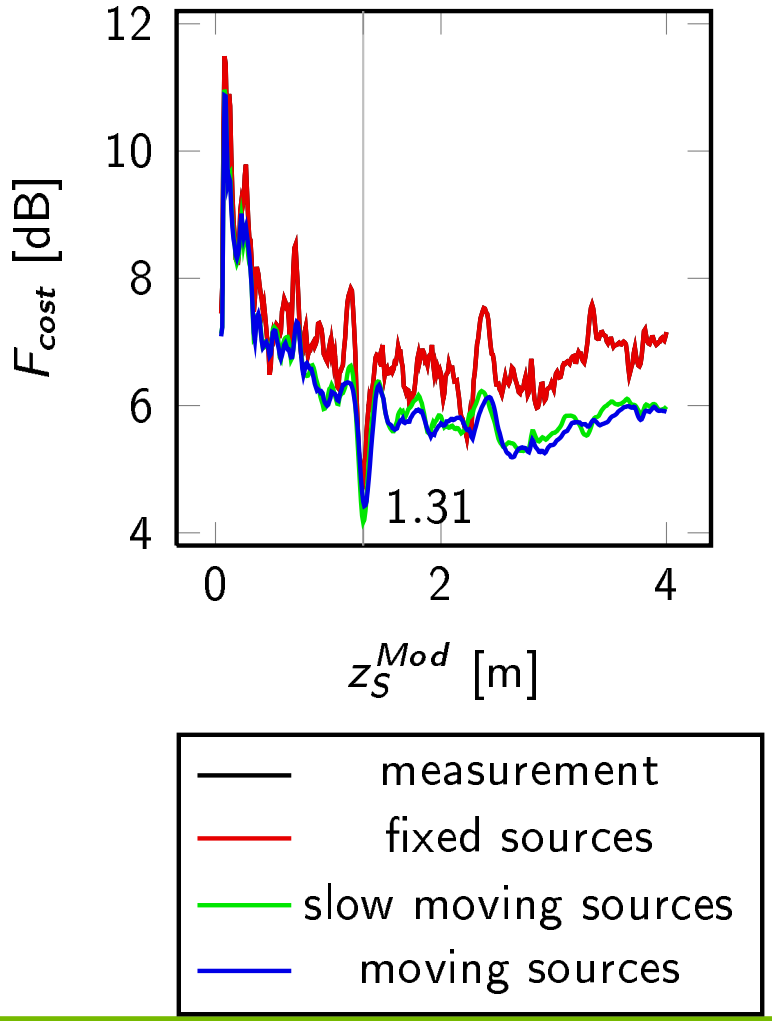
Moving source height: measurements results, $v = 73$ km.h^{-1}

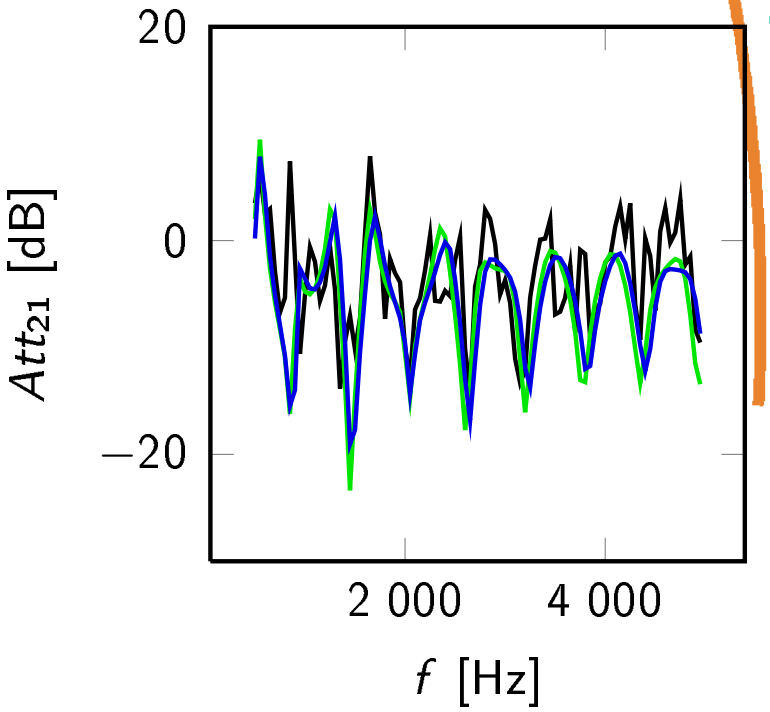


Moving source height: measurements results, $v = 73$ km.h^{-1}



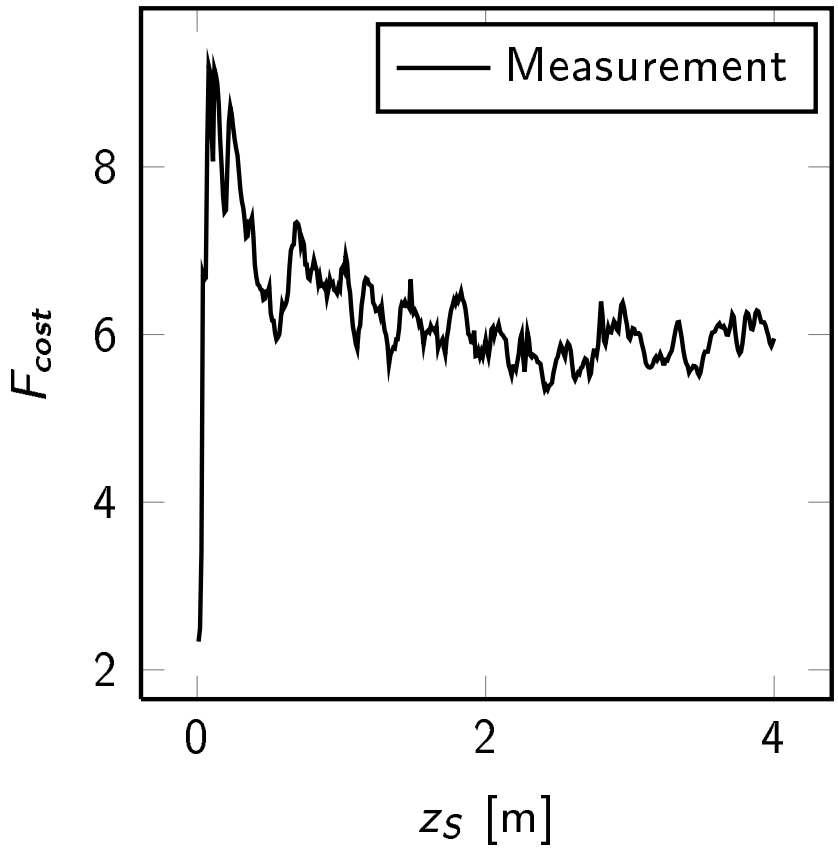
Moving source height: measurements results, $v = 73$ km.h^{-1}



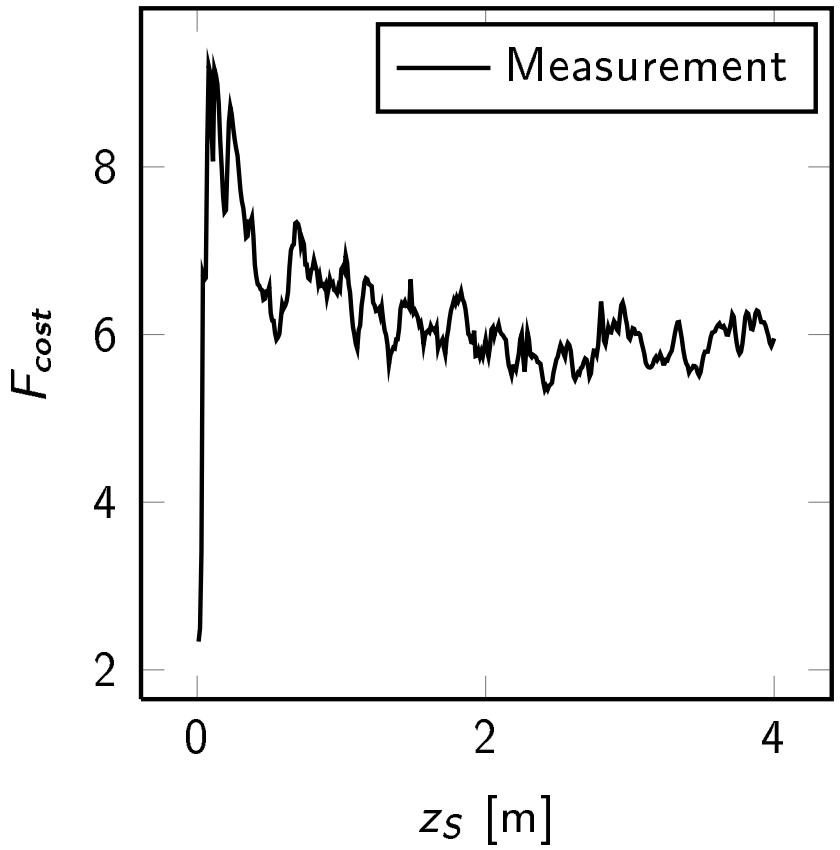


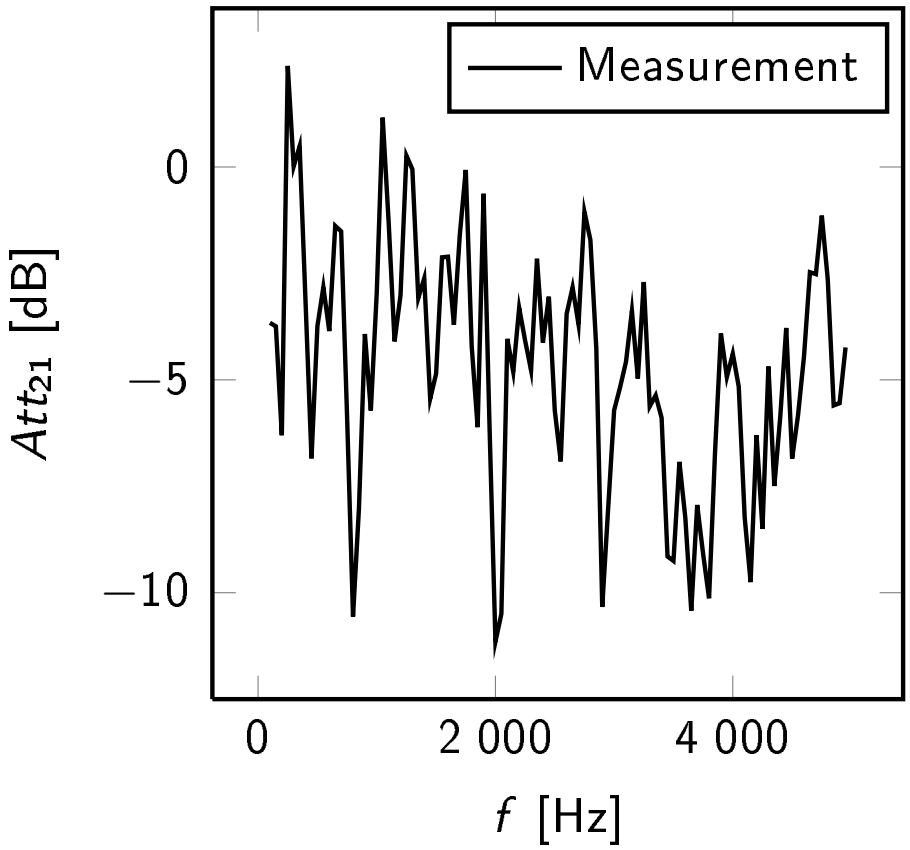
Fixed vehicle source height: measurement results

Fixed vehicle source height: measurement results

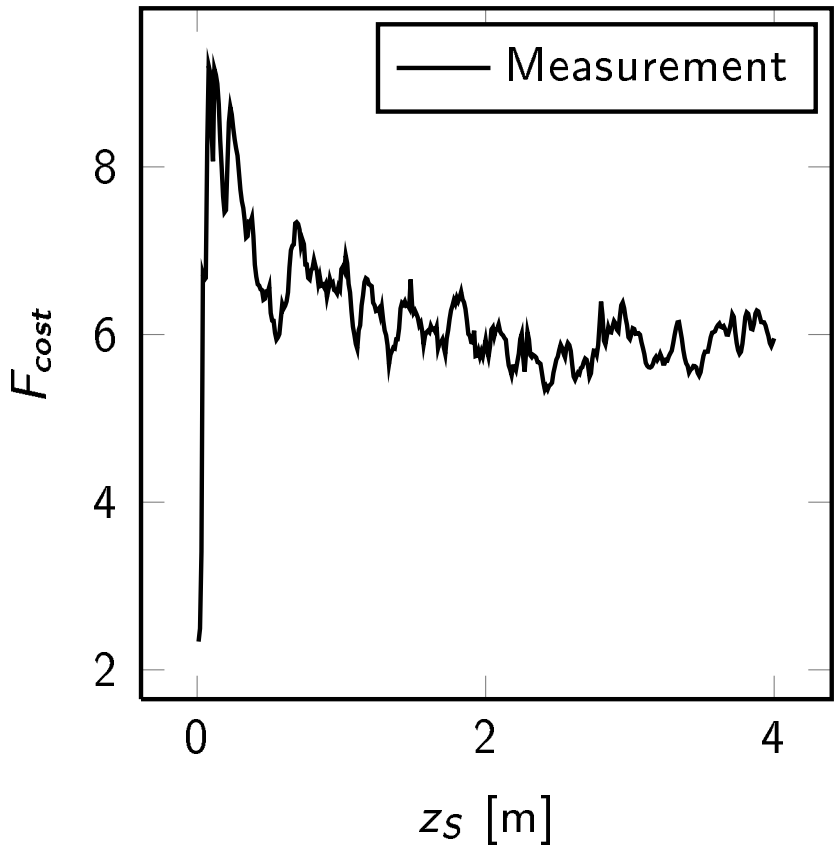


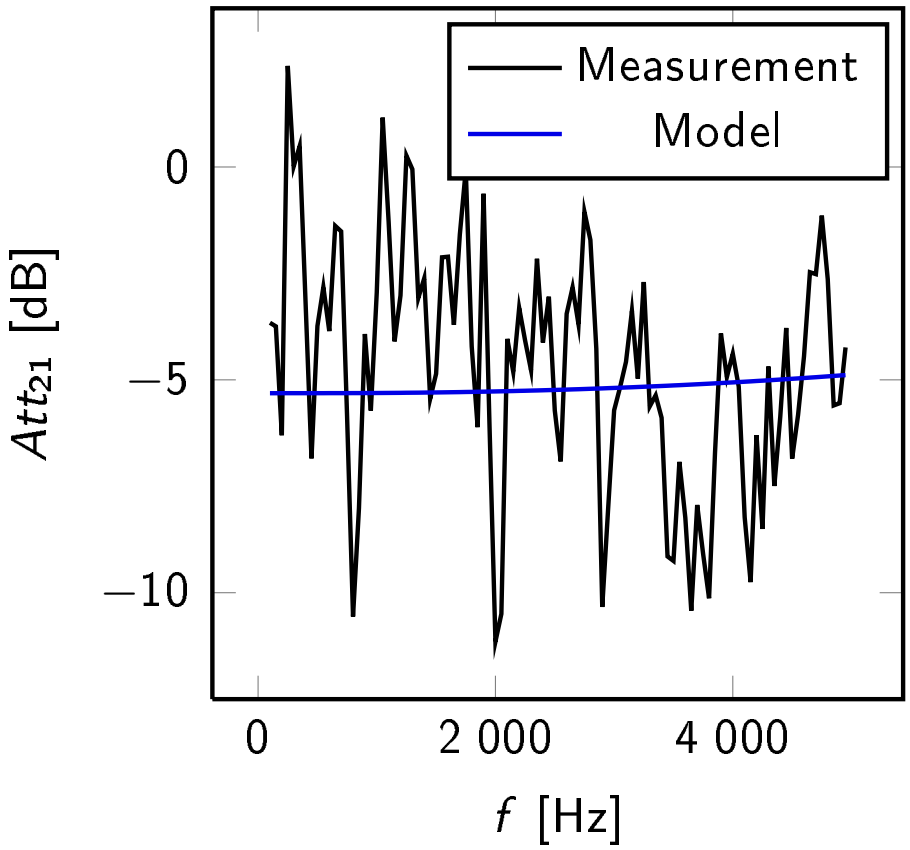
Fixed vehicle source height: measurement results





Fixed vehicle source height: measurement results



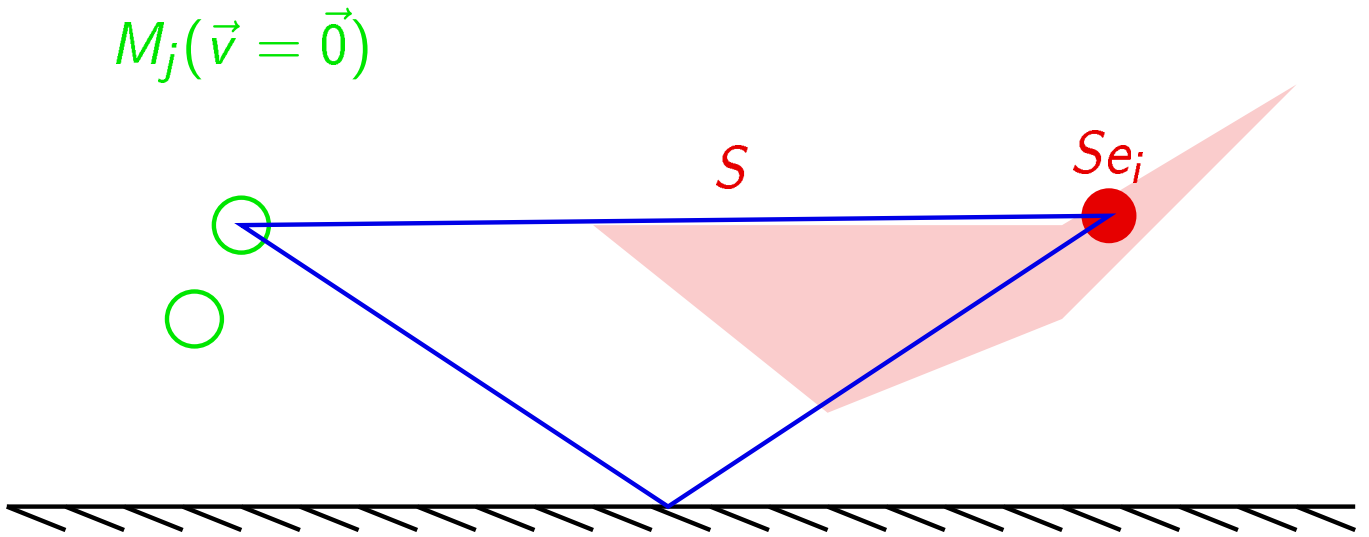


Source height: conclusion

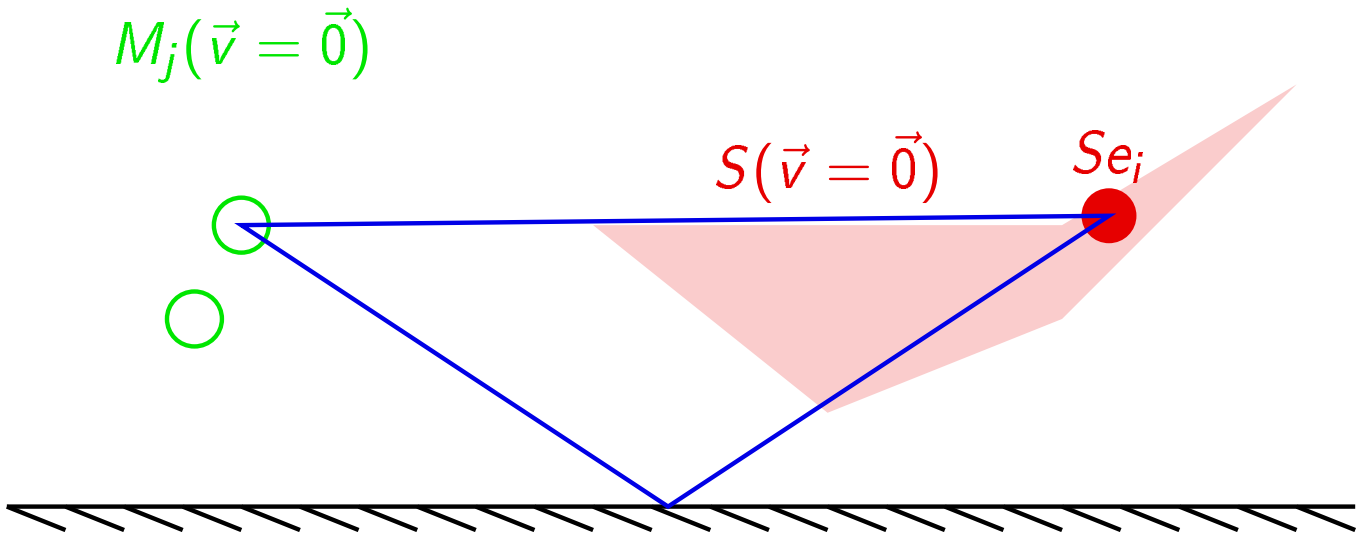
- fixed sources:
  - theory
  - numerical validation
  - experimental validation: mainly three sources with discontinuity
- moving sources:
  - theory
  - numerical simulations
  - experimental validation
- measurement on fixed vehicles

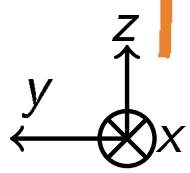
Table of contents

MÉCS: problem statement



MÉCS: problem statement





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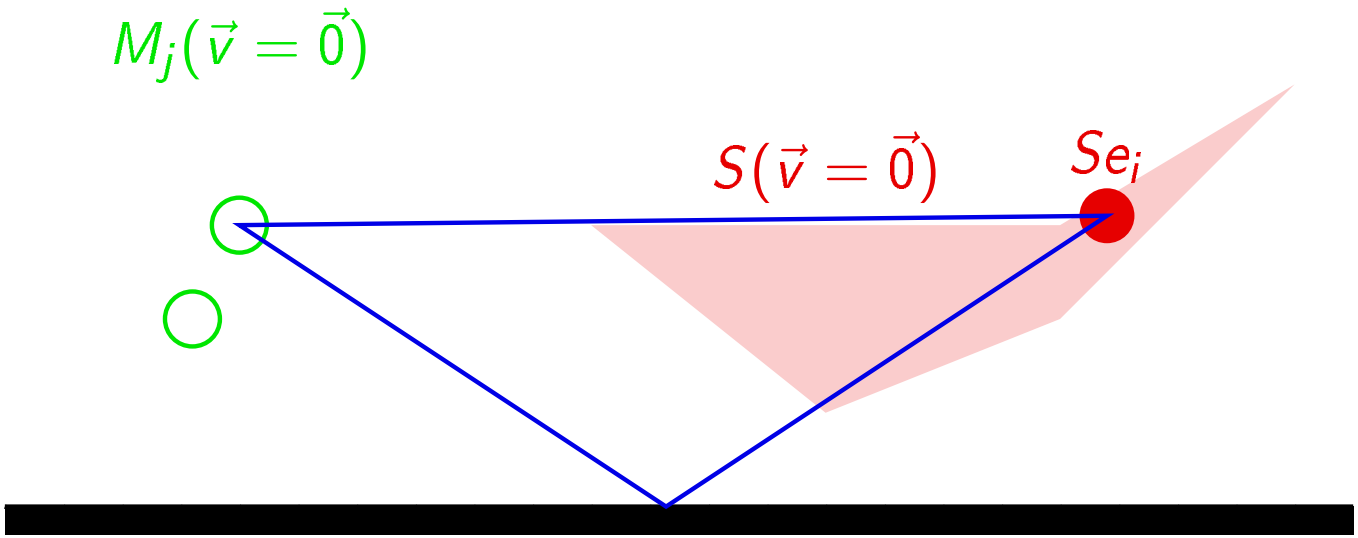

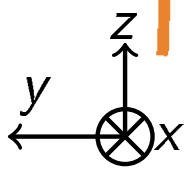

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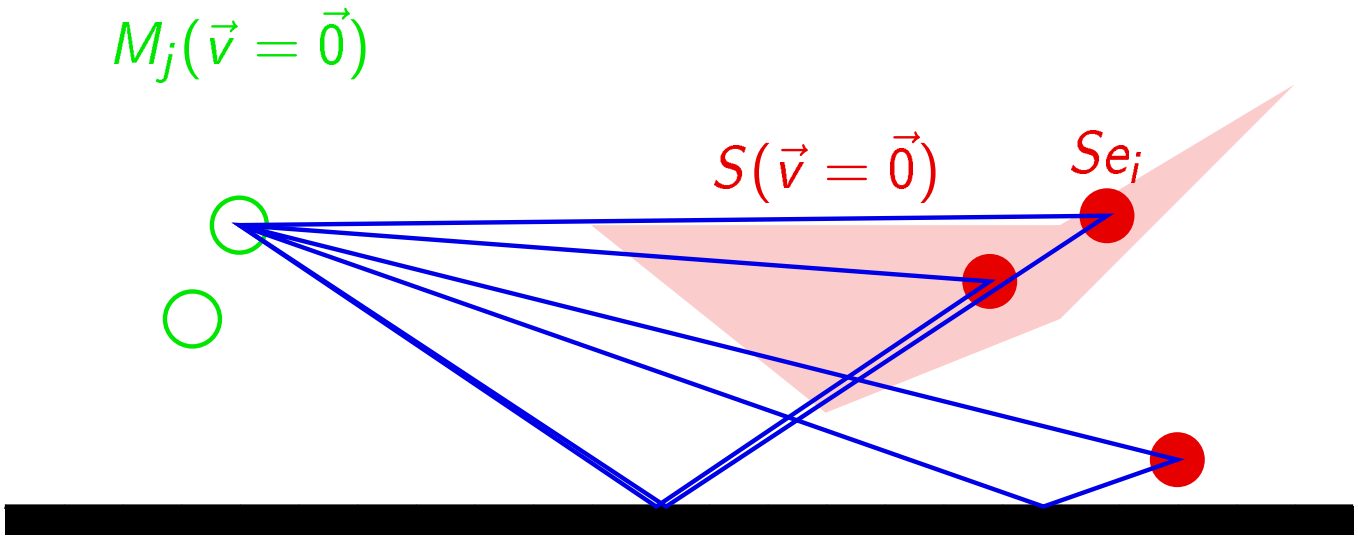

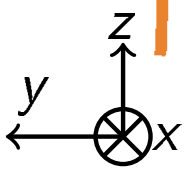

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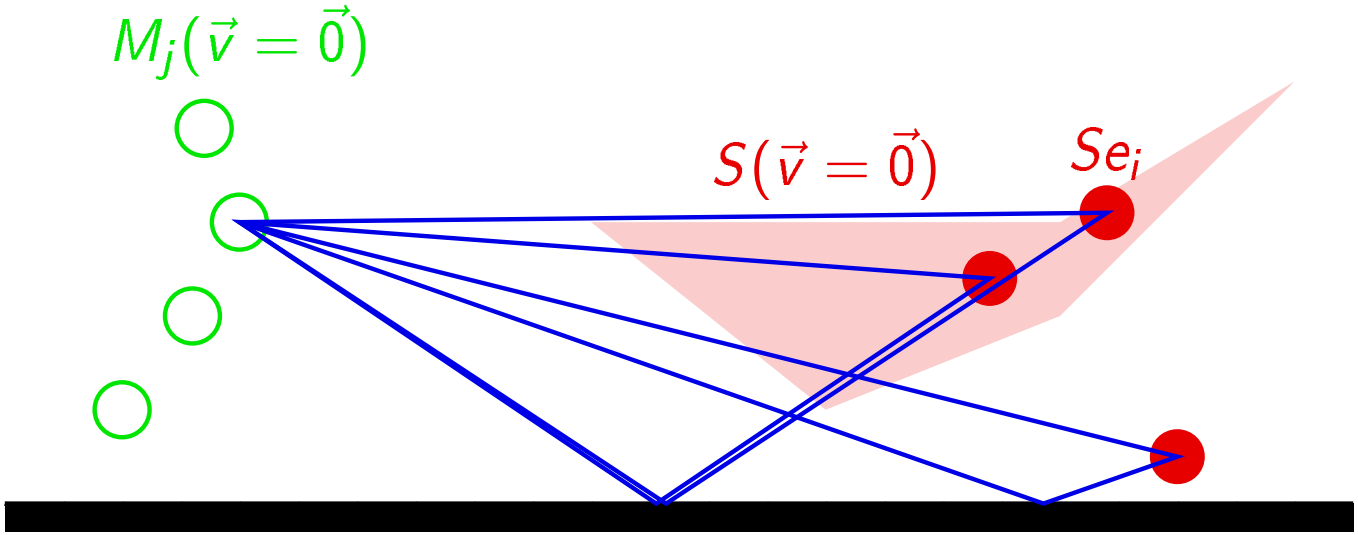

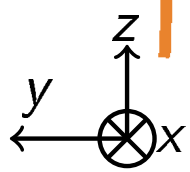

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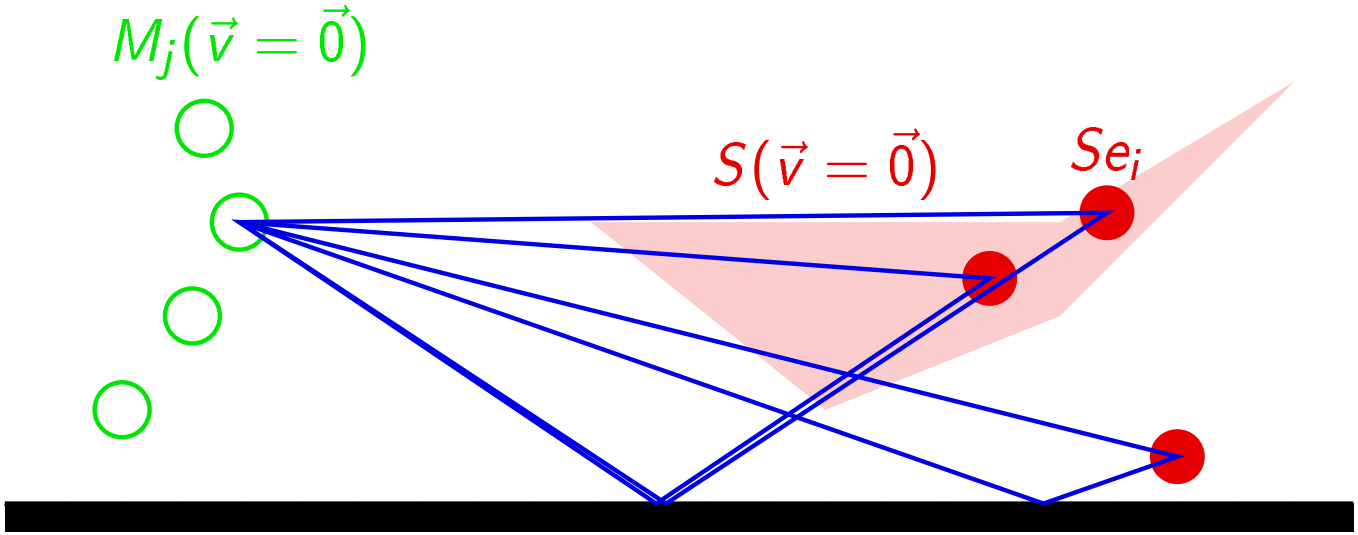
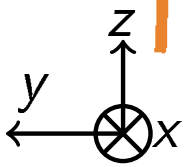
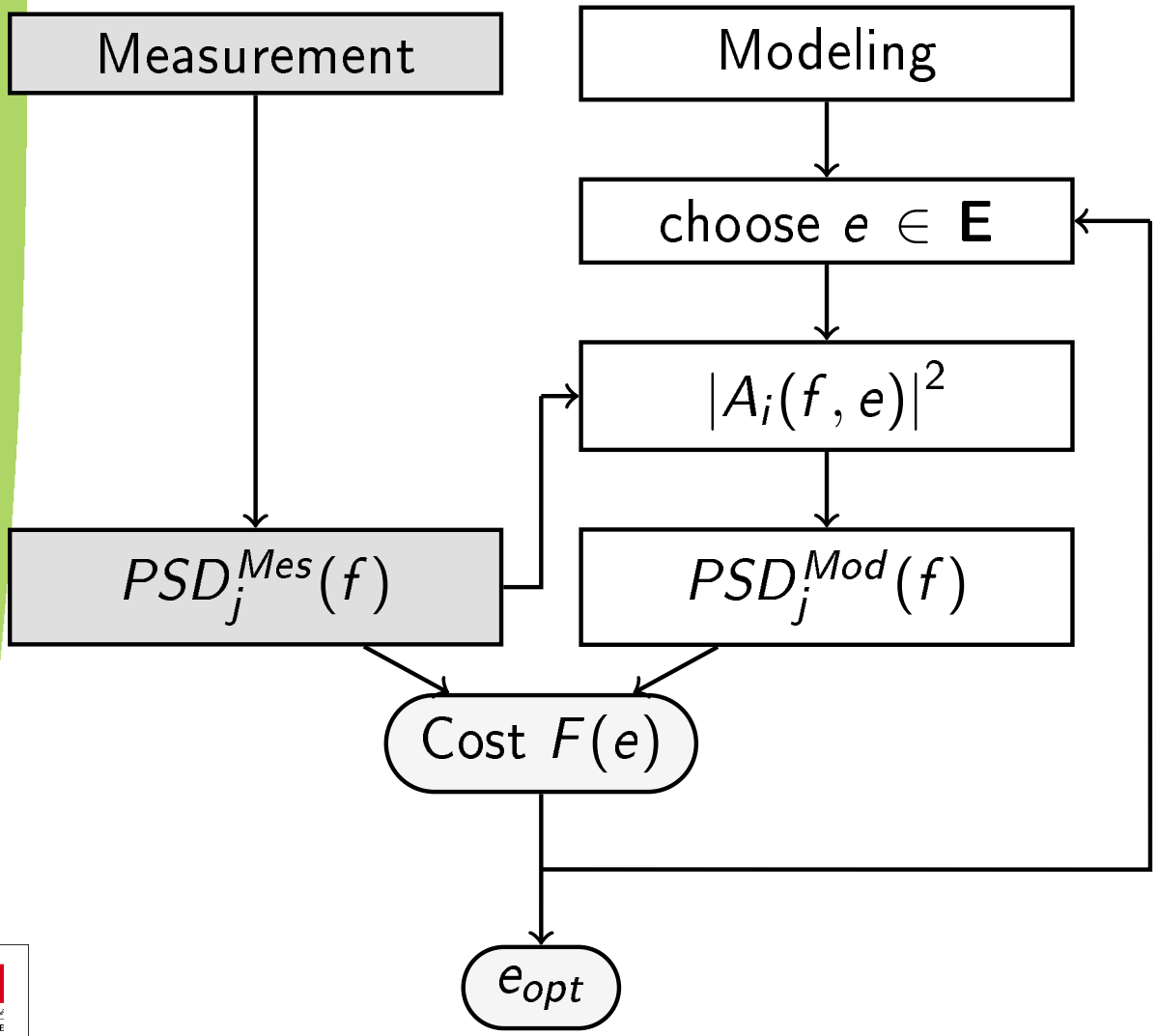




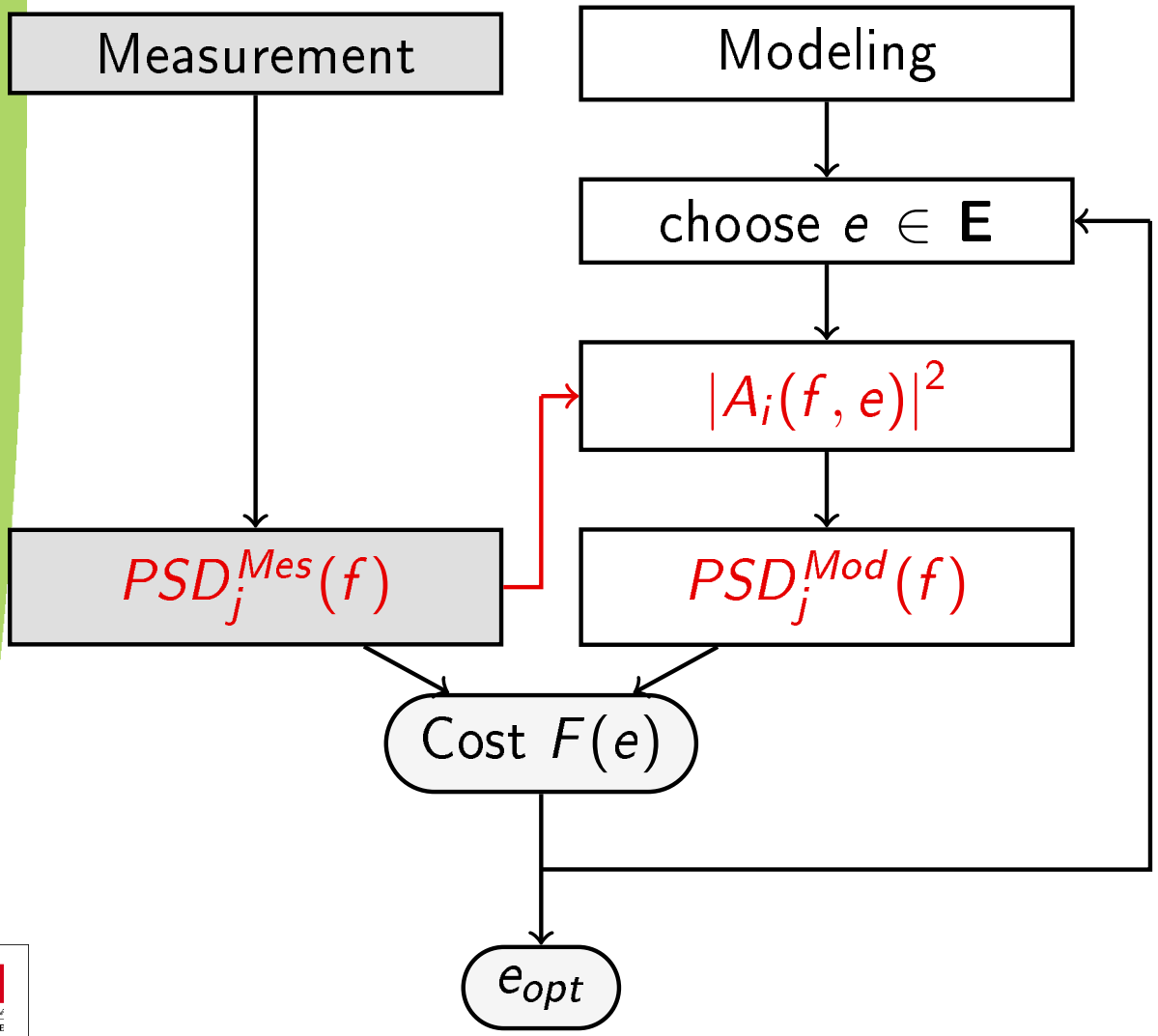
PSD_j → propagation^{-1} →

Emission
- N_{Se}
- $(x_{Se}, y_{Se}, z_{Se})_i$
- $|A_i|^2$

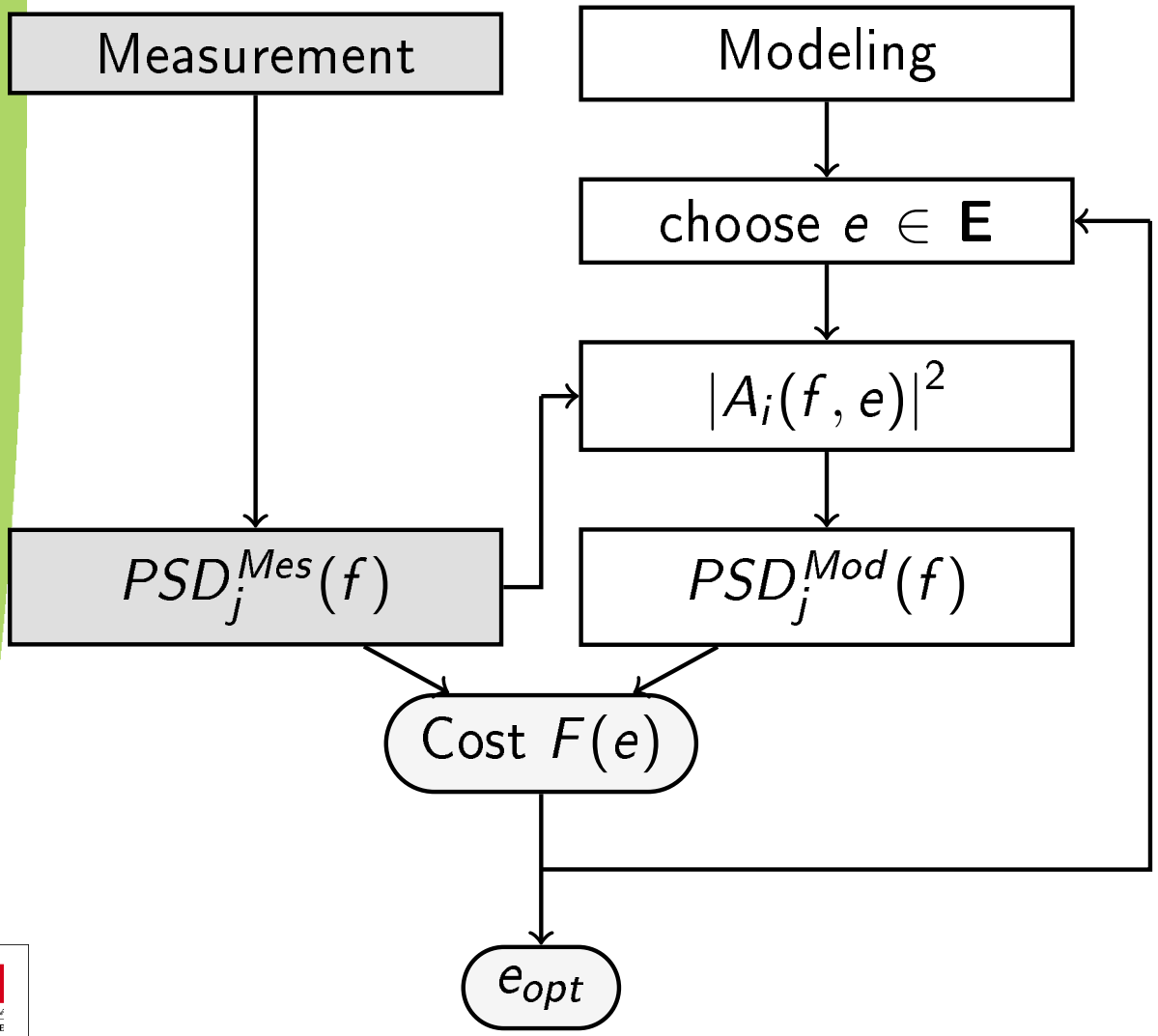
MÉCS: synoptic



MÉCS: synoptic



MÉCS: synoptic



Space **E** of solutions

- N_{Se}
- $(x_{Se}, y_{Se}, z_{Se})_i$

MÉCS: computation of $|A_i(f,e)|^2$

Formulation ...

$$\mathbf{DSP^{Mes} \approx |H(e)|^2 |A(e)|^2}$$

$$\begin{pmatrix} DSP_1^{Mes}(f_1) \\ \vdots \\ DSP_{N_M}^{Mes}(f_1) \\ \vdots \\ \vdots \\ DSP_1^{Mes}(f_{N_f}) \\ \vdots \\ DSP_{N_M}^{Mes}(f_{N_f}) \end{pmatrix} = \begin{pmatrix} \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ \cdots & h_{ij}(f_k) & \cdots \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \end{pmatrix} \begin{pmatrix} |A_1(f_1,e)|^2 \\ \vdots \\ |A_{N_S}(f_1,e)|^2 \\ \vdots \\ \vdots \\ |A_1(f_{N_f},e)|^2 \\ \vdots \\ |A_{N_S}(f_{N_f},e)|^2 \end{pmatrix}$$

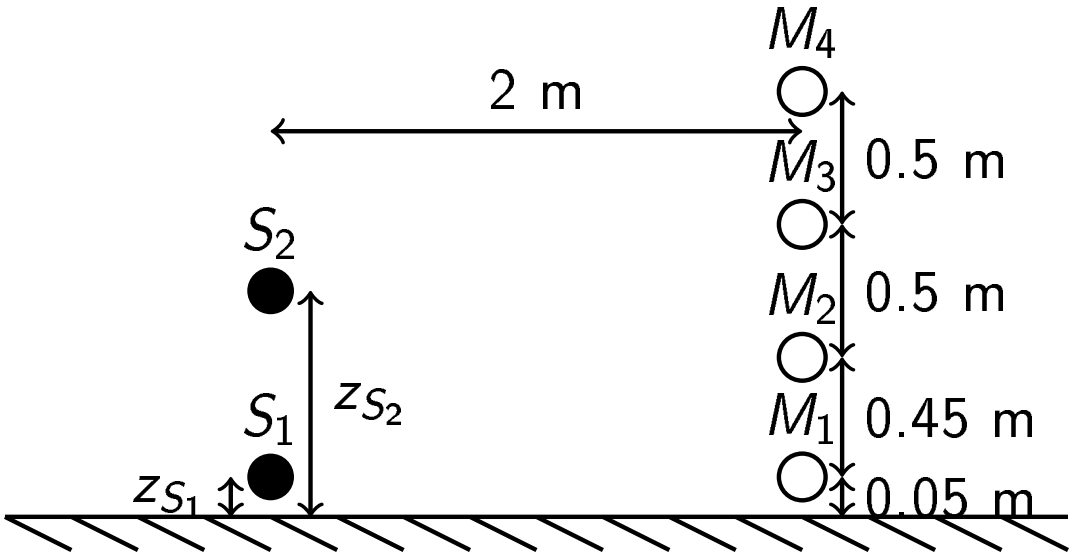
MÉCS: computation of $|A_i(f,e)|^2$

Formulation ... and LMS-solve

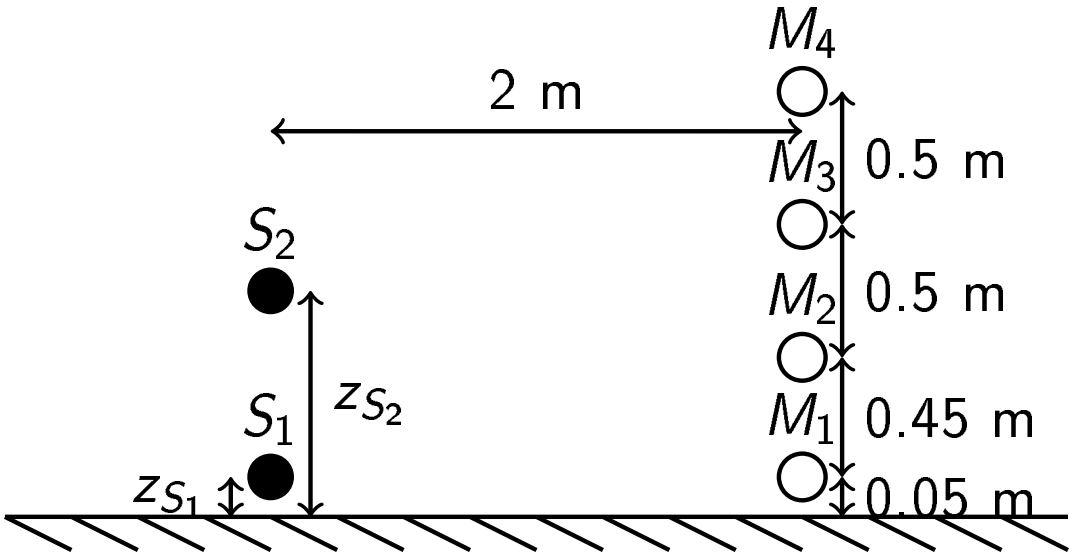
$$\mathbf{DSP^{Mes}} \approx \mathbf{|H(e)|^2 |A(e)|^2}$$

$$\begin{pmatrix} DSP_1^{Mes}(f_1) \\ \vdots \\ DSP_{N_M}^{Mes}(f_1) \\ \vdots \\ \vdots \\ DSP_1^{Mes}(f_{N_f}) \\ \vdots \\ DSP_{N_M}^{Mes}(f_{N_f}) \end{pmatrix} = \begin{pmatrix} \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ \cdots & h_{ij}(f_k) & \cdots \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \end{pmatrix} \begin{pmatrix} |A_1(f_1,e)|^2 \\ \vdots \\ |A_{N_S}(f_1,e)|^2 \\ \vdots \\ \vdots \\ |A_1(f_{N_f},e)|^2 \\ \vdots \\ |A_{N_S}(f_{N_f},e)|^2 \end{pmatrix}$$

MÉCS: configurations used for numerical simulation



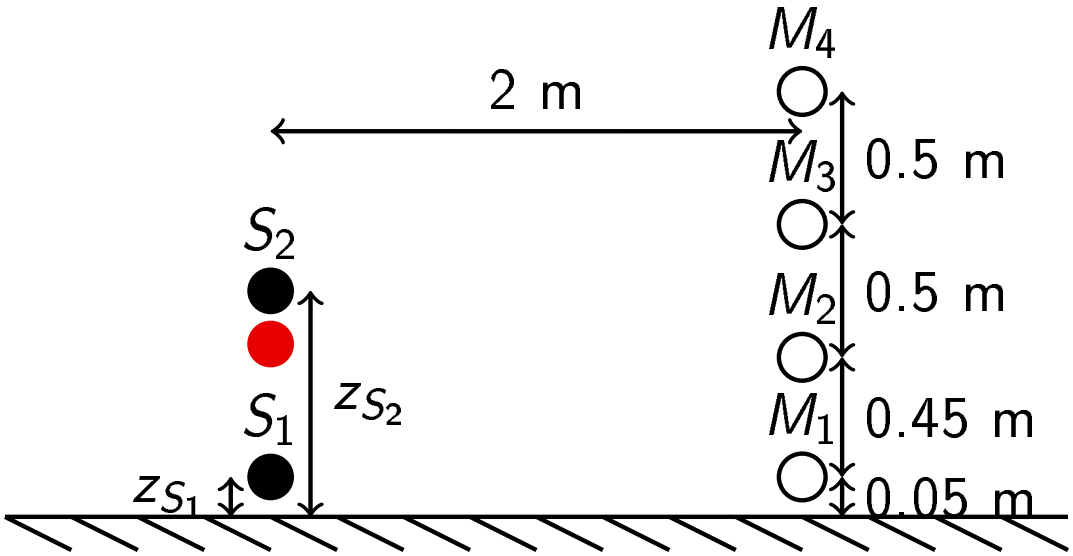
MÉCS: configurations used for numerical simulation



Hypotheses:

- white noise
- uncertainties along X, Y, Z
- SNR 15 dB

MÉCS: configurations used for numerical simulation



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- SNR 15 dB

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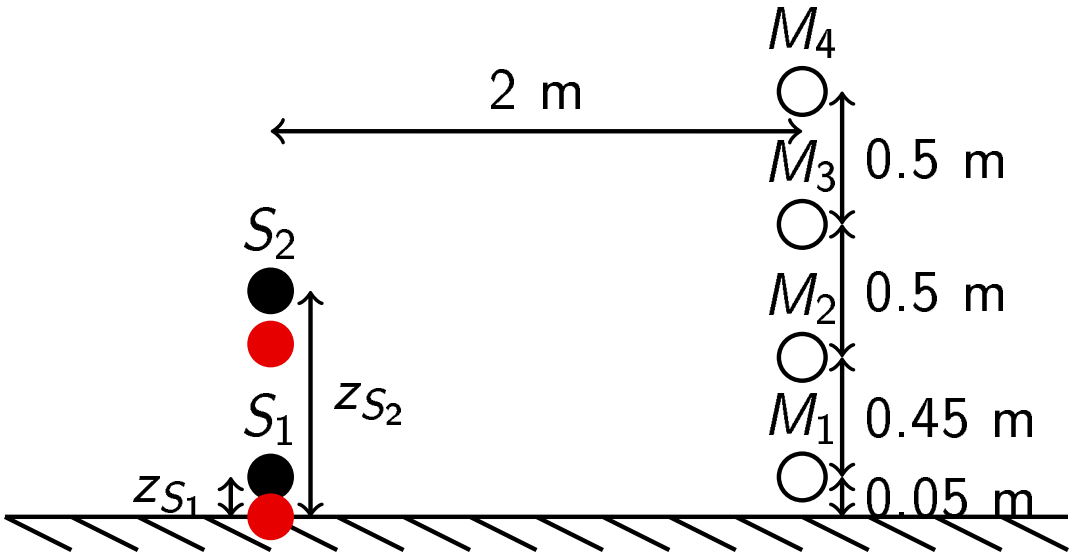
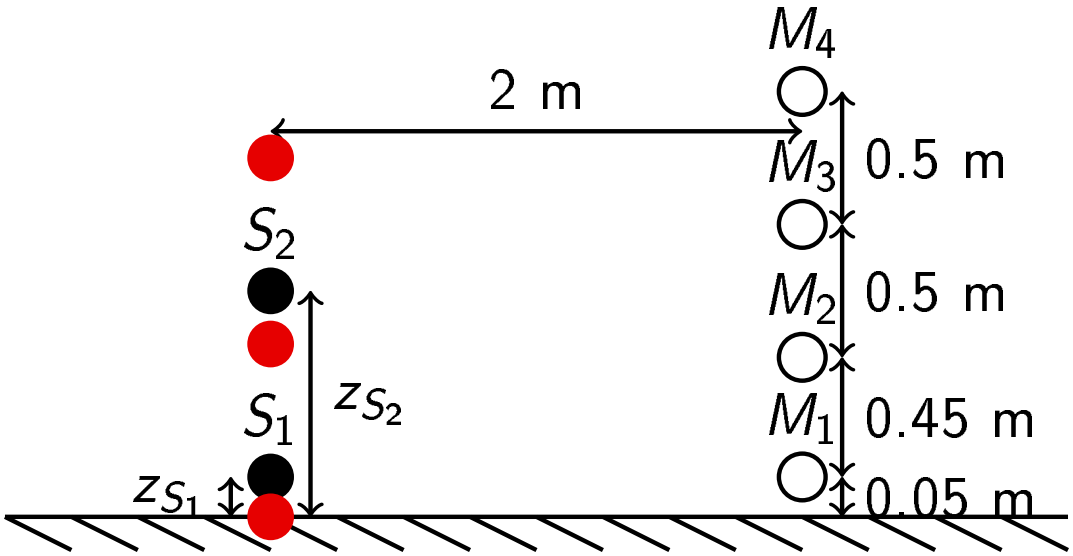


Hypotheses:

- white noise
- uncertainties along X, Y, Z
- SNR 15 dB

MÉCS: configurations used for numerical simulation



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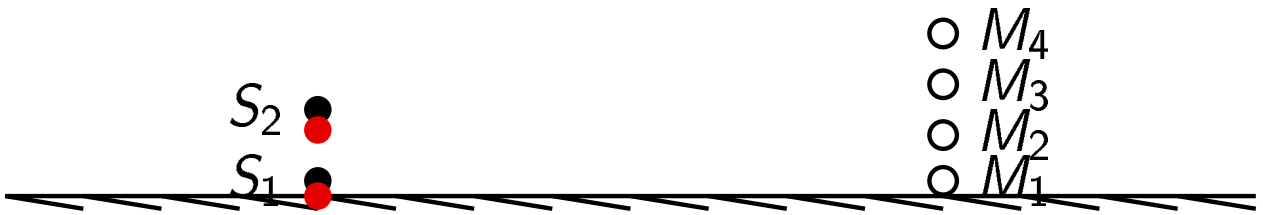

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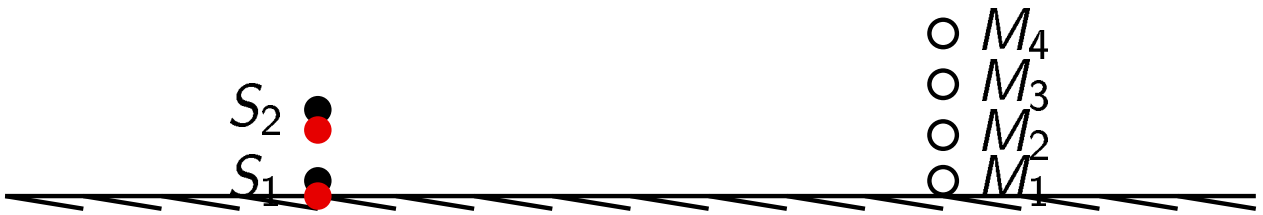

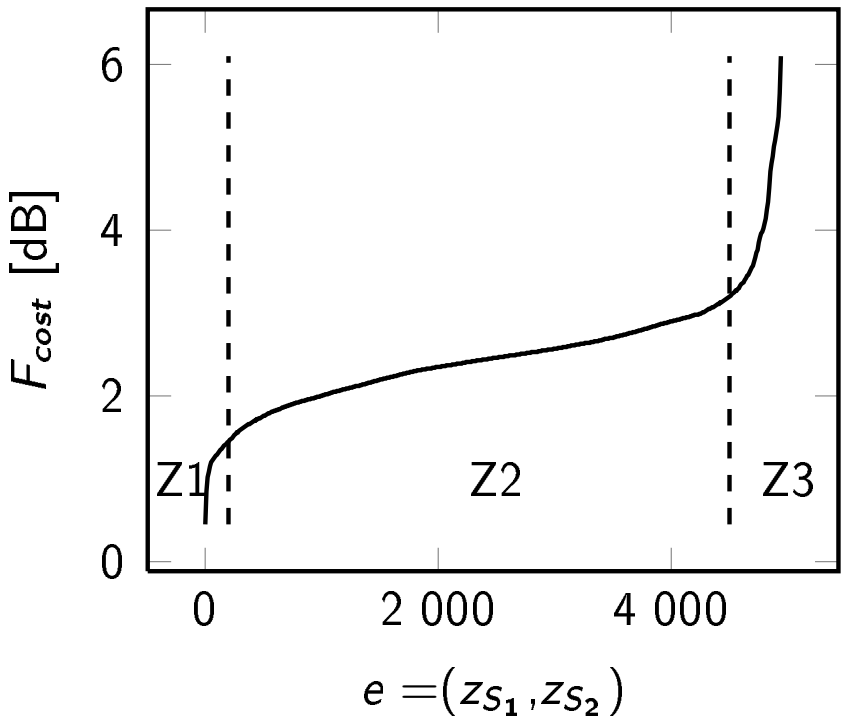

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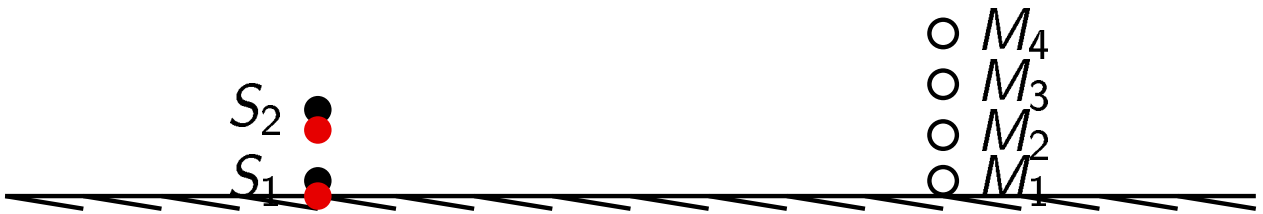

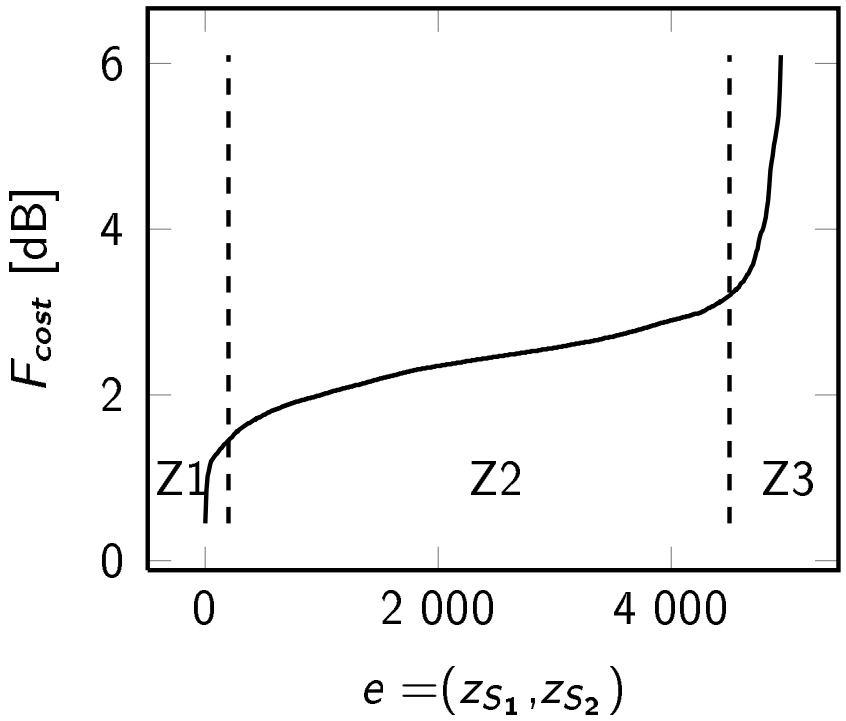

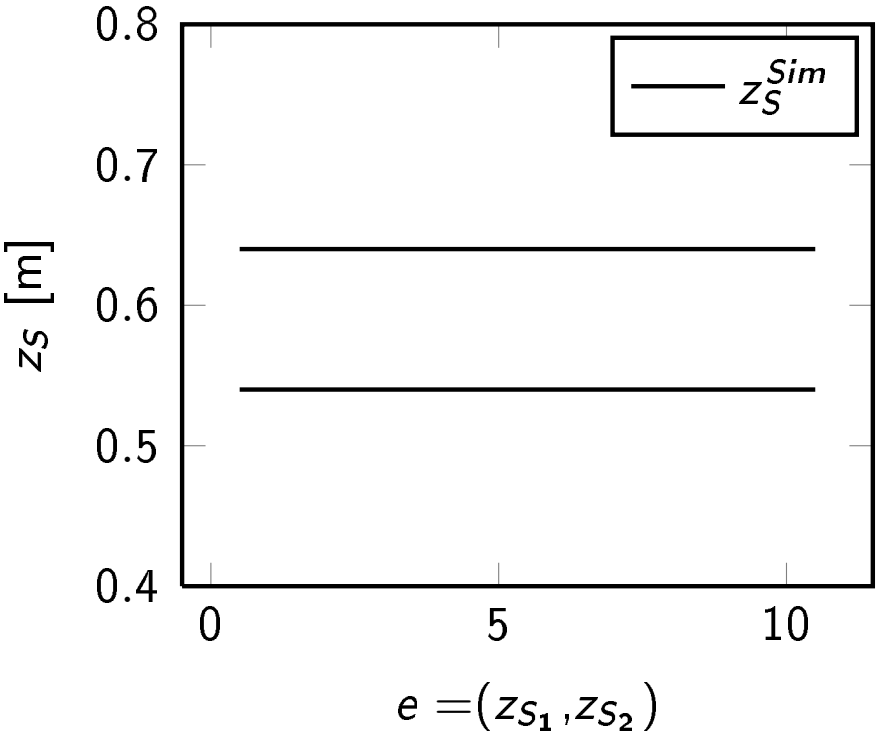

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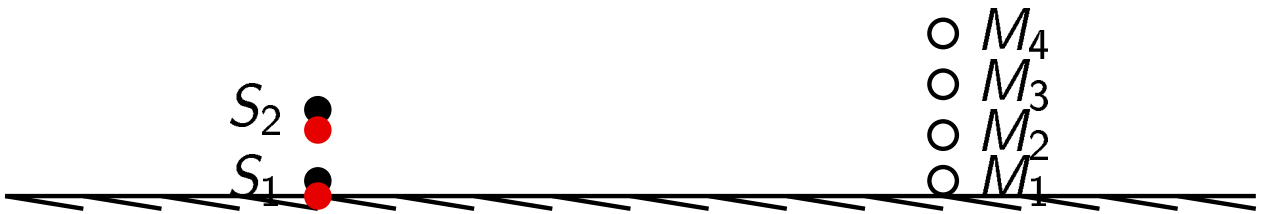
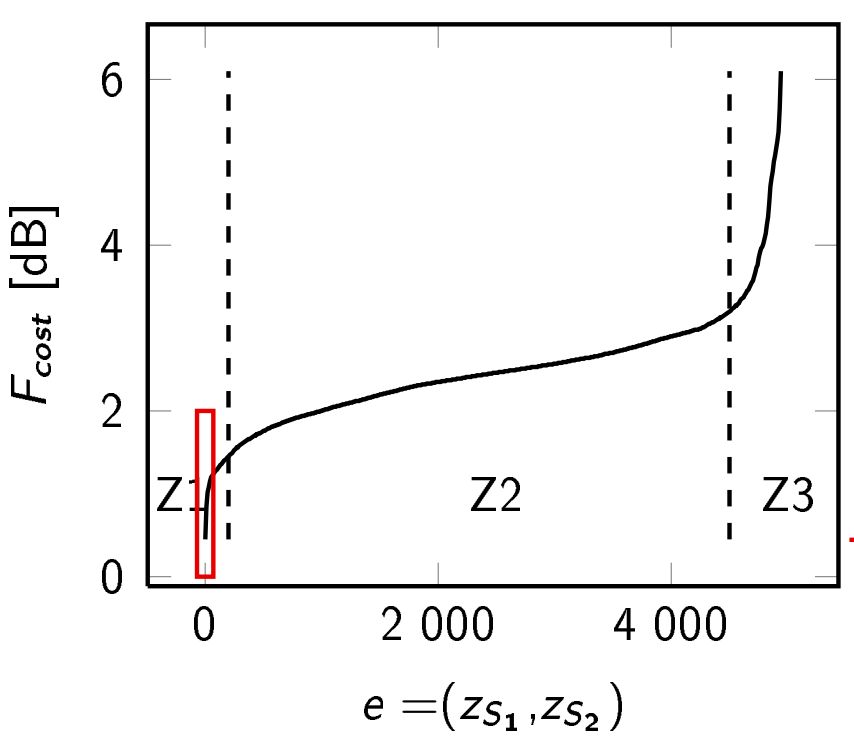
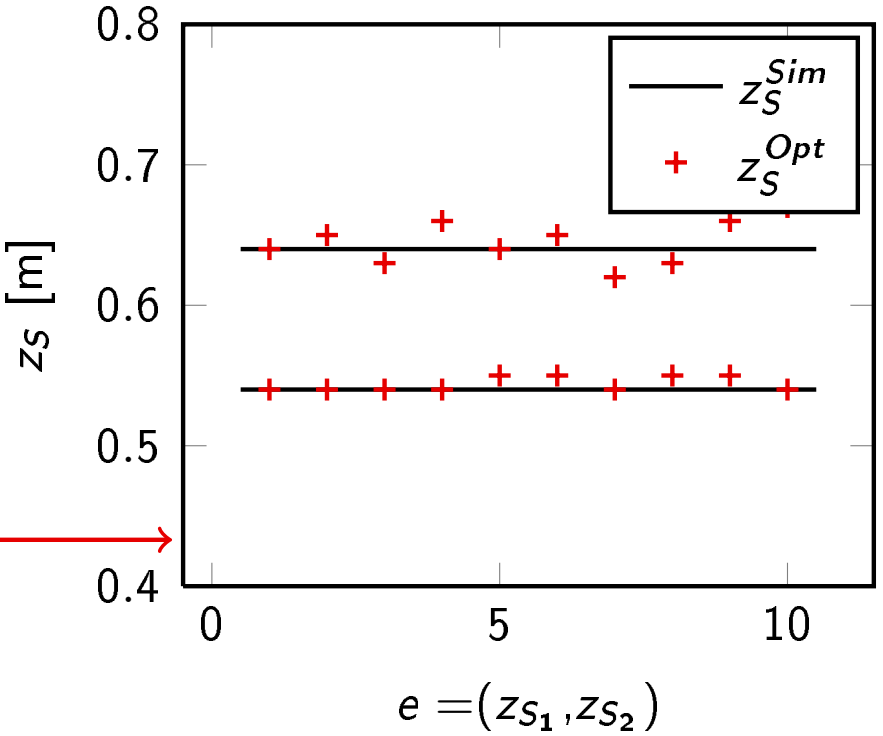
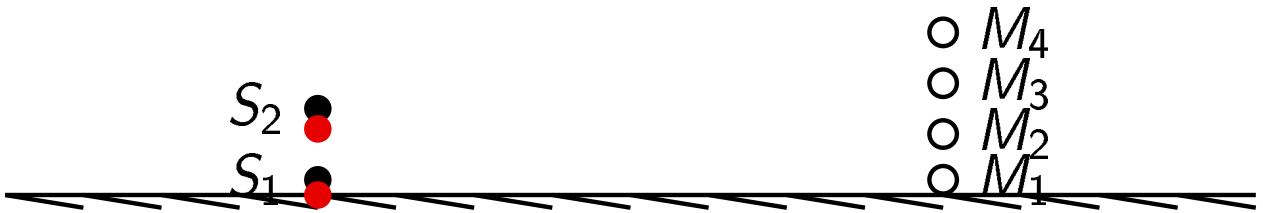
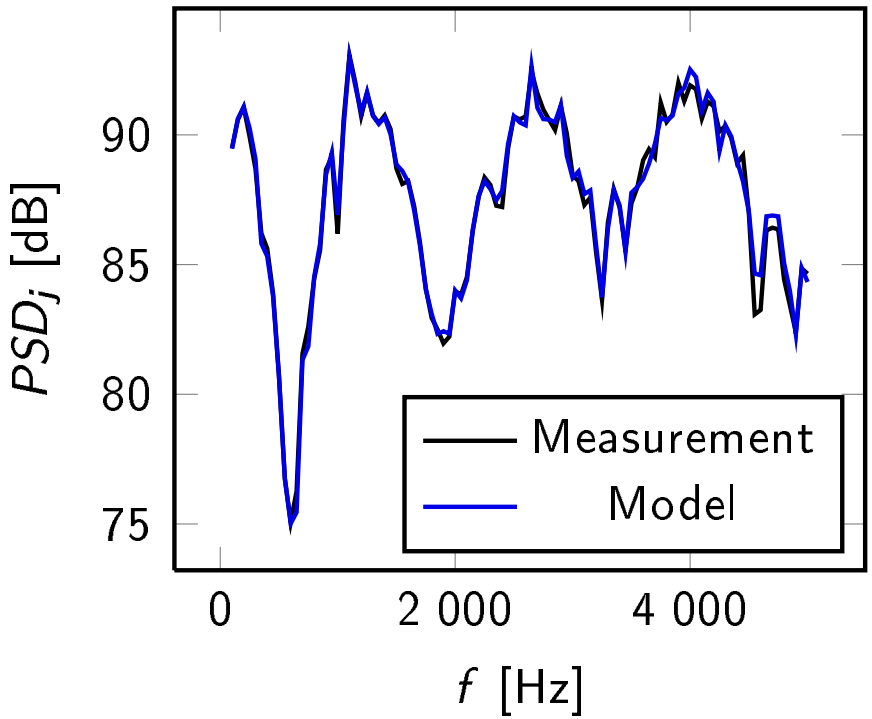






MÉCS: numerical results (2/4)





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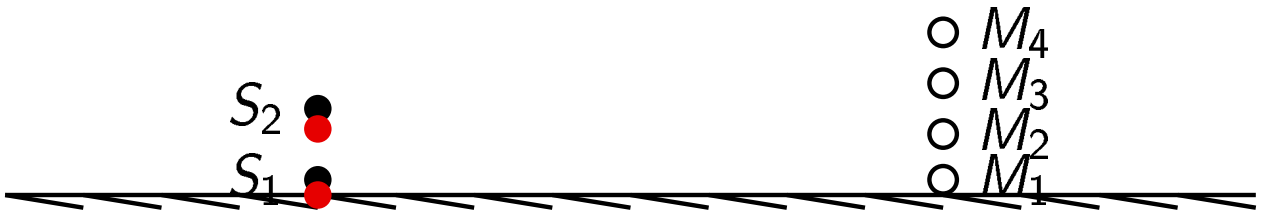

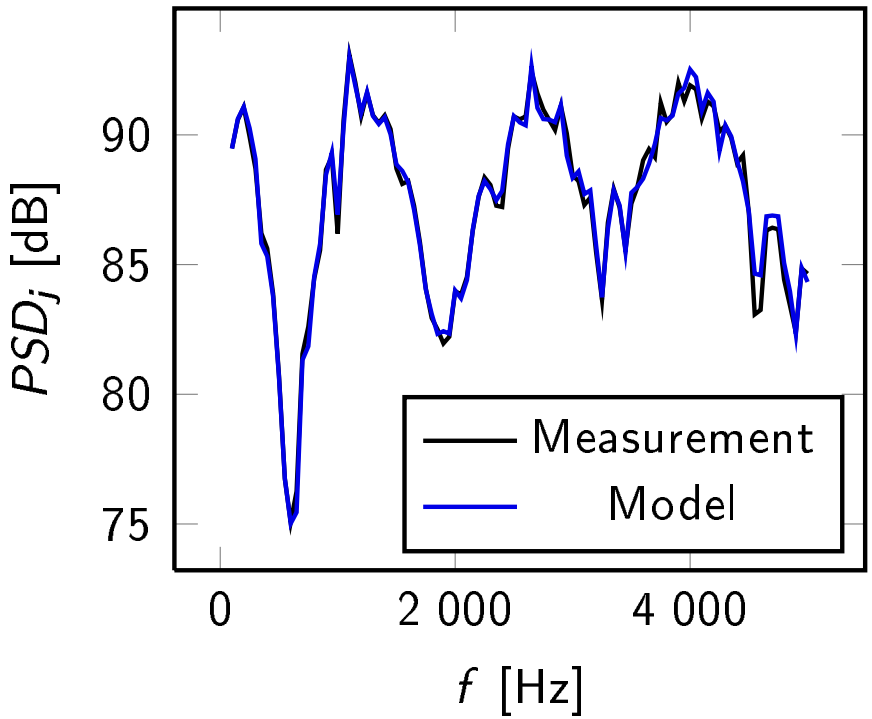

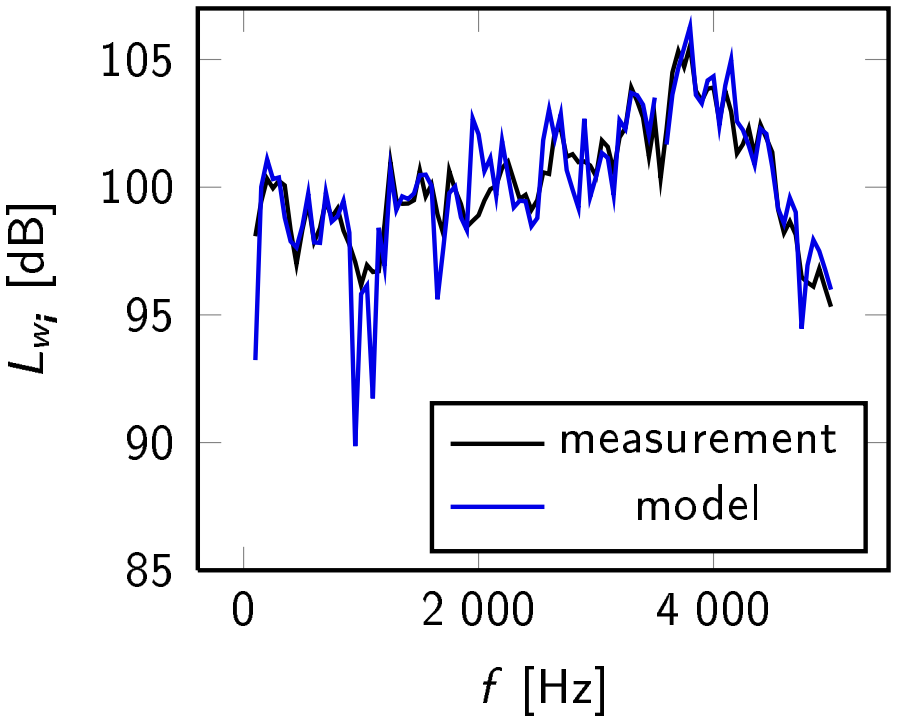

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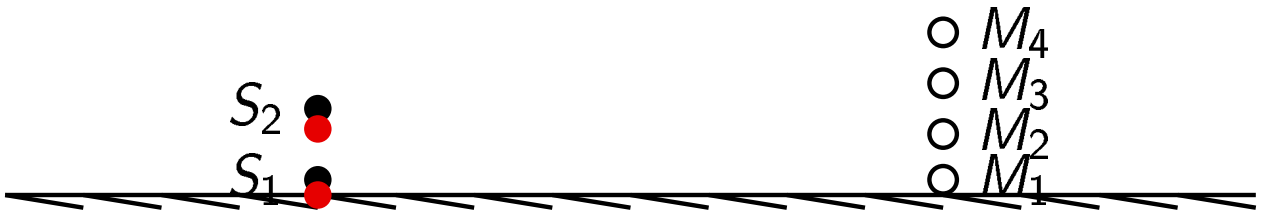

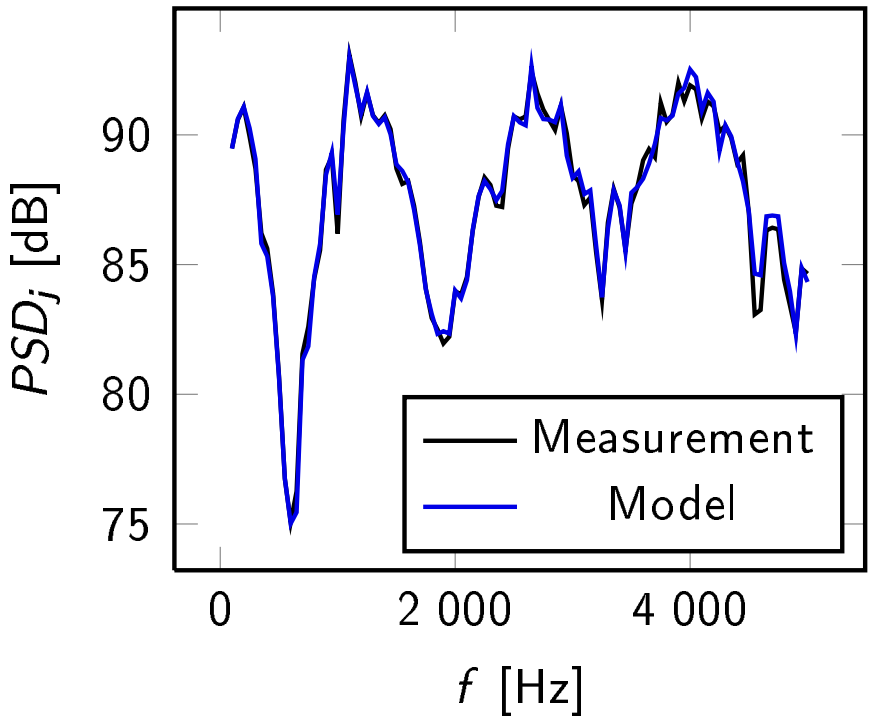

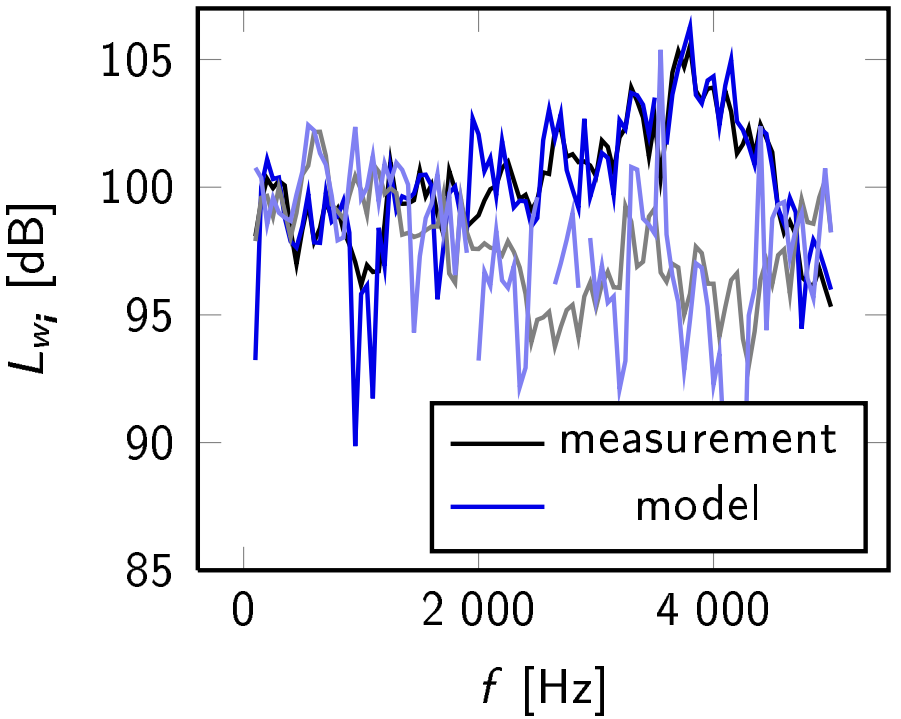

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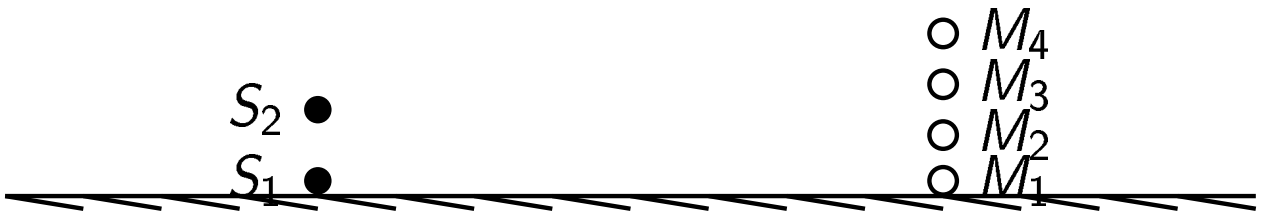

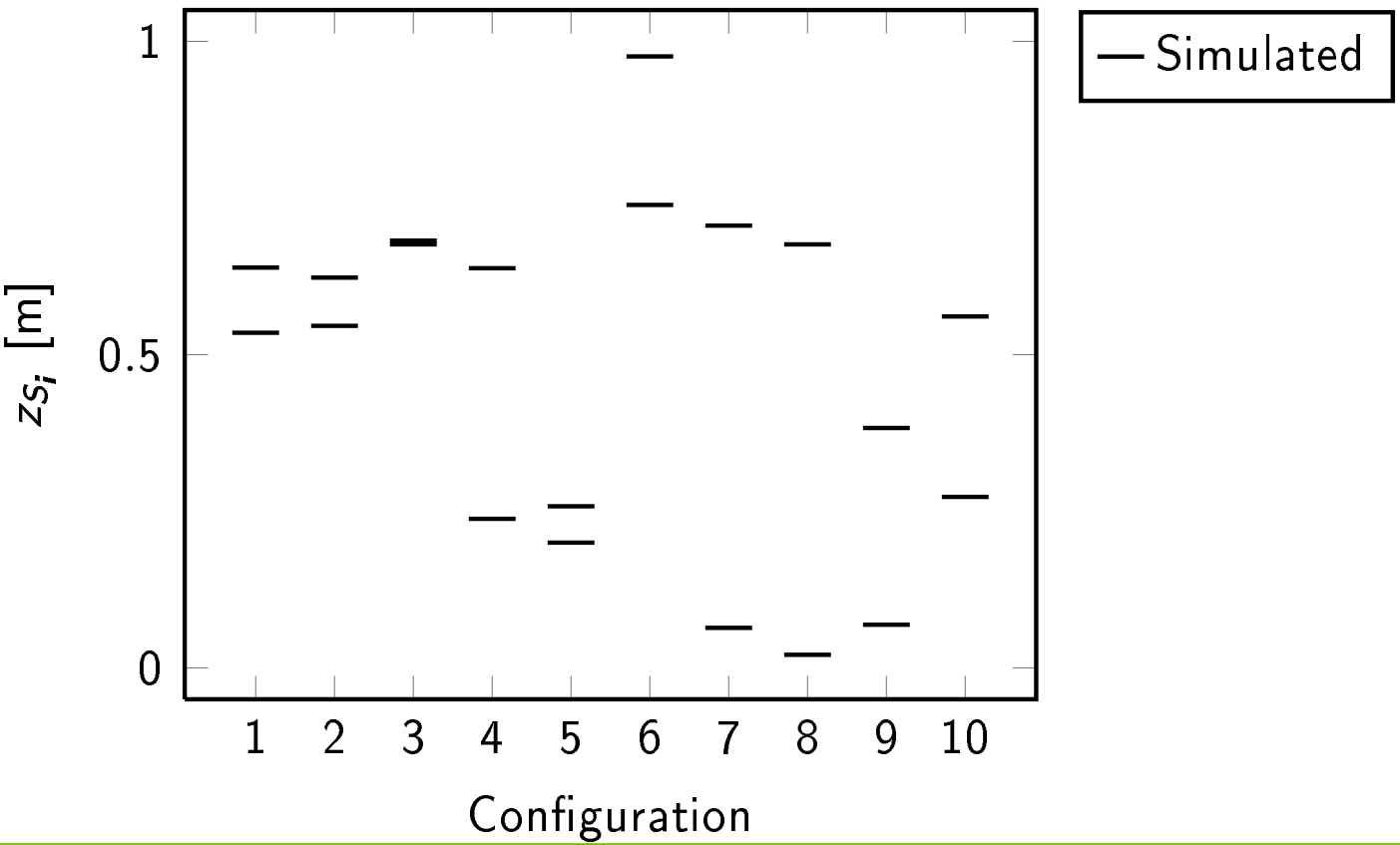

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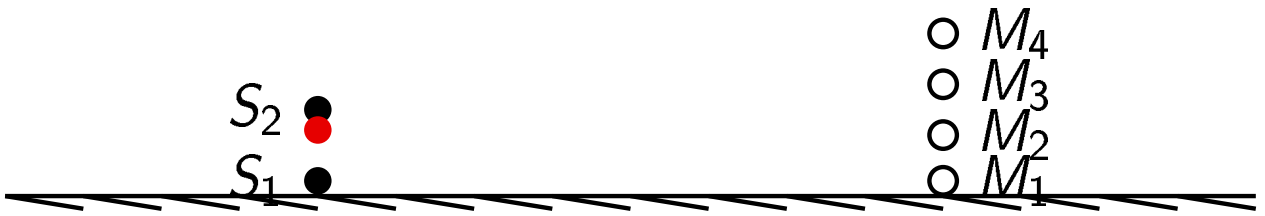

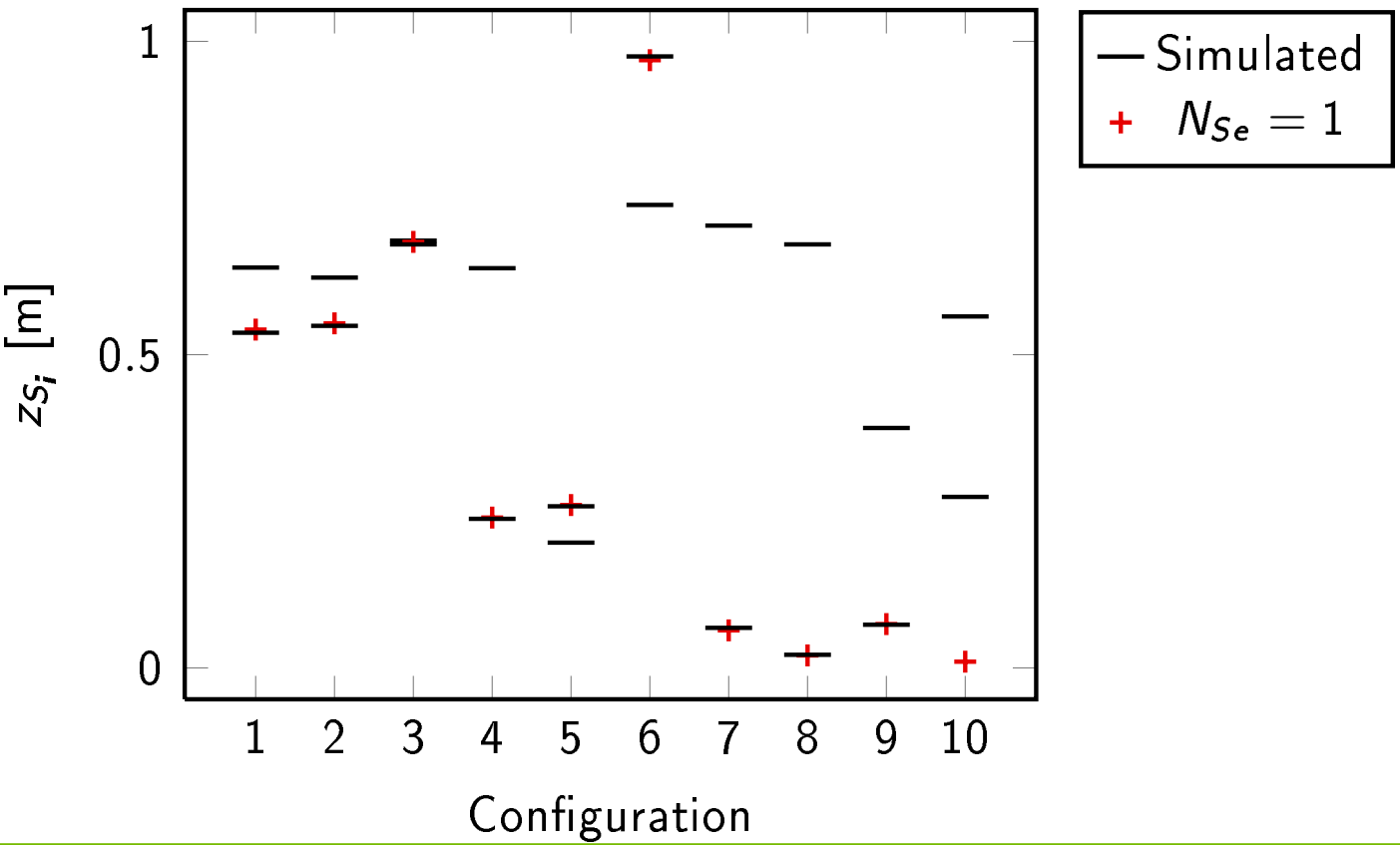

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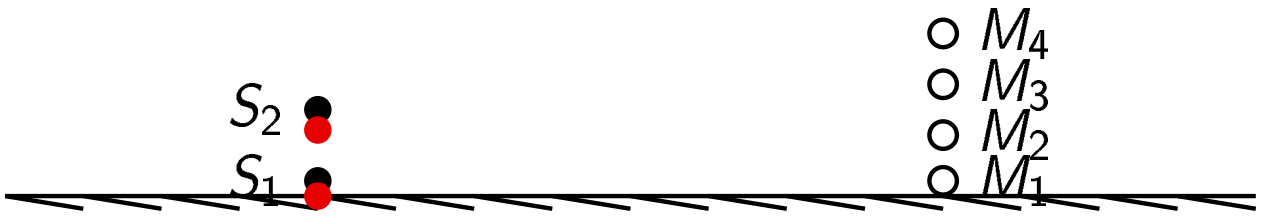

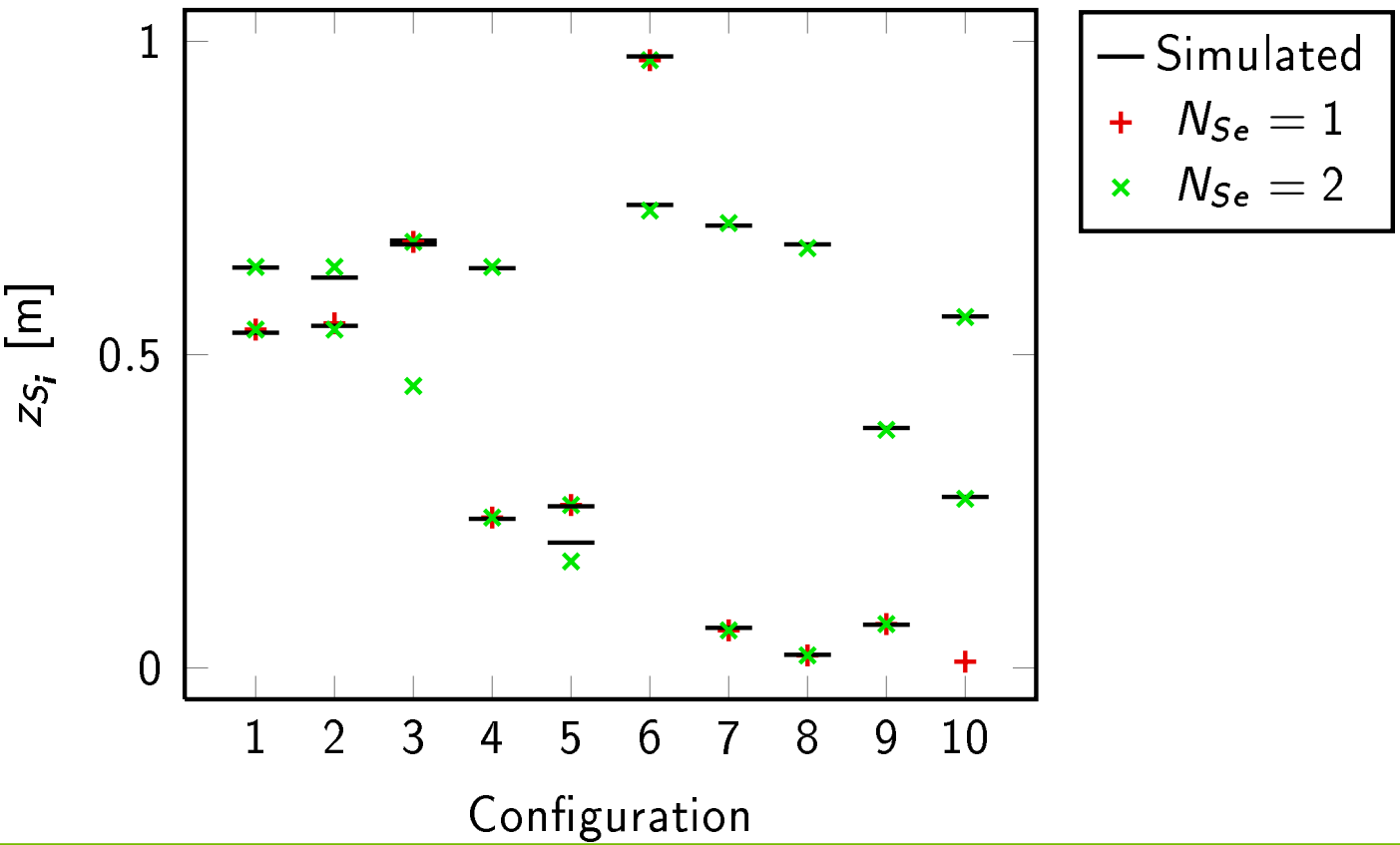

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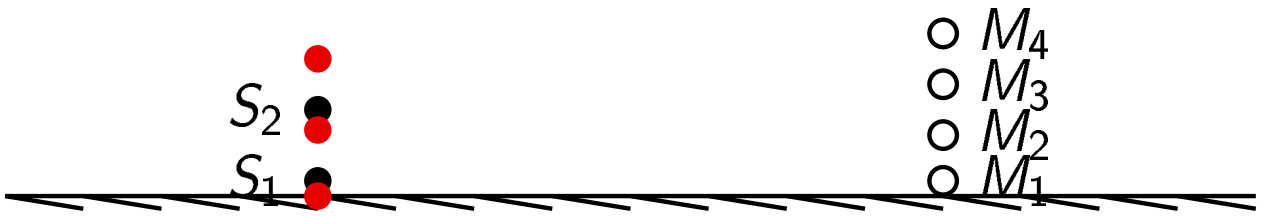

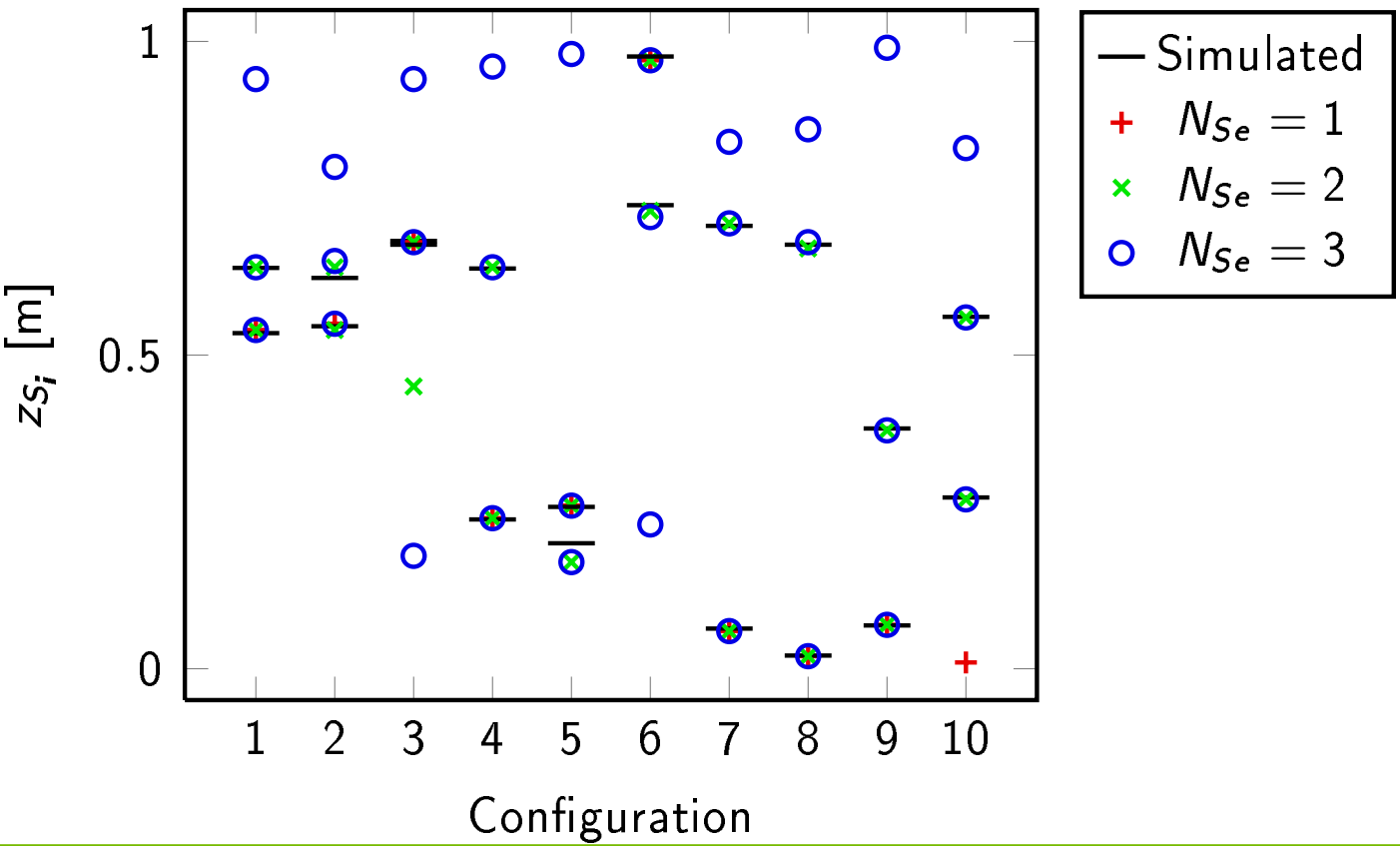

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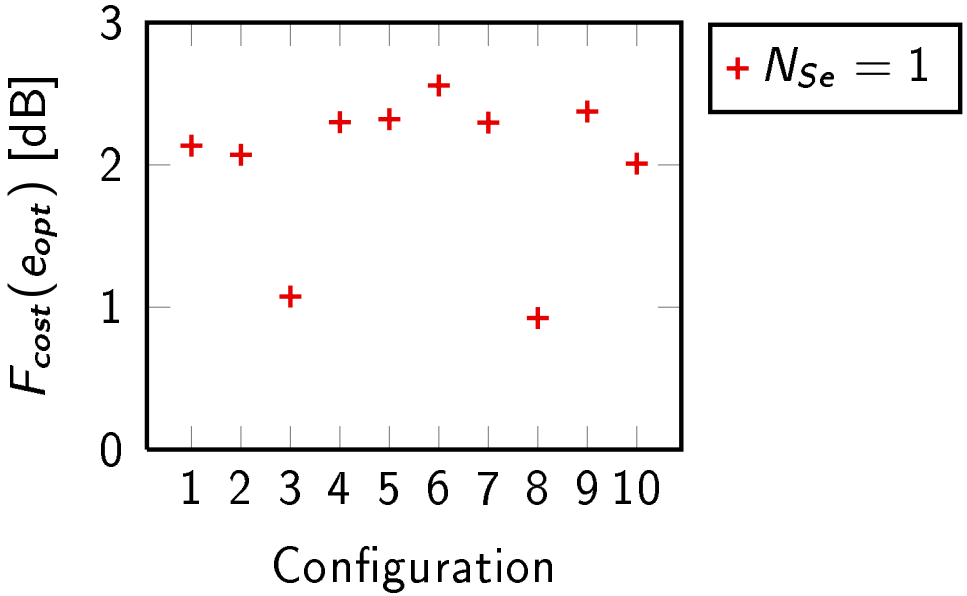

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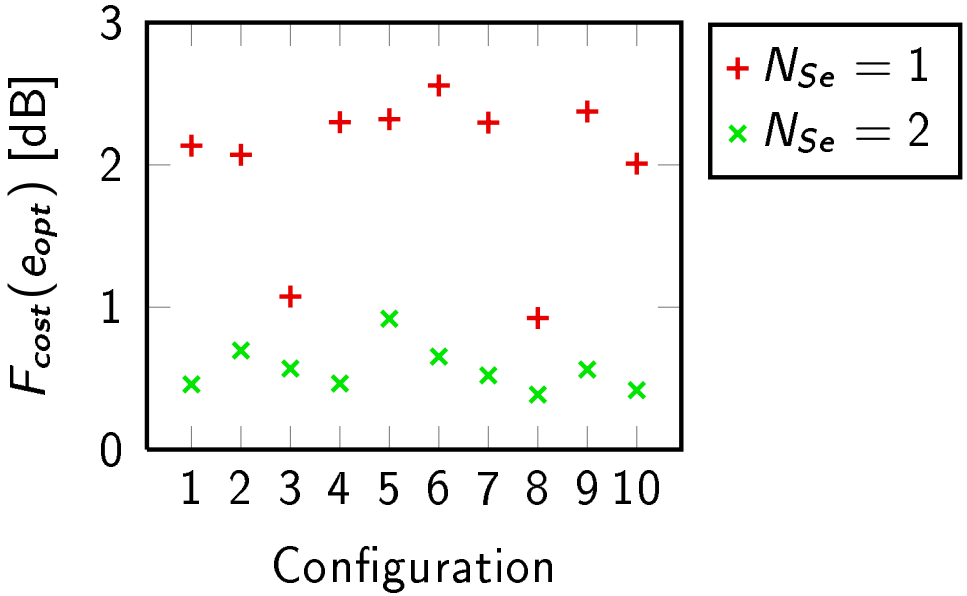

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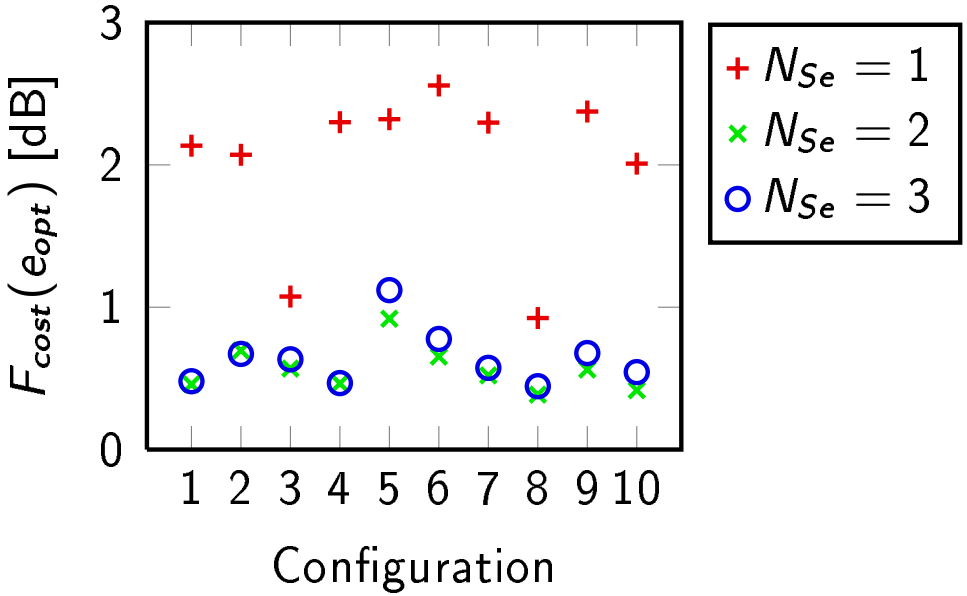

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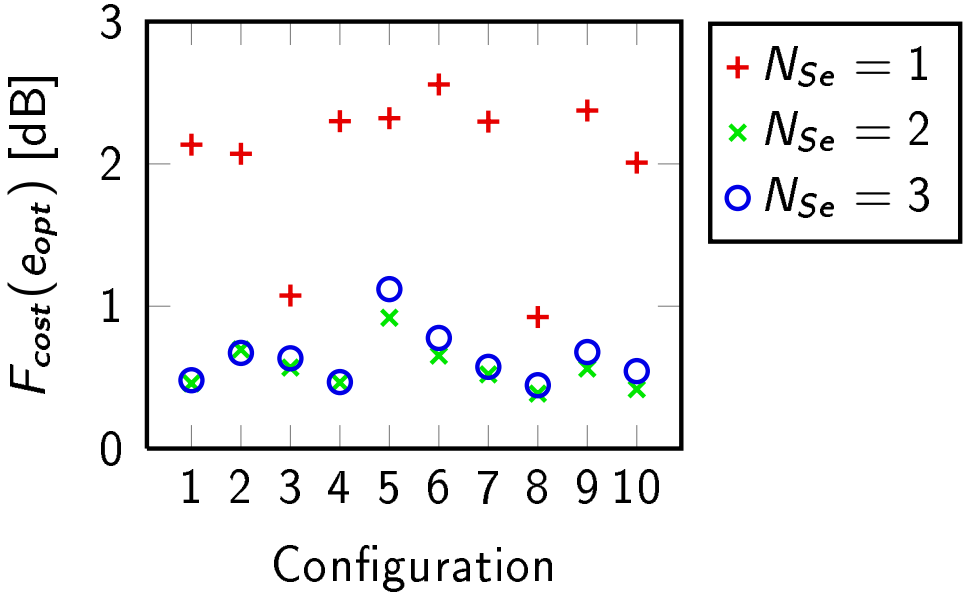

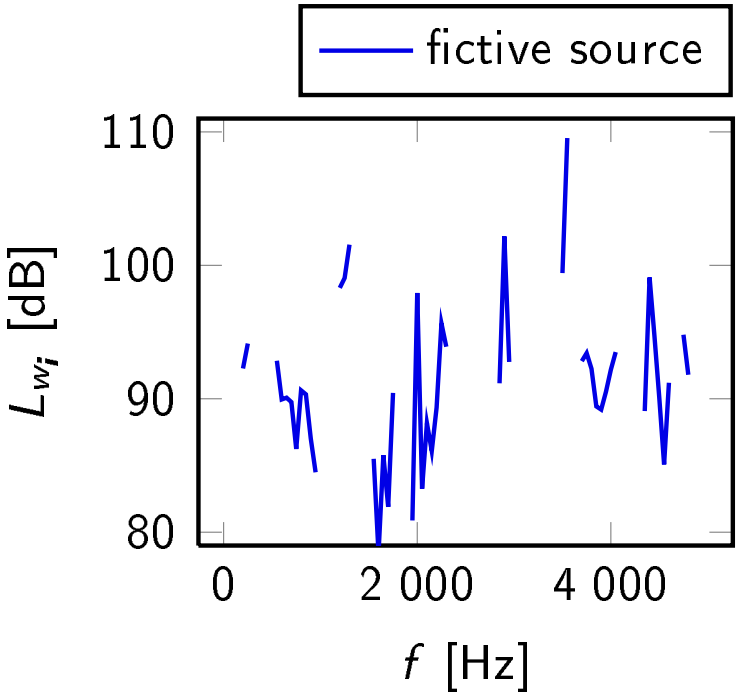

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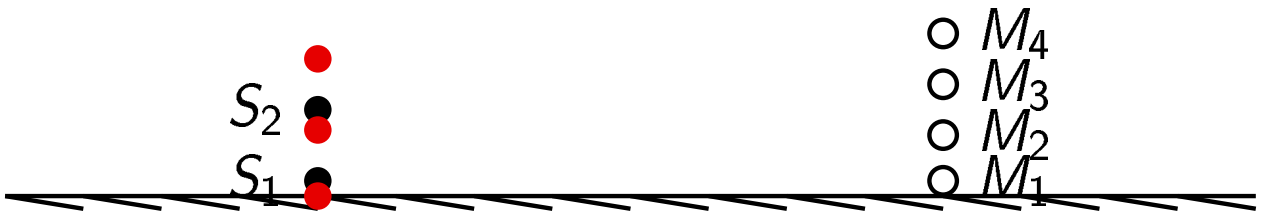
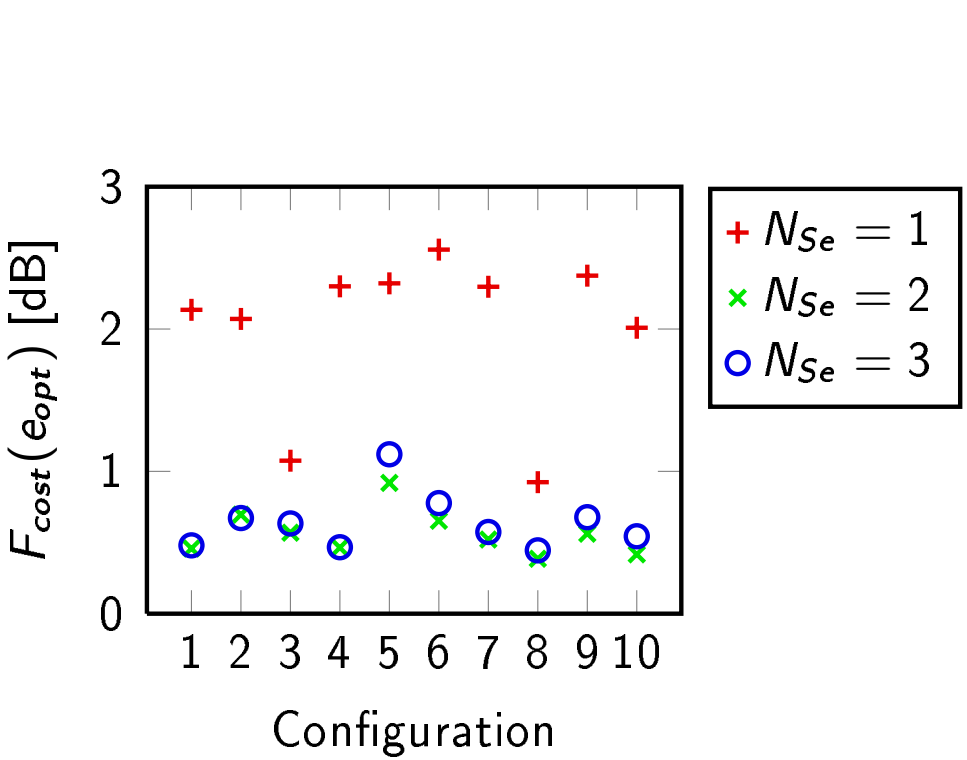
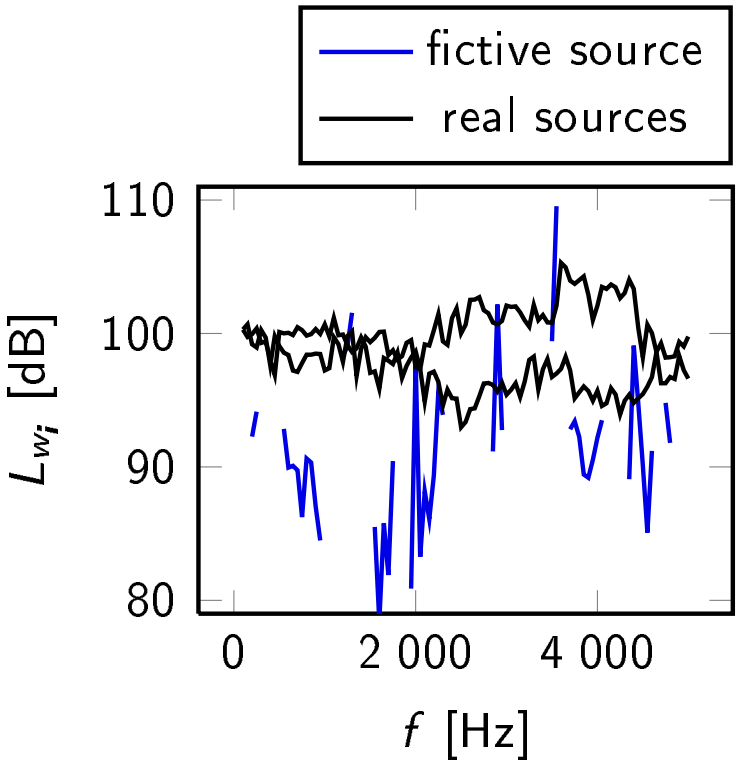
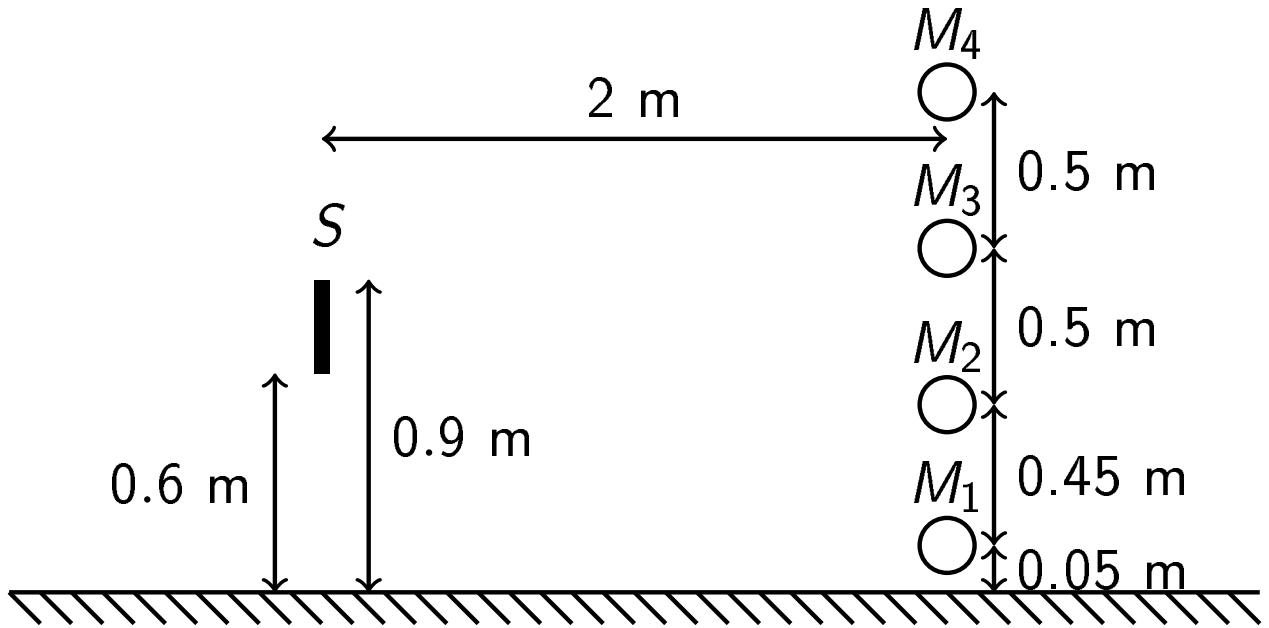






MÉCS: large source simulation



Hypotheses

- 50 sources modeling one large real source
- different spectra
- uncertainties on localization

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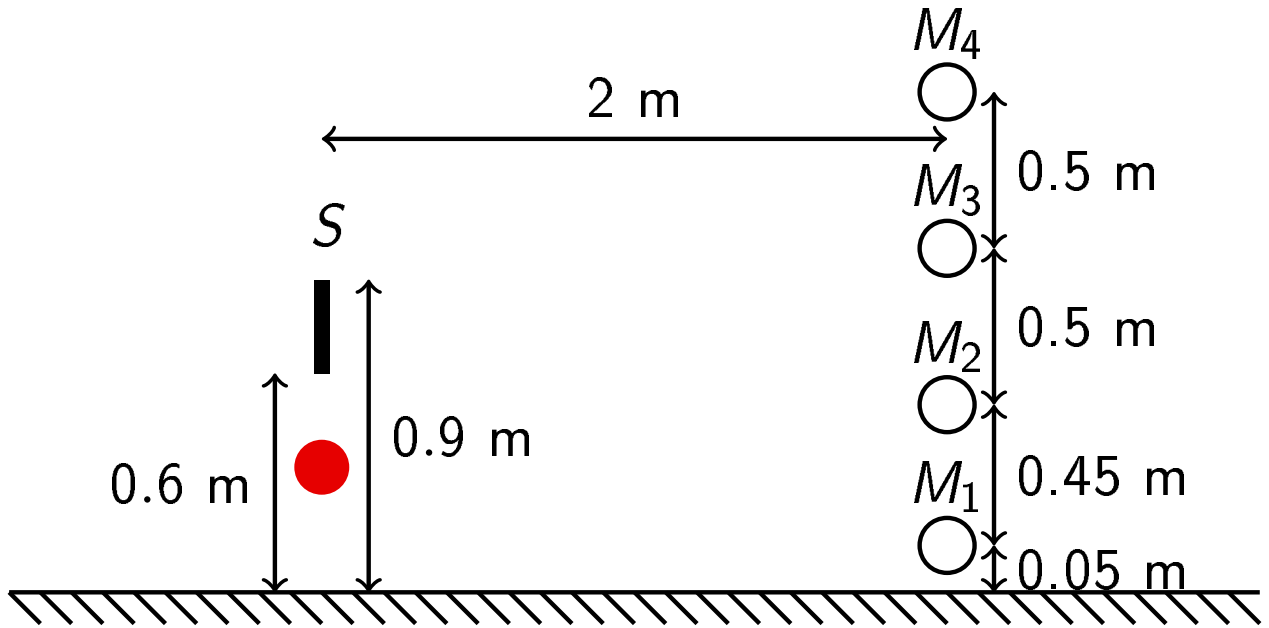

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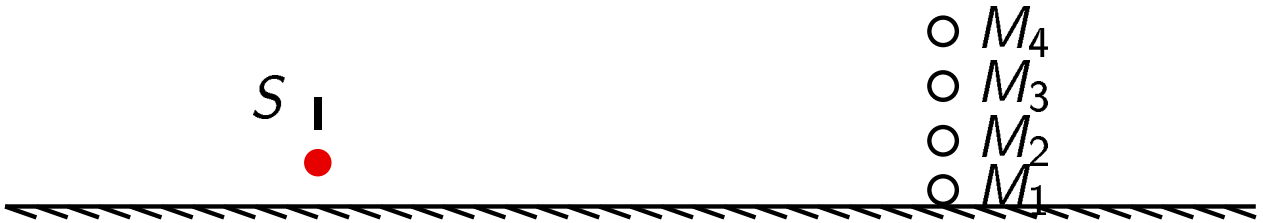

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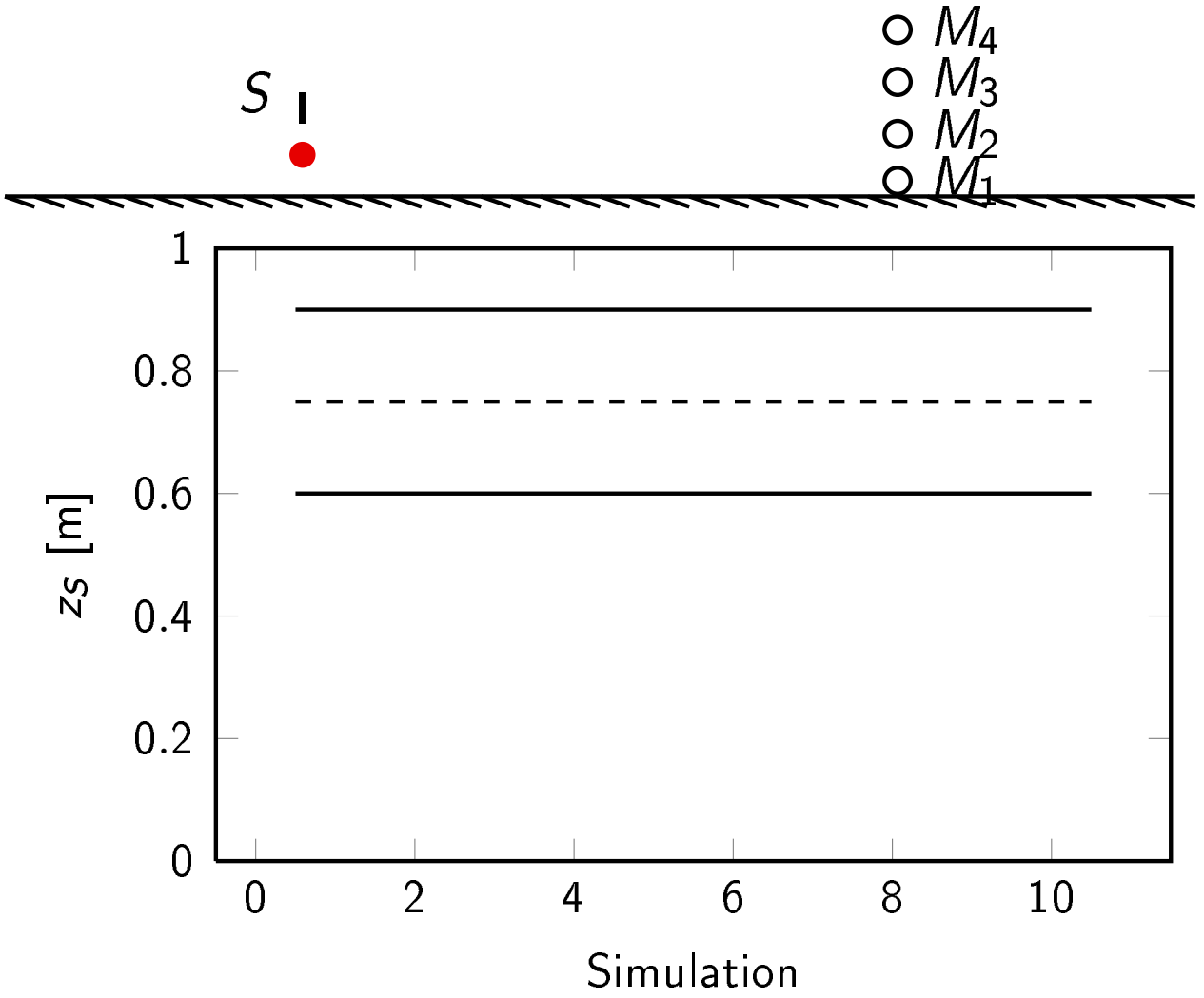

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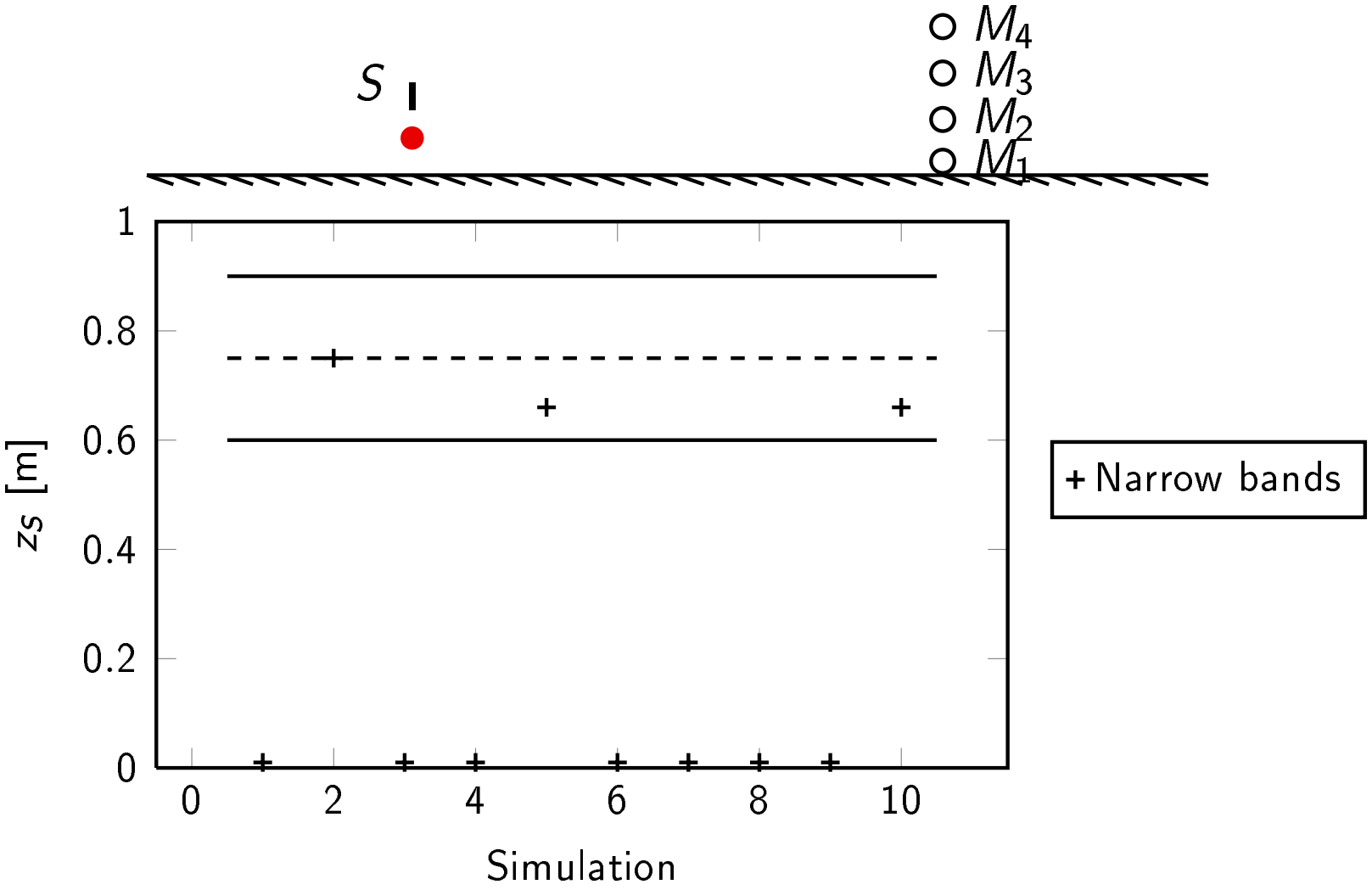

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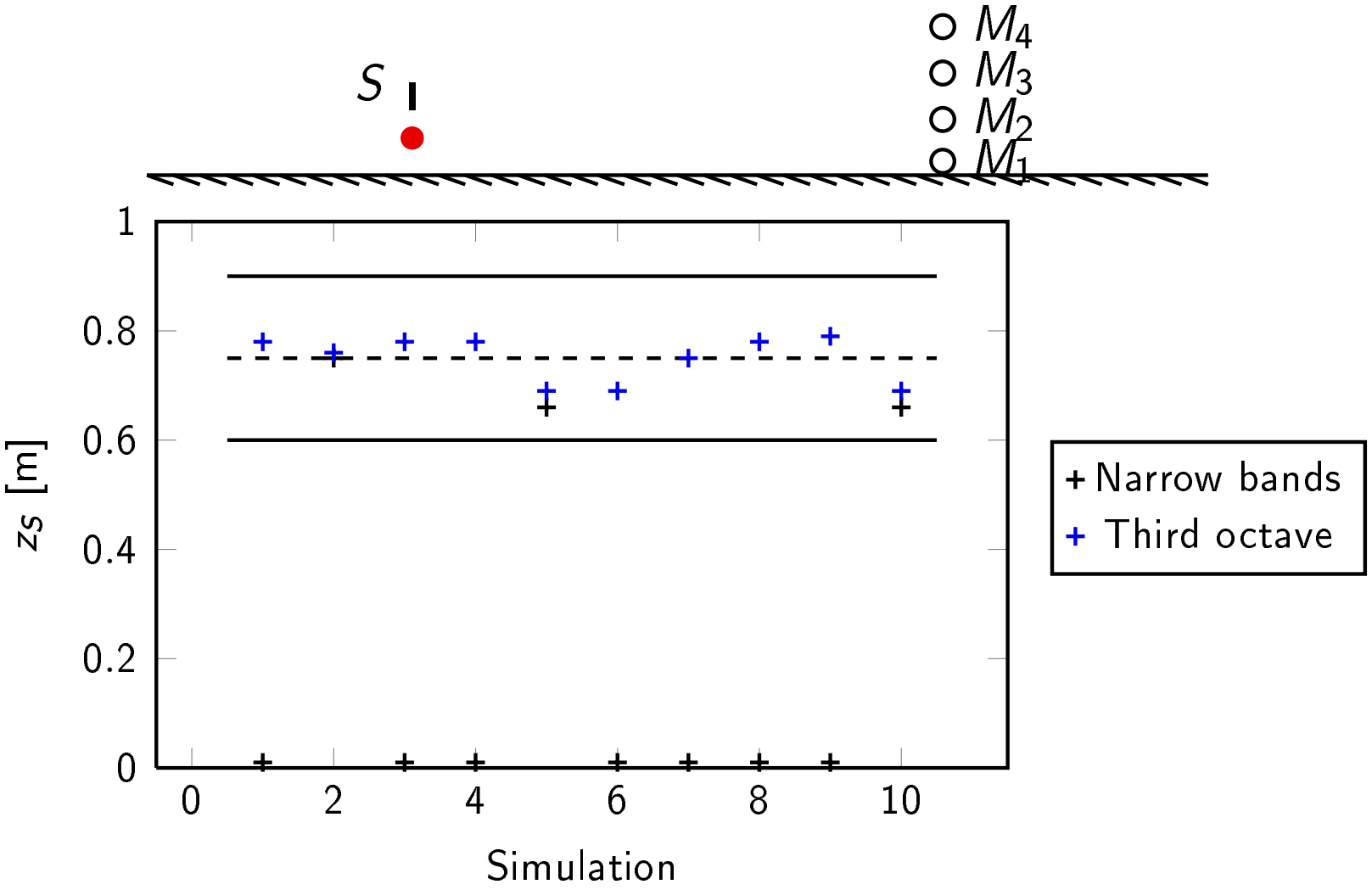

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  - LMS to compute $|A_i(f)|^2$

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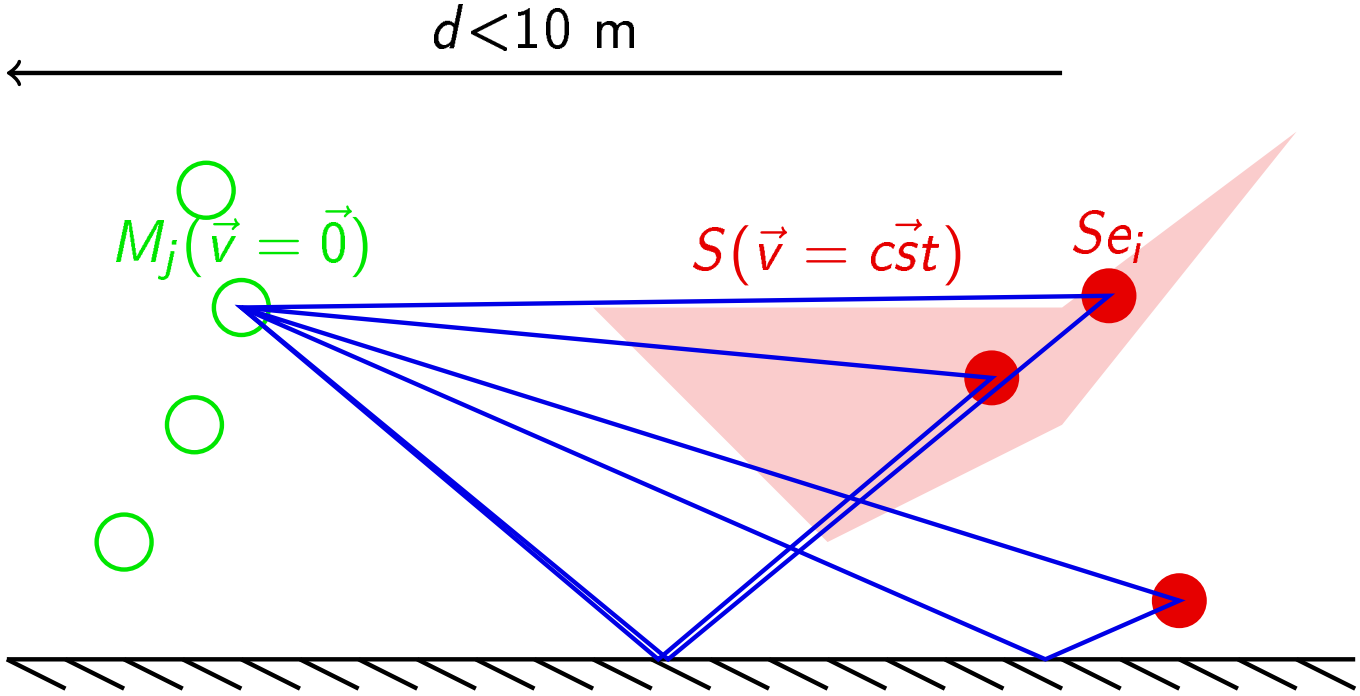
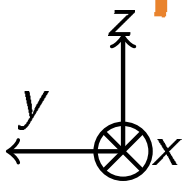
- simulation of a large source
  - F_{cost} based on narrow bands gives often sources near the ground
  - F_{cost} based on third octaves approaches physical height

Conclusion (1/3)



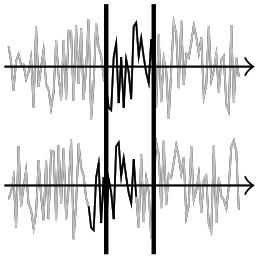


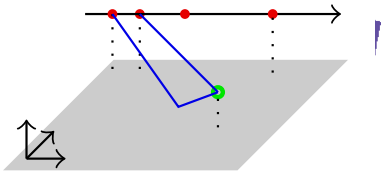
PSD_j → propagation^{-1} →

Emission
- N_{Se}
- $(x_{Se}, y_{Se}, z_{Se})_i$
- $|A_i|^2$

Conclusion (2/3)

- improvements of models
  - for broadband noise
  - for moving sources





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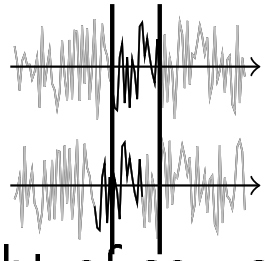

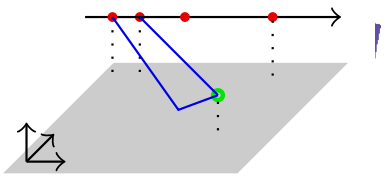

Att_j —propagation^{-1}→

Emission
- $N_{Se} = 1$
- $(\cancel{x_{Se}, y_{Se}}, z_{Se})_i$
- $\cancel{|A_i|^2}$

Conclusion (2/3)

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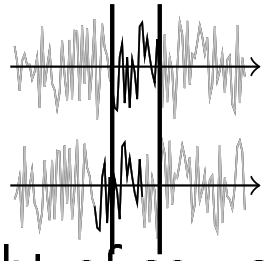
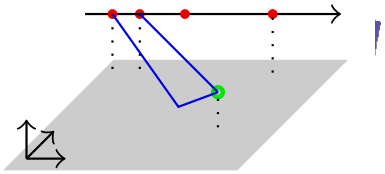
  - vehicles
- MÉCS
  - theory
  - numerical validation





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MECS: Perspectives

Optimization and validation of MÉCS

- microphone localization
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Acknowledgments

Close supervision

- Christophe AYRAULT, LAUM
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- Laurent SIMON, LAUM

Monitoring committee

- Fabienne ANFOSSO-LEDEE, LCPC
- David ÉCOTIÈRE, LRS
- Franck POISSON, SNCF

Other

- Charlotte, Thérèse, Auguste, Gustave...
- Chritophe H., Thierry F., Jean-Louis A., Loic T., Laurent B.

Thank you for your attention

Ressources, territoires et habitats
Énergie et climat
Développement durable
Prévention des risques
Infrastructures, transports et mer

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Centre d'Études techniques de l'Équipement de l'Est

Ministère de l'Écologie, de l'Énergie, du Développement durable et de l'Aménagement du Territoire