Jan. 5, 2020 at SciTech Forum 2020, Orlando, Florida

Far-field Waveform Prediction by JAXA

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Numerical Simulation Research Unit

Outline

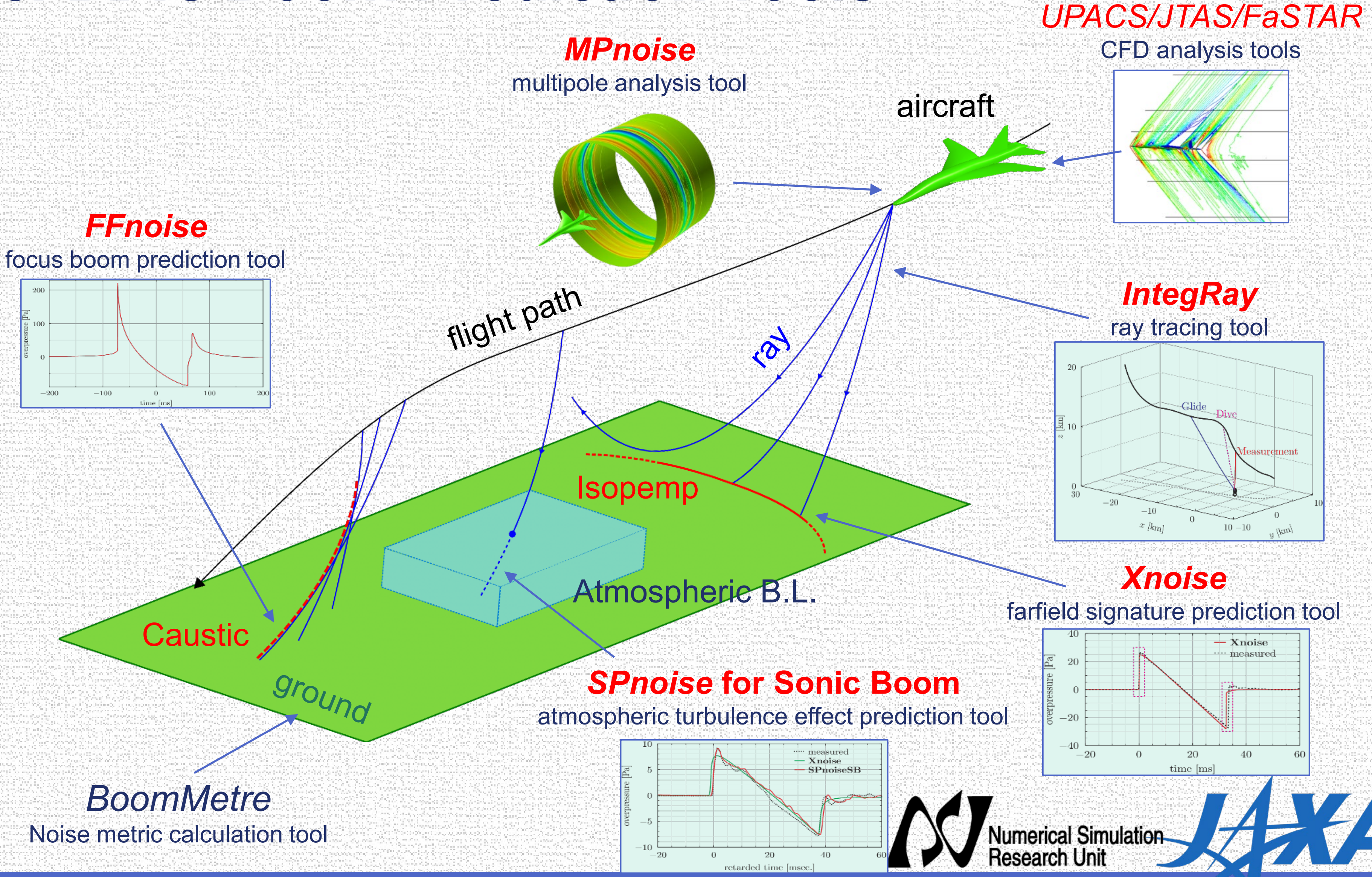
- ✓ Introduction of Numerical Prediction Tool of Sonic Boom Waveform

- ✓ Case 1, Required
  - ✓ C25P, a powered equivalent of the NASA C25D

- ✓ Case 2, Required
  - ✓ C609, an earlier version of X-59

- ✓ Case 1, Optional
  - ✓ C25P, a powered equivalent of the NASA C25D
  - ✓ Focus case for level acceleration

JAXA's Boom Prediction Tools



UPACS/JTAS/FaSTAR
CFD analysis tools

MPnoise
multipole analysis tool

FFnoise
focus boom prediction tool

IntegRay
ray tracing tool

Xnoise
farfield signature prediction tool

SPnoise for Sonic Boom
atmospheric turbulence effect prediction tool

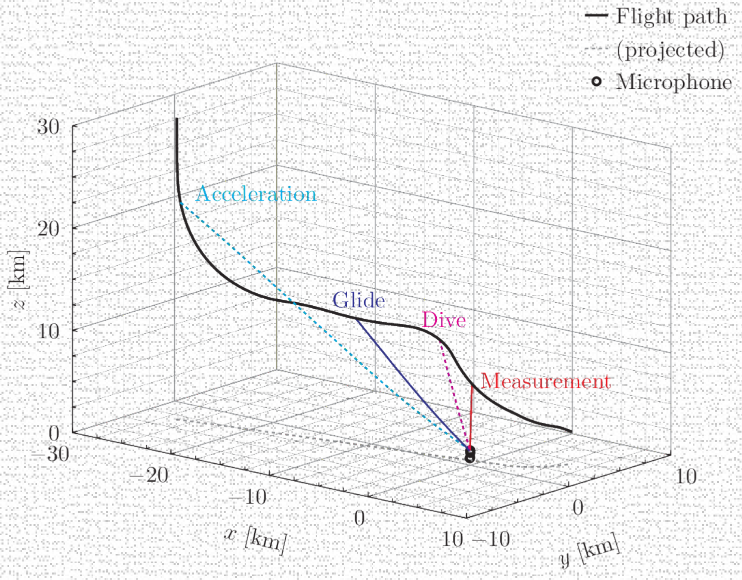
BoomMetre
Noise metric calculation tool

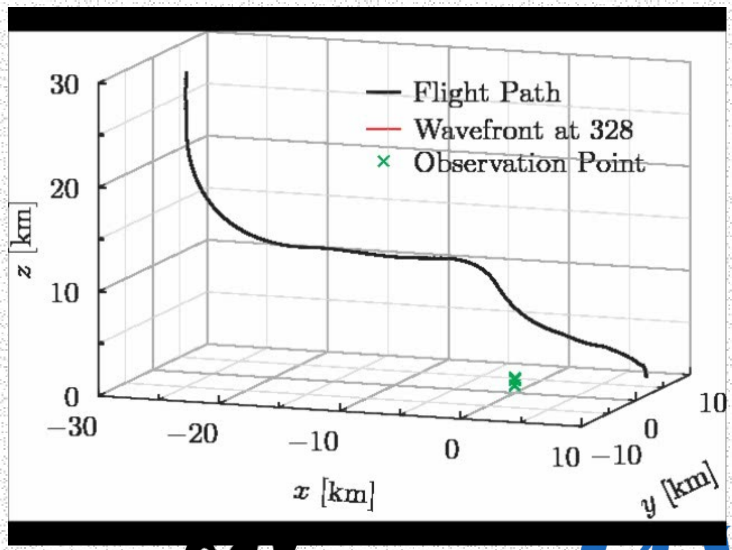
IntegRay – Raypath Integration Tool –

- ✓ calculates acoustical rays by integrating ray path equation
- ✓ has several functionalities:
  - ✓ calculating raypaths, wavefront and caustic
  - ✓ specifying the origin of sound

◆ Application to D-SEND#2 flight test

- eight rays reached to the microphone (Bottom left)
- progression of wavefront is also shown (Bottom right)





Kanamori et al., AIAA J., vol.56, No.7, pp.2743—2755

Xnoise – Nonlinear Propagation Analysis Tool –

- ✓ solves augmented Burgers equation shown below (Cleveland *et al*, 1995)
- ✓ simulates acoustical effects including nonlinearity, attenuation and dispersion.
- ✓ validated with measurements of D-SEND#1 flight test
  - ◆ Application to D-SEND#1 flight test
    - both *N* wave and flattop signature were tried
    - fairly good agreement was achieved including rise time

$$\frac{\partial p}{\partial s} = \frac{\beta}{2\rho_0 c_0^3}\frac{\partial p^2}{\partial \tau}$$

: *Nonlinearity*

$$-\frac{1}{2B}\frac{\partial B}{\partial s}p$$

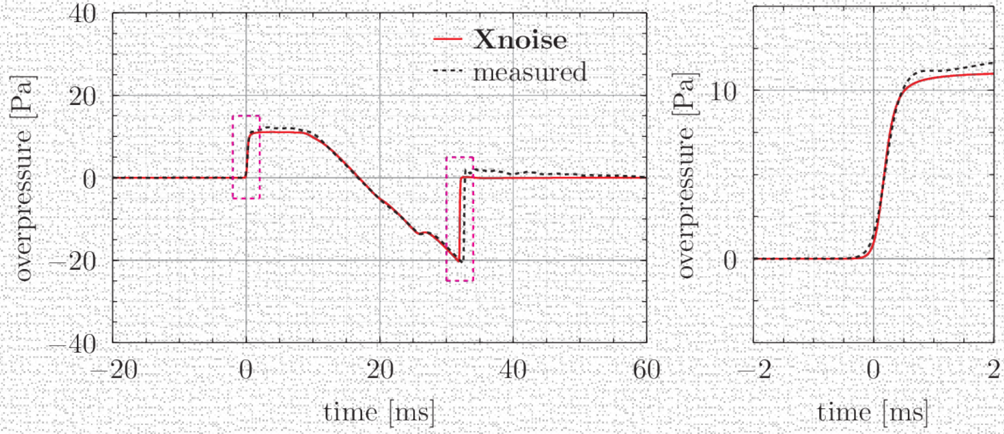
: *Blokhintsev Energy Conservation*

$$+\frac{\delta}{2c_0^3}\frac{\partial^2 p}{\partial \tau^2}$$

: *Thermo-Viscous Effect*

$$+\sum_{\nu}\frac{(\Delta c)_\nu \tau_\nu}{c_0^2}\left(1+\tau_\nu\frac{\partial}{\partial \tau}\right)^{-1}\frac{\partial^2 p}{\partial \tau^2}$$

: *Molecular Relaxation Effect*



Kanamori et al., AIAA J., vol.56, No.7, pp.2743—2755

FFnoise – Focusing Prediction Tool –

- ✓ solves lossy nonlinear Tricomi equation (Salamone *et al*, 2013)
- ✓ achieves highly accurate predictions with a remarkable speed of computation by combining a splitting scheme and multigrid-like acceleration
- ✓ validated with measurements of SCAMP flight test by NASA
  - ◆ Application to SCAMP flight test
    - focusing of incoming *N* wave was clearly reproduced

$$\frac{\partial^2 P}{\partial Z^2} - Z\frac{\partial^2 P}{\partial \tau^2}$$

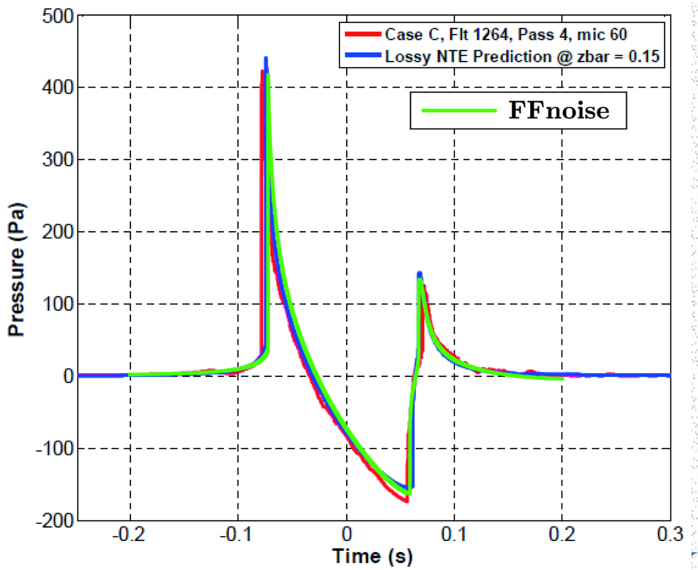
: Diffraction

$$+ \frac{\mu}{2}\frac{\partial^2 P^2}{\partial \tau^2}$$

: Nonlinezarity

$$+ \left[\frac{\alpha}{\varepsilon^2} + \sum_{\nu} \frac{\theta_\nu/\varepsilon^2}{1 + \tau_\nu \partial/\partial\tau}\right]\frac{\partial^3 P}{\partial \tau^3} = 0$$

: Thermo-viscous & molecular relaxation



Kanamori et al., AIAA J., vol.55, No.6, pp.2029—2042

BoomMetre –Loudness Metric Calculation Tool –

- ✓ calculates
    - ✓ Perceived Level(PL) (Stevens, 1972)
    - ✓ A-weighted Sound Exposure Level(ASEL) (ANSI S1.42-2001, 2001)
    - ✓ B-SEL, C-SEL …

Case 1, Required:
C25P, a powered equivalent of the NASA C25D

Numerical Simulation
Research Unit

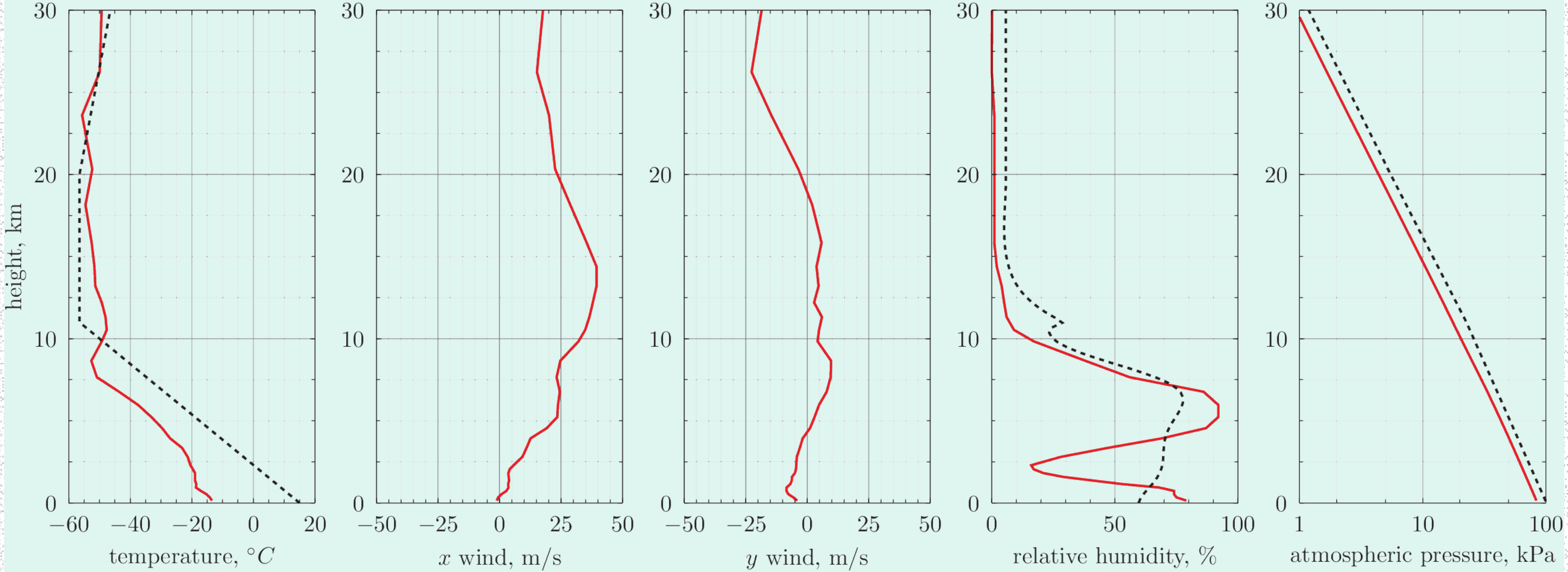
Required Run

1. Use near-field $\mathrm{d}p/p$ at all role angles from -70 to 70 in 10 -degree increments (with 0 being under-track) to predict the ground signatures using the provided atmospheric profile. If a specific azimuthal angle is beyond your computed lateral cut-off, submit $(0.0, 0.0)$ as the ground signature
2. Determine lateral cut-off angles and ground intersection locations on both sides

Configuration

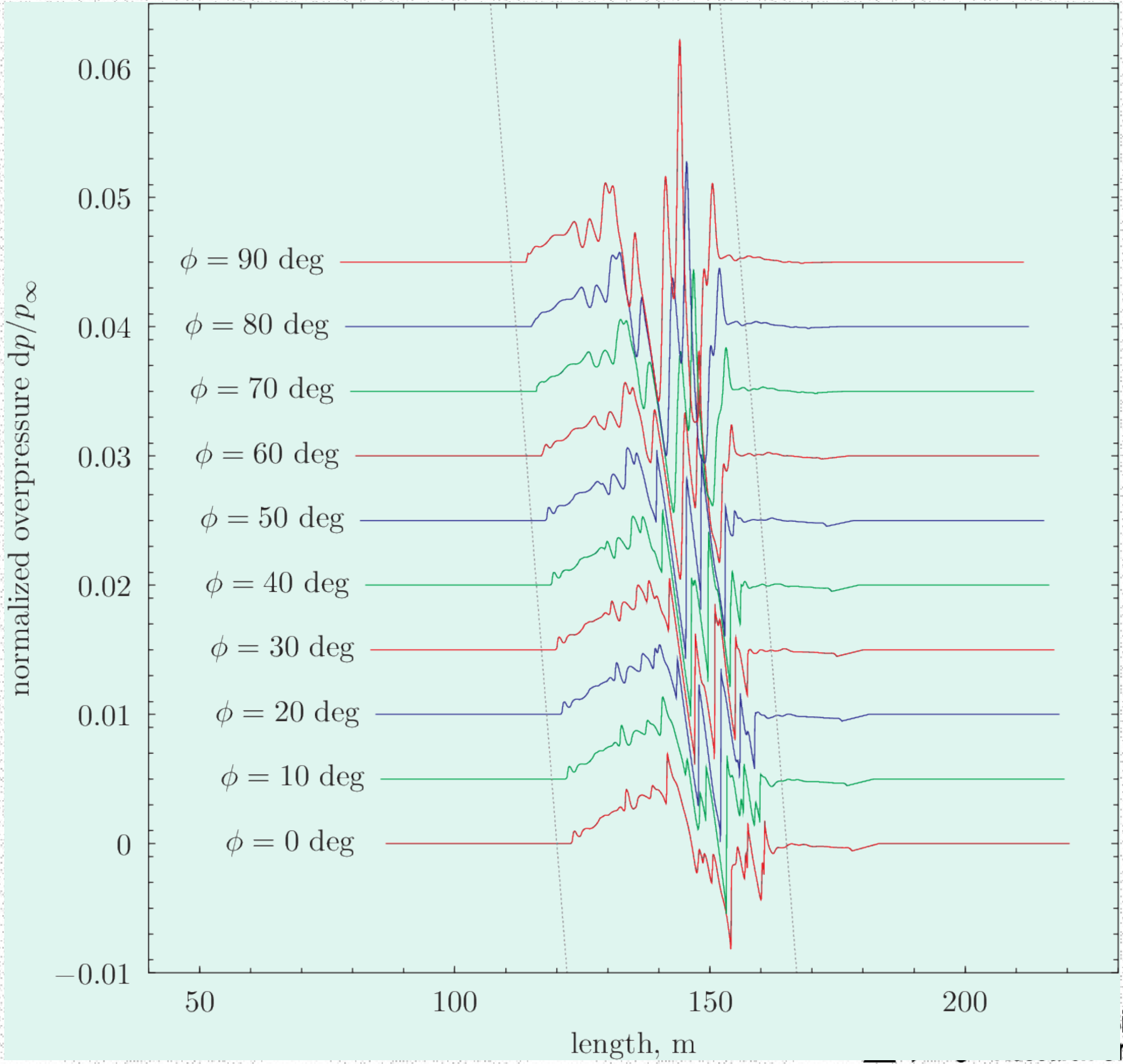
Parameters	Values	Unit
Mach number	1.6	-
cruise altitude	15,760.0	m
propagation start distance, R	100.584	m
R/L	3.0	-
ground altitude	264.069	m
ground reflection factor	1.9	-
heading	toward east (x direction)	
role angle	[-70,70] every 10 deg	-

Atmospheric Profiles



Numerical Simulation Research Unit

Nearfield (Input) Signature



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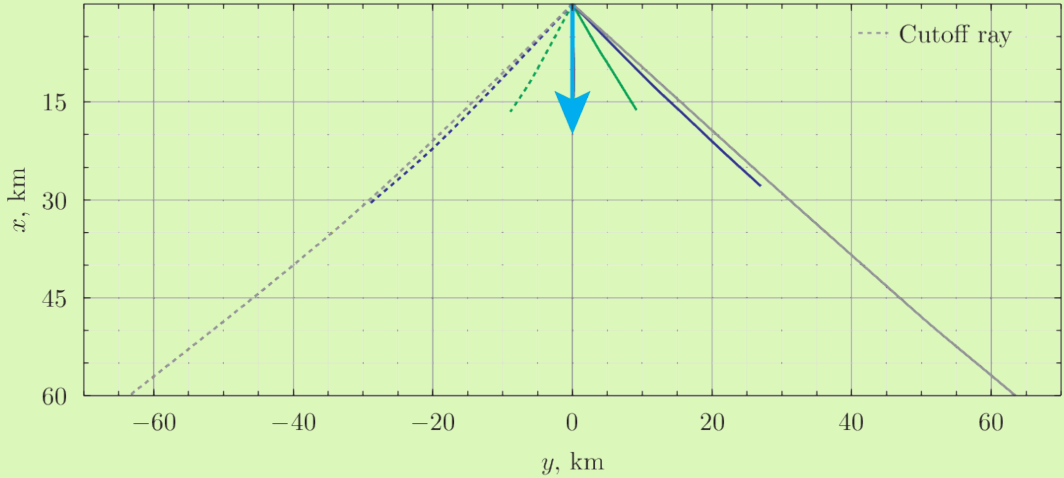
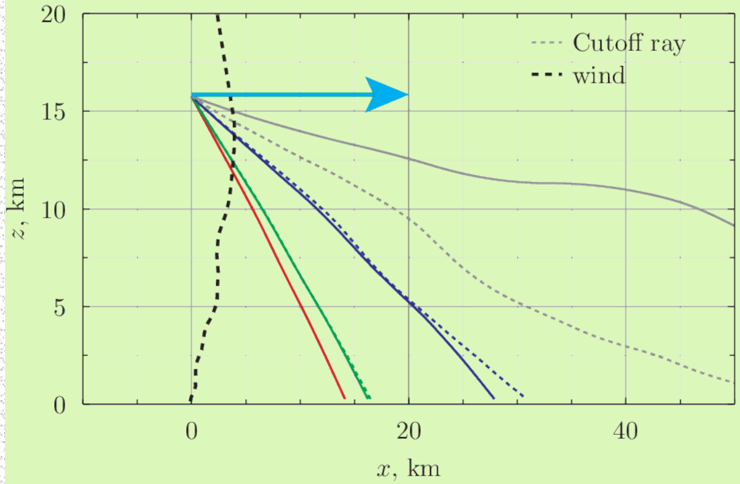
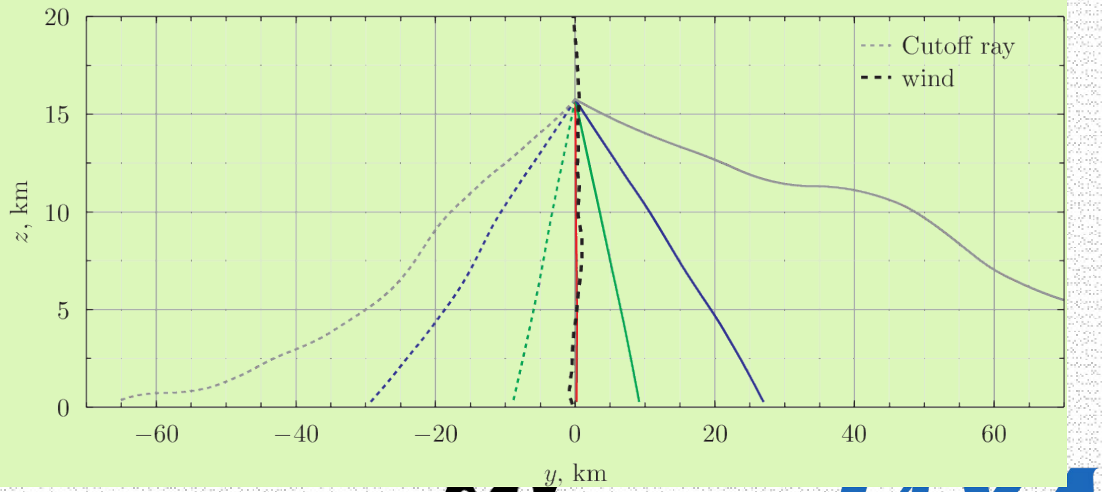
Case 1, Cut-offs and Corresponding Raypaths

Cut-off angle:

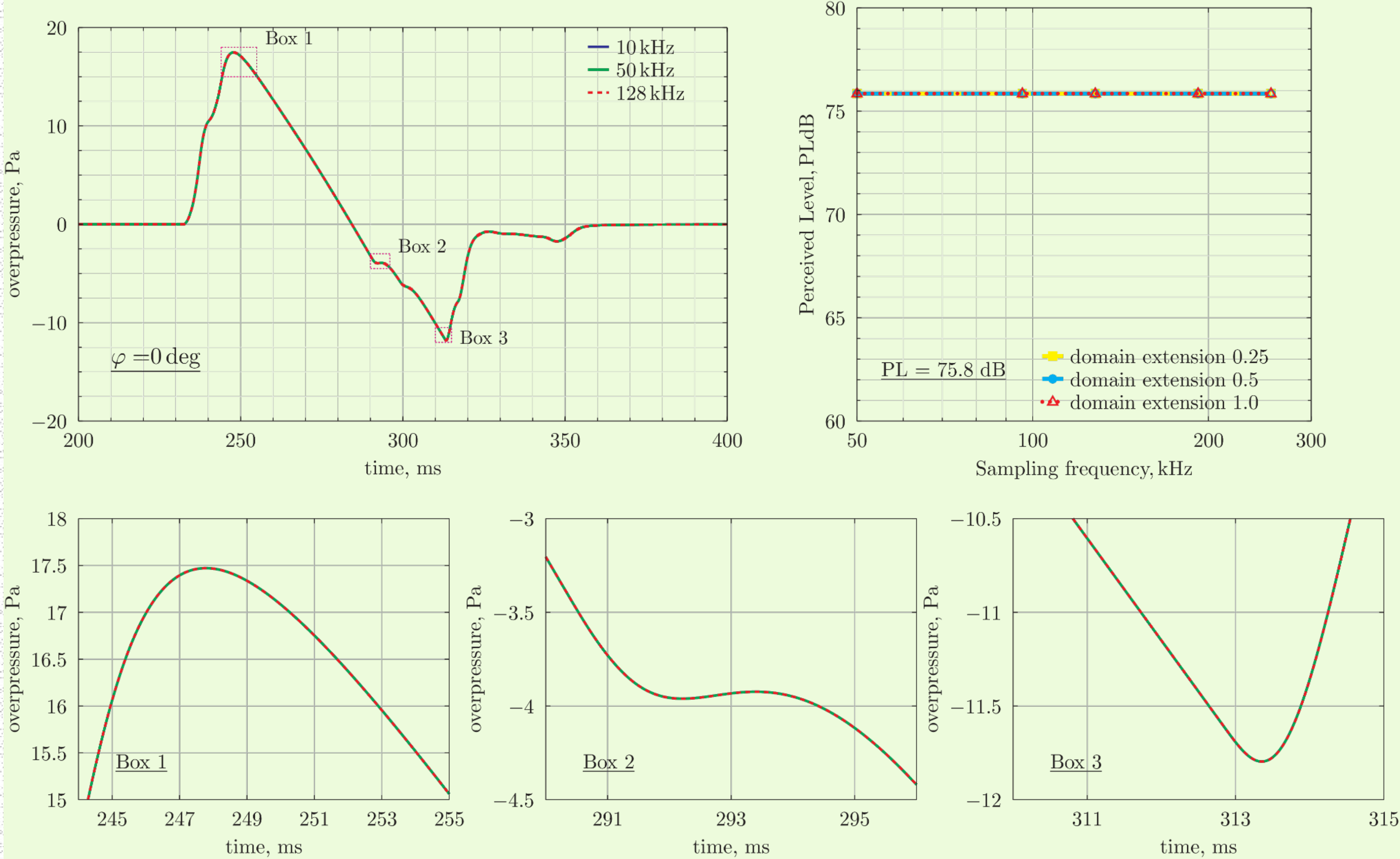
-78.37 deg, 69.01 deg







Case 1, Required, $\varphi = 0$ deg



Case 2, Required:
C609, an earlier version of X-59

Numerical Simulation
Research Unit

Required Run

1. For the measured atmospheric profile, use near-field $\mathrm{d}p/p$ at the following azimuthal angles to predict the ground signatures. If a specific azimuthal angle is beyond your computed cut-off, submit $(0.0, 0.0)$ as the ground signature
    1. From -60 to 60 in 10-degree increments (with 0 being under-track)
    2. From -70 to -60 in 2-degree increments
    3. From 70 to 60 in 2-degree increments

2. For both the standard atmospheric profile and the measured atmospheric profile, determine lateral cut-off angles on both sides

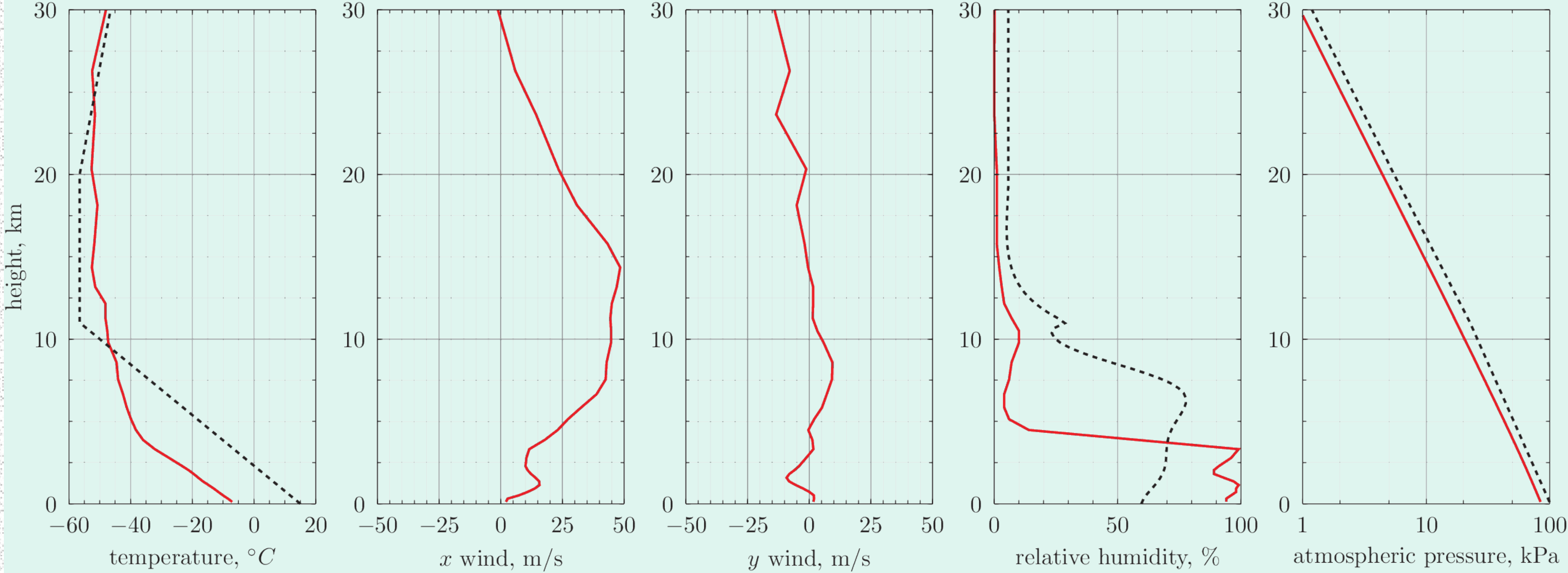
3. Using near-field pressure data as given below, compute ground signatures, ground intersection locations and loudness metrics associated with the lateral cut-off angles computed
    1. For the measured atmospheric profile, use -70 and 70 degrees from Case2_dpp.plt
    2. For the standard atmospheric profile, use -50 and 50 degrees from Case2_dpp.plt

Numerical Simulation Research Unit

Configuration

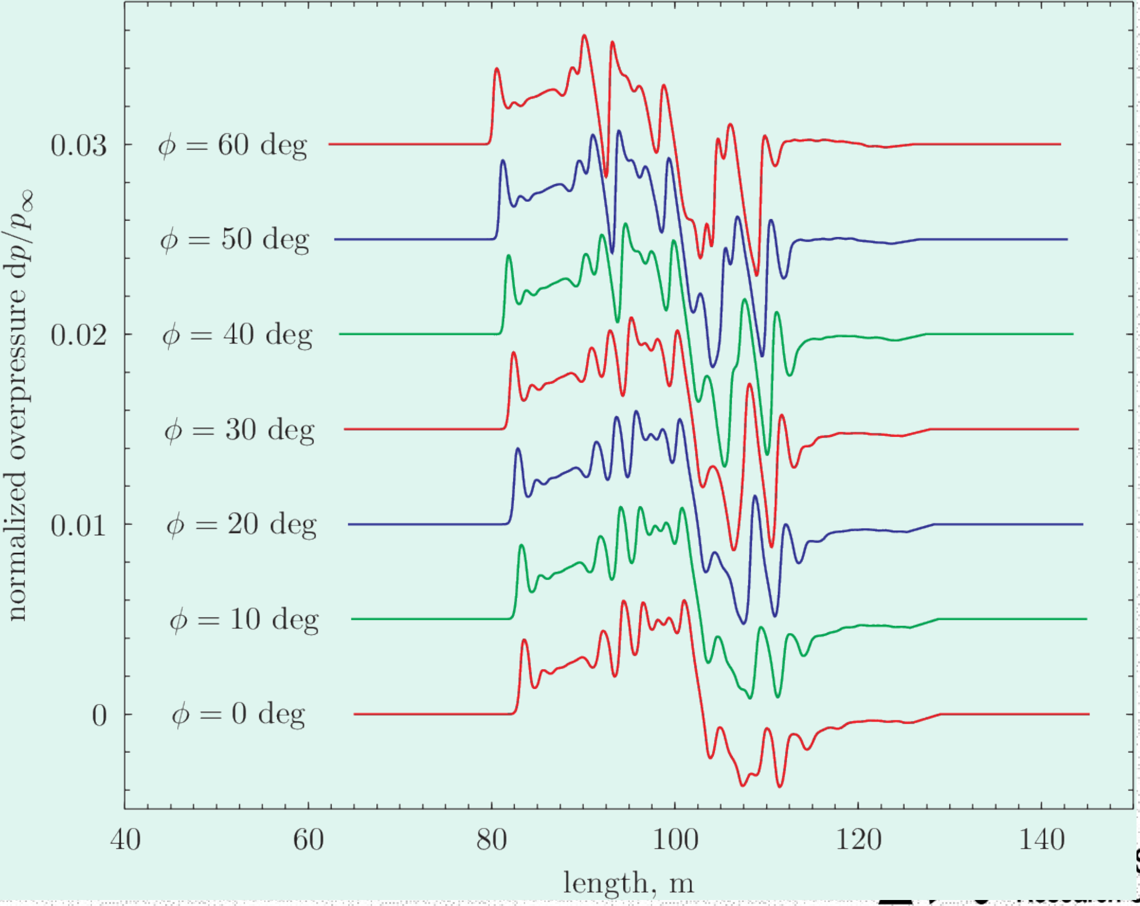
Parameters	Values	Unit
Mach number	1.4	-
cruise altitude	16,459.2	m
propagation start distance, R	82.296	m
R/L	3.0	-
ground altitude	110.011	m
ground reflection factor	1.9	-
heading	toward east (x direction)	-
role angle	[-60, 60] every 10 deg [-70,-60] every 2 deg [60, 70] every 2 deg	-

Atmospheric Profiles

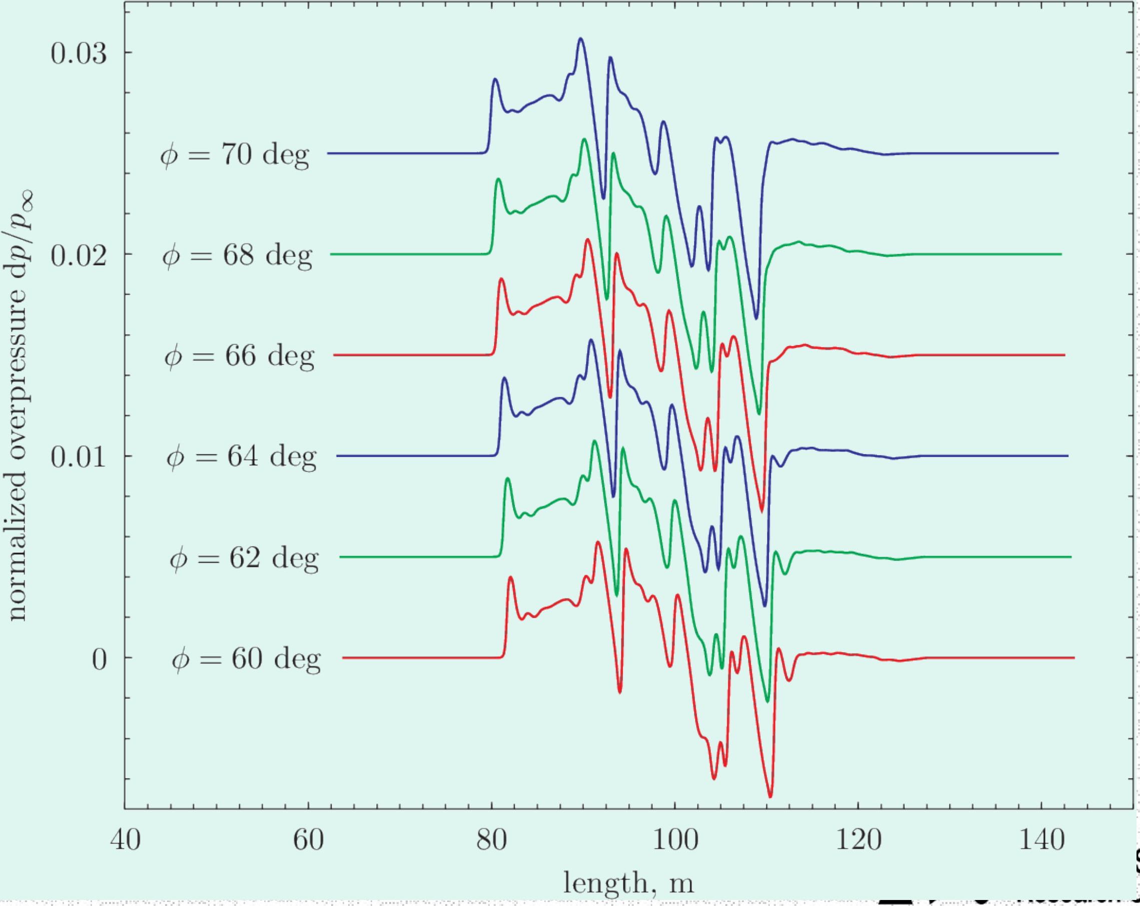


Numerical Simulation Research Unit

Nearfield (Input) Signatures



Nearfield (Input) Signatures

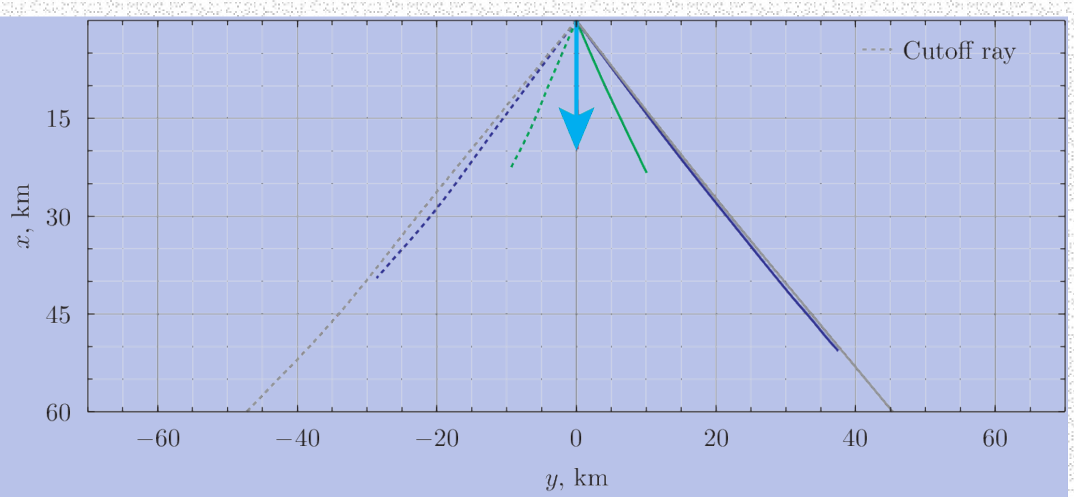


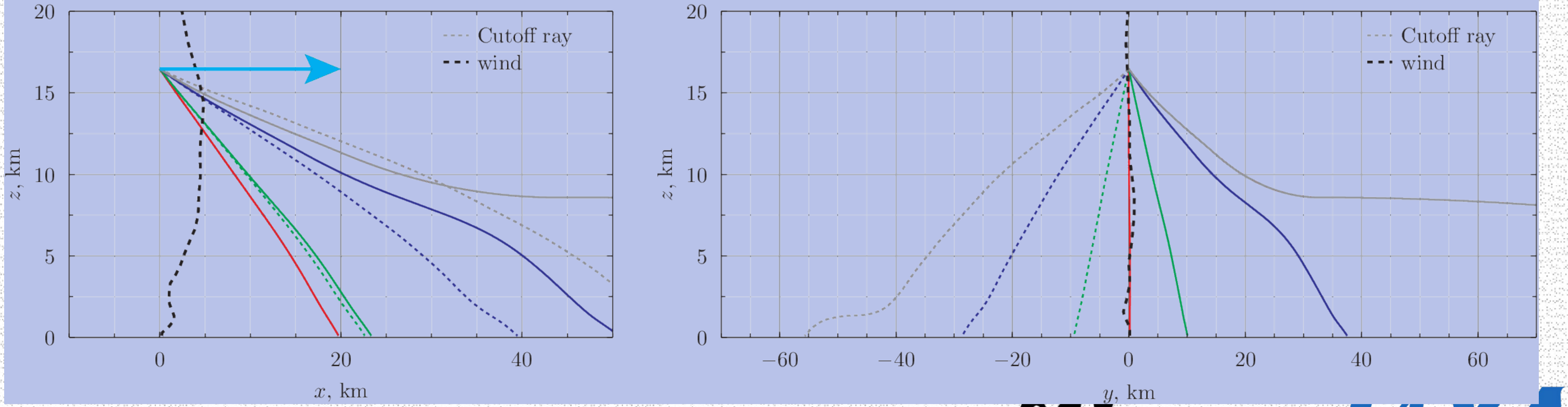
Simulation
Unit

Case 2, Cut-offs for MEASURED Atmos. Profile

Cut-off angle:

-64.07 deg, 70.49 deg





Numerical Simulation Research Unit

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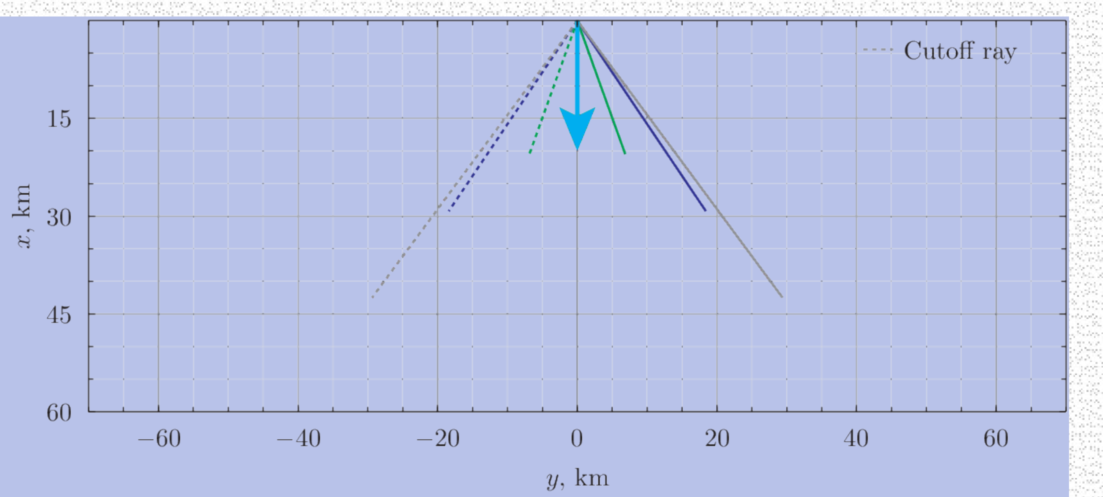
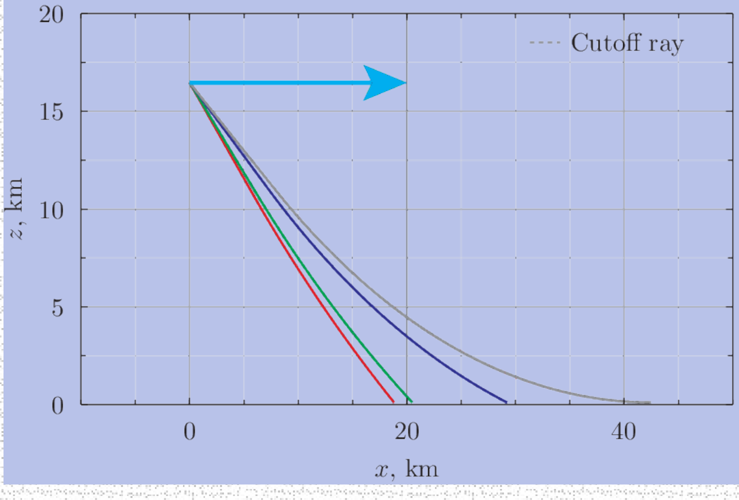
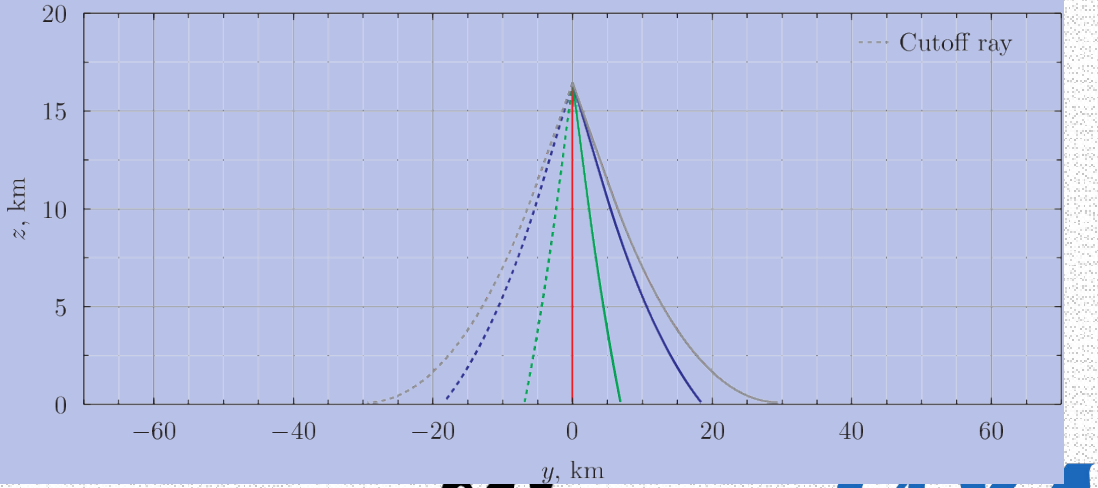
Case 2, Cut-offs for STANDARD Atmos. Profile

Cut-off angle:

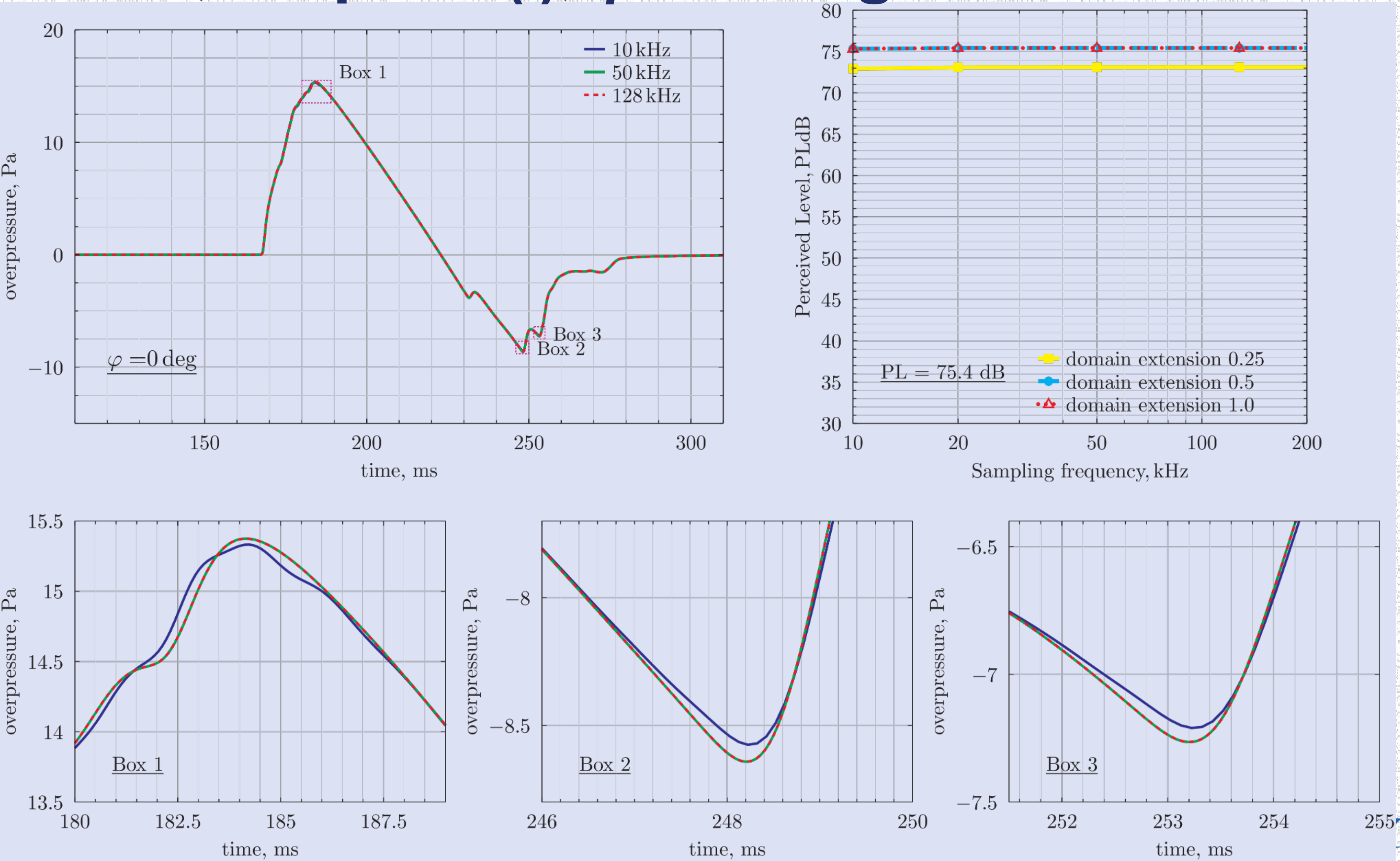
-44.89 deg, 44.89 deg



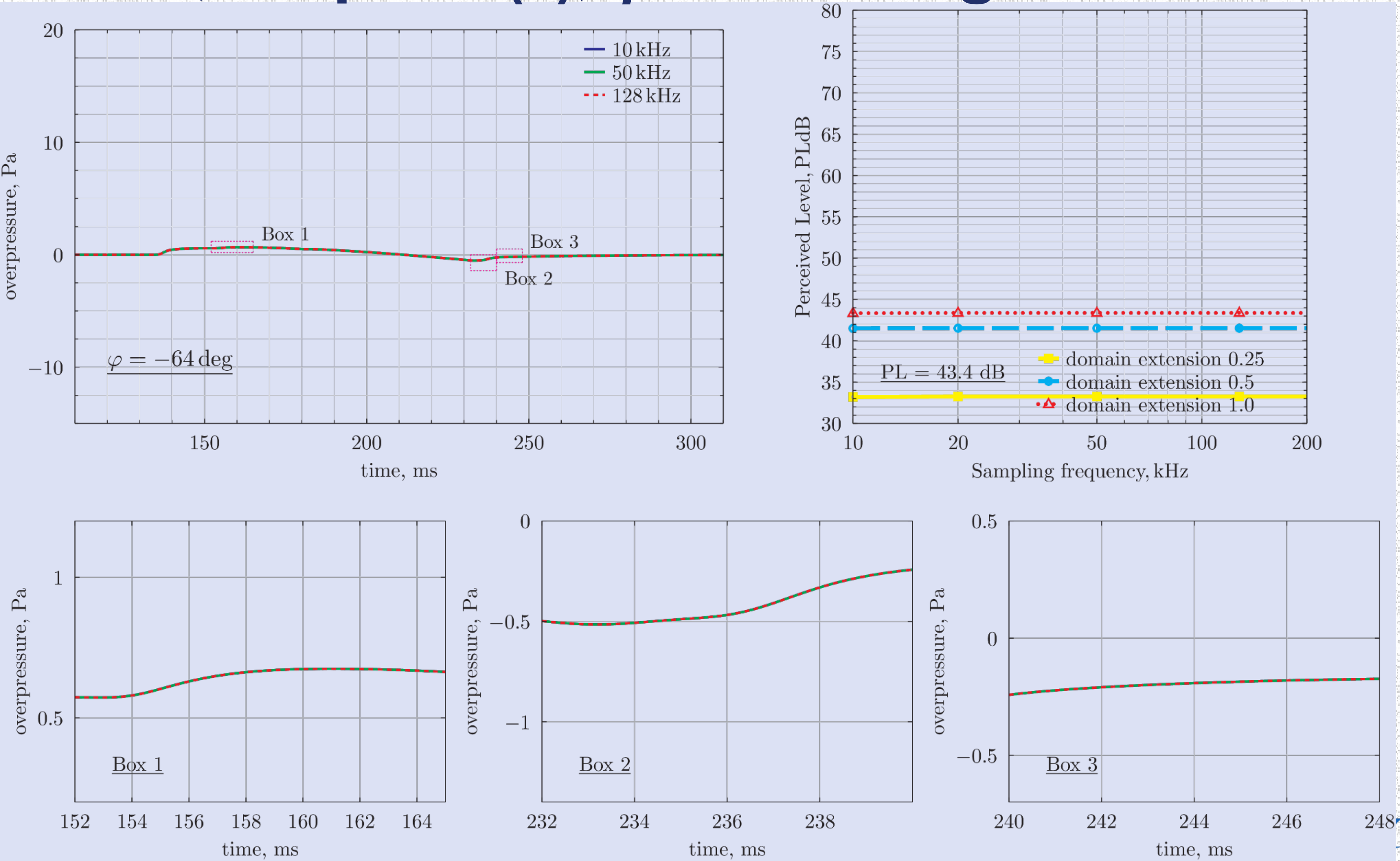




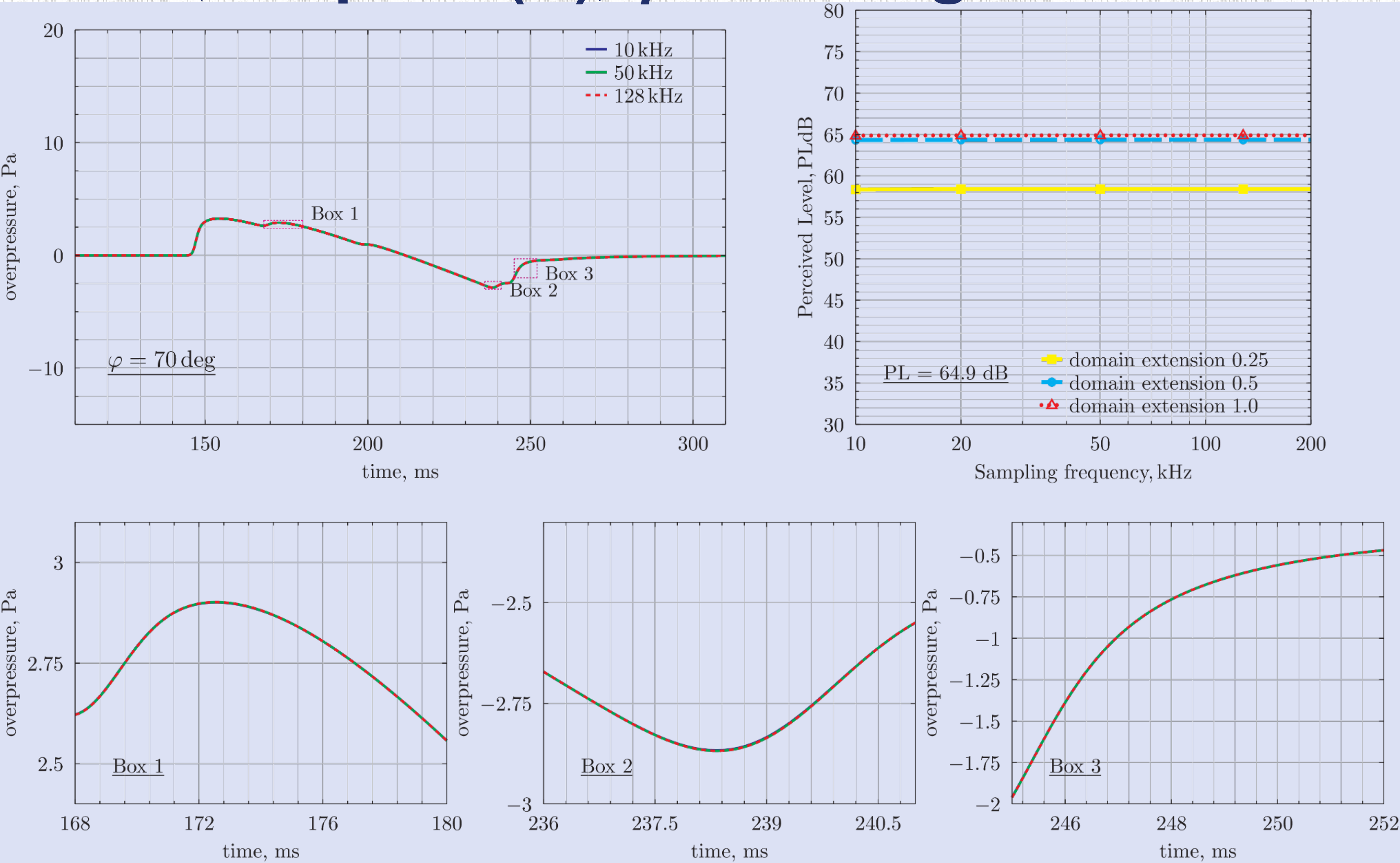
Case 2, Required(i), $\varphi = 0$ deg



Case 2, Required(ii), $\varphi = -64$ deg



Case 2, Required(iii), $\varphi = 70$ deg



Case 1, Optional:
C25P, a powered equivalent of the NASA C25D

Numerical Simulation
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Optional Run

For zero azimuthal angle, determine focus signature at $\bar{Z}$ locations of: -1.0 (Evanescent wave), 0.0 (Focus location) and 1.0 (Edge of post-focus region predicting the outgoing wave)

1. Ground signatures (Time (seconds) vs. Pressure (Pascals))
2. Loudness metrics (PL, ASEL, BSEL, CSEL) corresponding to all the ground signatures
3. The ground intersection location in meters corresponding to $\bar{Z} = 0.0$ and propagation time in seconds

Numerical Simulation Research Unit

Configuration

- ✓Parameters provided:

Parameters	Values	Unit
Mach number, M	1.4121	-
$\dot{M}$	0.015681	$1/s$
$\ddot{M}$	0.000359	$1/s^2$
Flight path angle	0	deg
diffraction boundary layer thickness, δ	682.45	m
Atmospheric profile	Standard Atmosphere	-

- ✓Some additional conditions must be specified:
  - ✓ δ-tangent ray and corresponding flight conditions FOR obtaining incoming waveform
  - ✓ Few parameters FOR specifying the parameters appeared in Lossy NTE

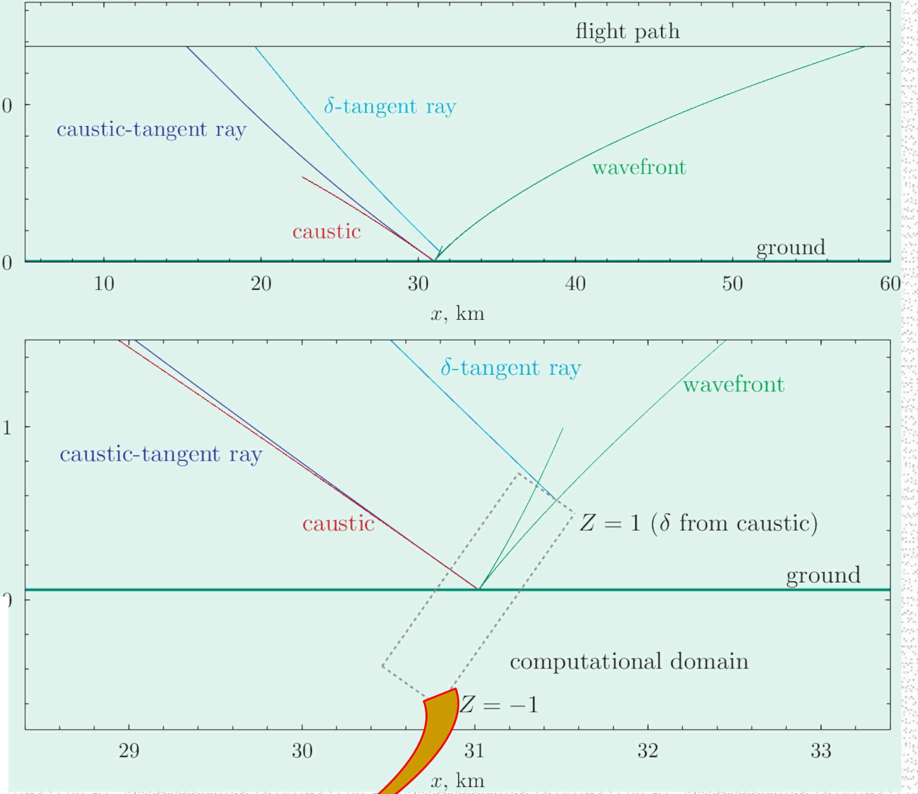
Numerical Simulation Research Unit

What We Need for Lossy NTE Analysis?

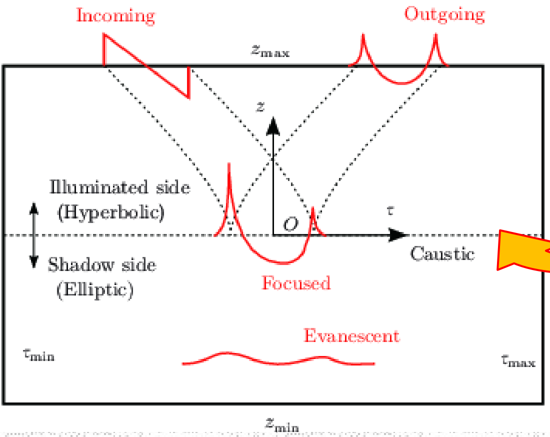
- ✓To set computational domain
- ✓To specify δ-tangent ray

Questions:

- ✓ Where is the caustic?
- ✓ Which raypath does the provided condition $\left(M, \dot{M}, \ddot{M}\right)$ correspond?



Computational domain of Lossy NTE



Setting Flight Path

- ✓Assuming $\ddot{M} = \mathrm{Const.}$:

$$\dot{a} = \ddot{M}c$$
$$a(t) = a_0 + \dot{a}t$$
$$u(t) = u_0 + a_0 t + \frac{1}{2}\dot{a}t^2$$

- ✓At the time $t = \bar{t}$, $a(\bar{t}) = \dot{M}c$, $u(\bar{t}) = Mc$:

$$a_0 = \left(\dot{M} - \ddot{M}\bar{t}\right)c$$
$$u_0 = \left(M - \dot{M}\bar{t} + \frac{1}{2}\ddot{M}\bar{t}^2\right)c$$

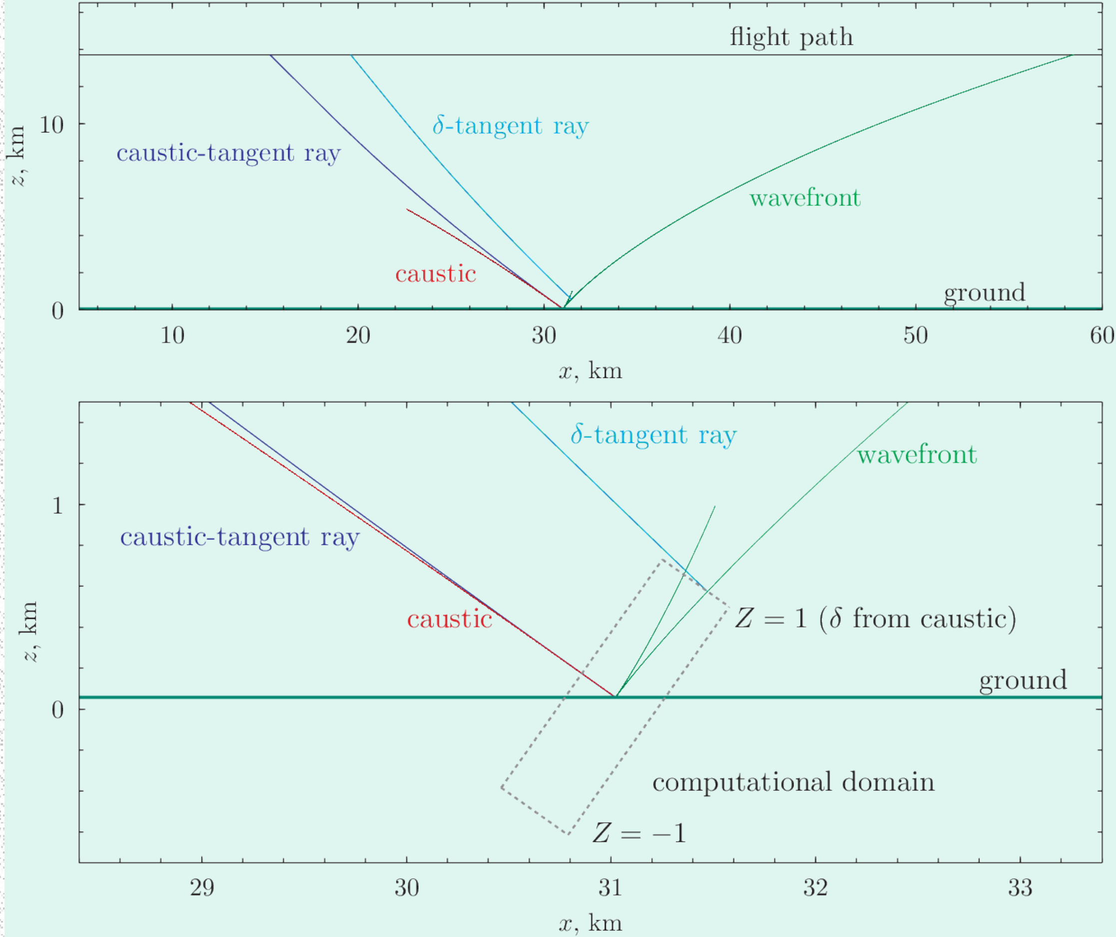
⇒

$$a(t) = \dot{M}c + \ddot{M}c(t - \bar{t})$$
$$u(t) = Mc + \dot{M}c(t - \bar{t}) + \frac{1}{2}\ddot{M}c(t - \bar{t})^2$$

Numerical Simulation Research Unit

Flight path, Wavefront, Raypaths and Caustic

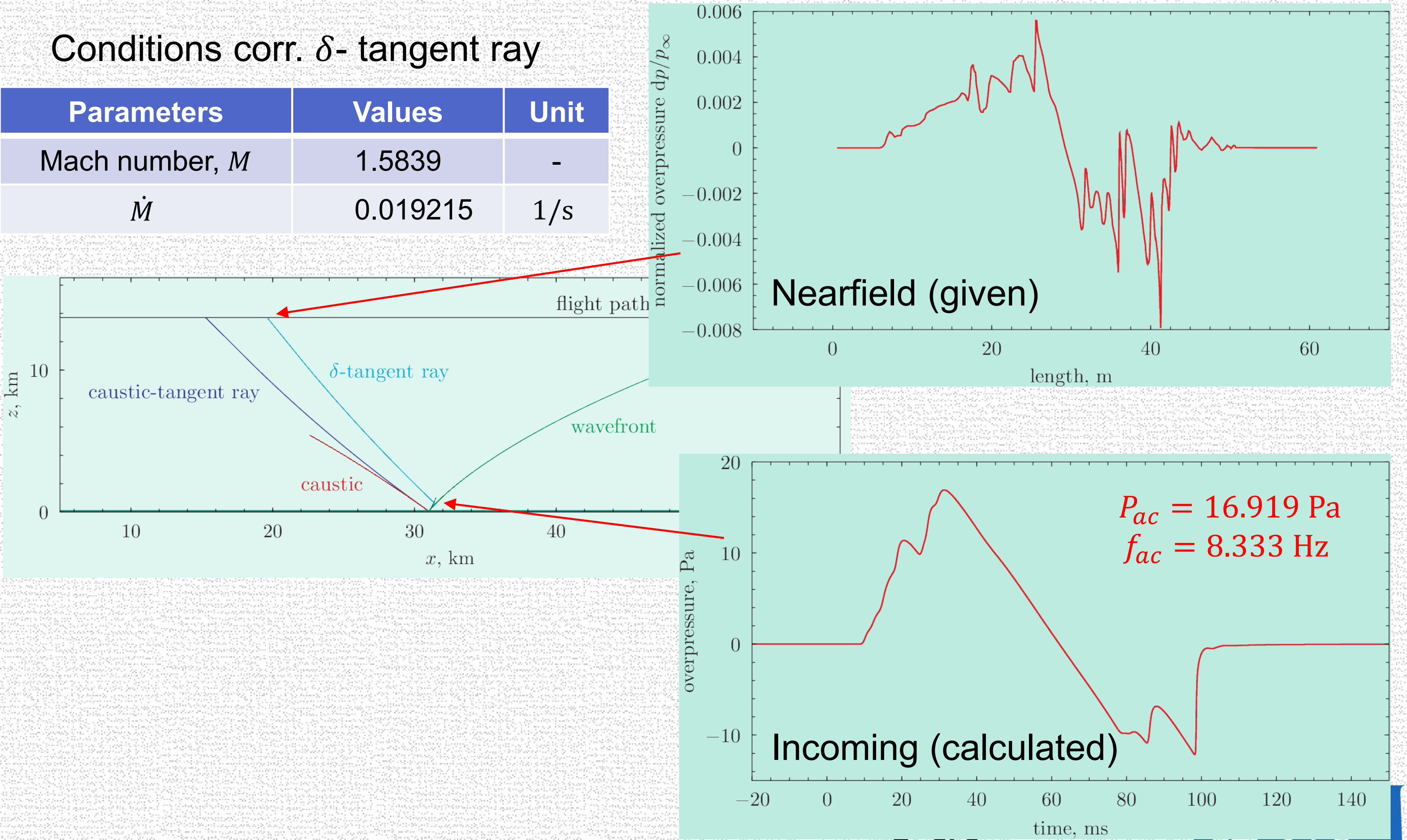
- ✓ The provided condition $(M, \dot{M}, \ddot{M})$ corresponds to “caustic-tangent ray”
- ✓ δ-tangent ray should be specified to calculate incoming waveform



Nearfield (Input) Signature for Focusing case

Conditions corr. δ- tangent ray

Parameters	Values	Unit
Mach number, M	1.5839	-
$\dot{M}$	0.019215	$1/s$



Nearfield (given)

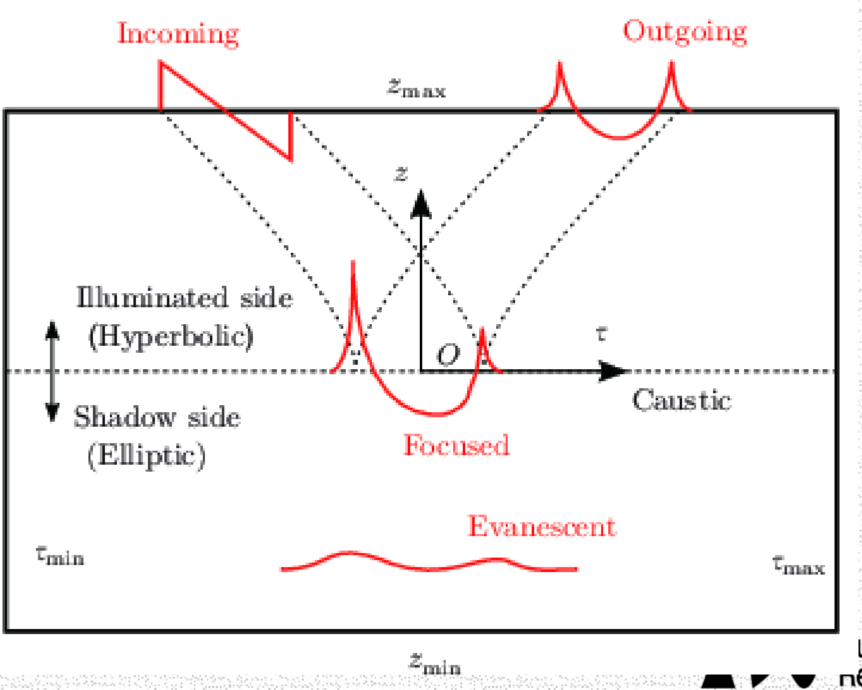
Incoming (calculated)

$P_{ac} = 16.919$ Pa

$f_{ac} = 8.333$ Hz

Definition of Computational Region

parameters	range
number of division in τ, n_τ	$16{,}384 - 131{,}072$
number of division in Z, n_Z	$4{,}096 - 16{,}384$
lower bound of Z, $Z_{\min}$	$-1, -3, -7$
lower/upper bound of τ, $\tau_{\max} = \lvert\tau_{\min}\rvert$	$-3, -6, -12$



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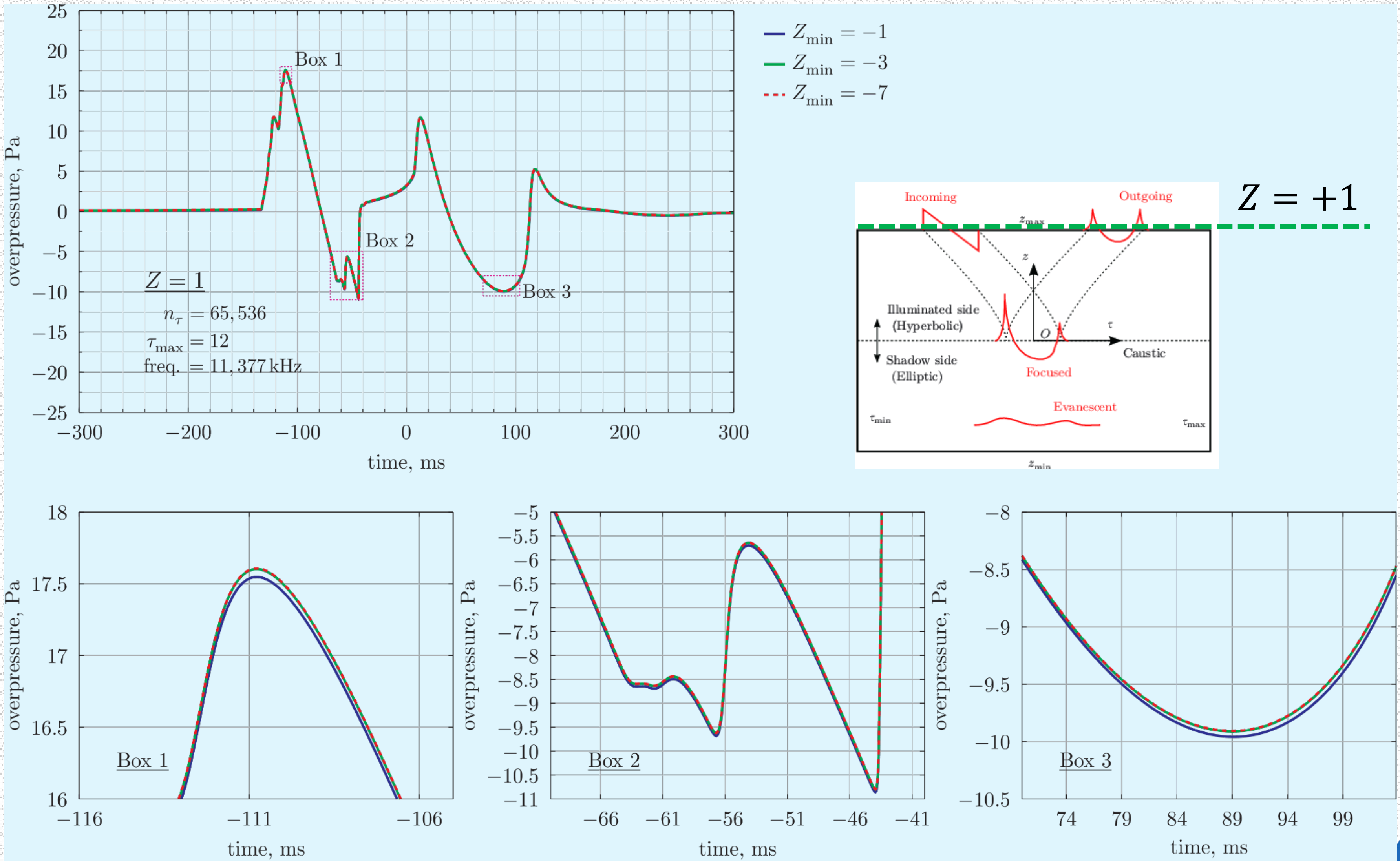
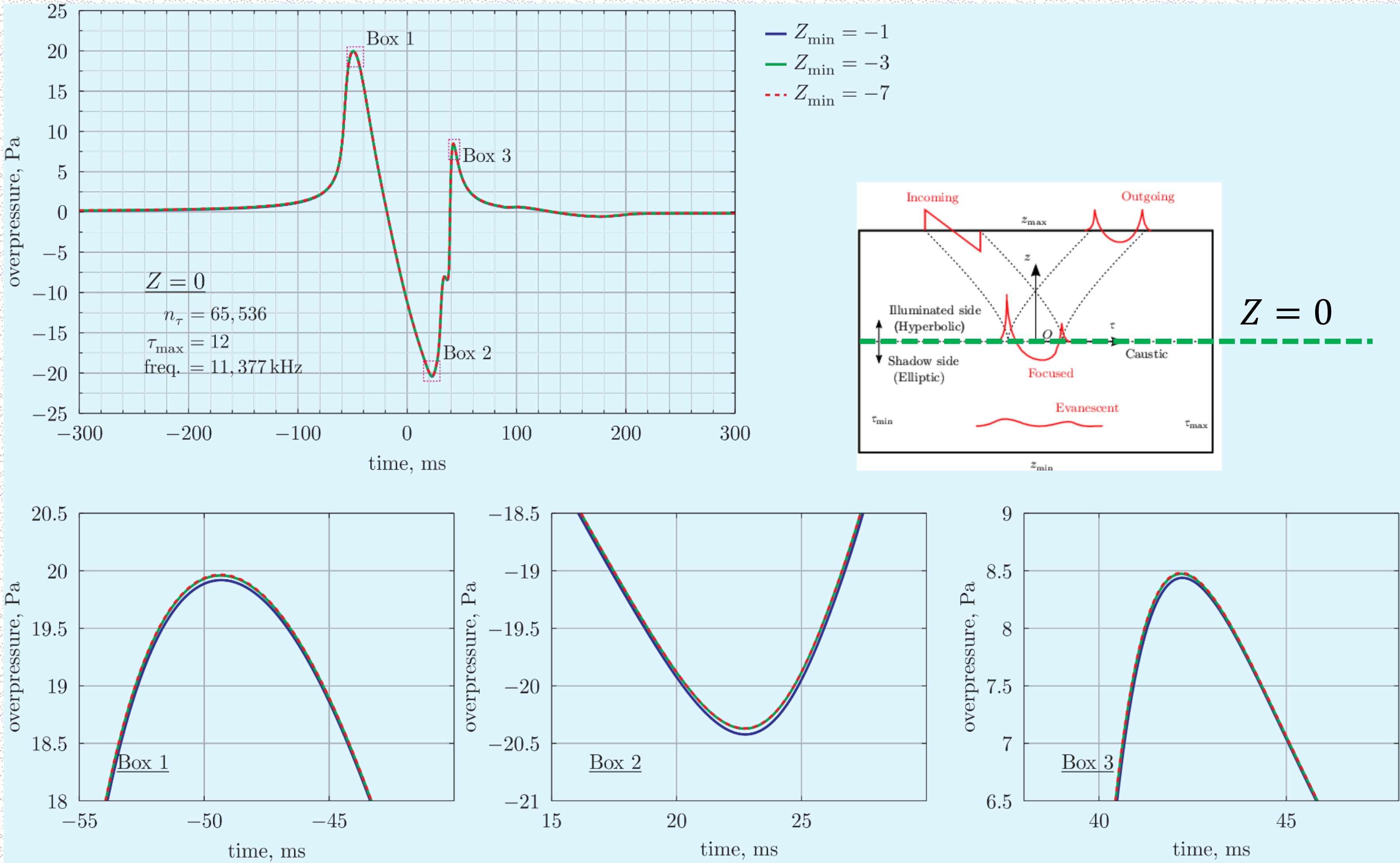
Case1, Optional, Variable Domain Size in *Z*

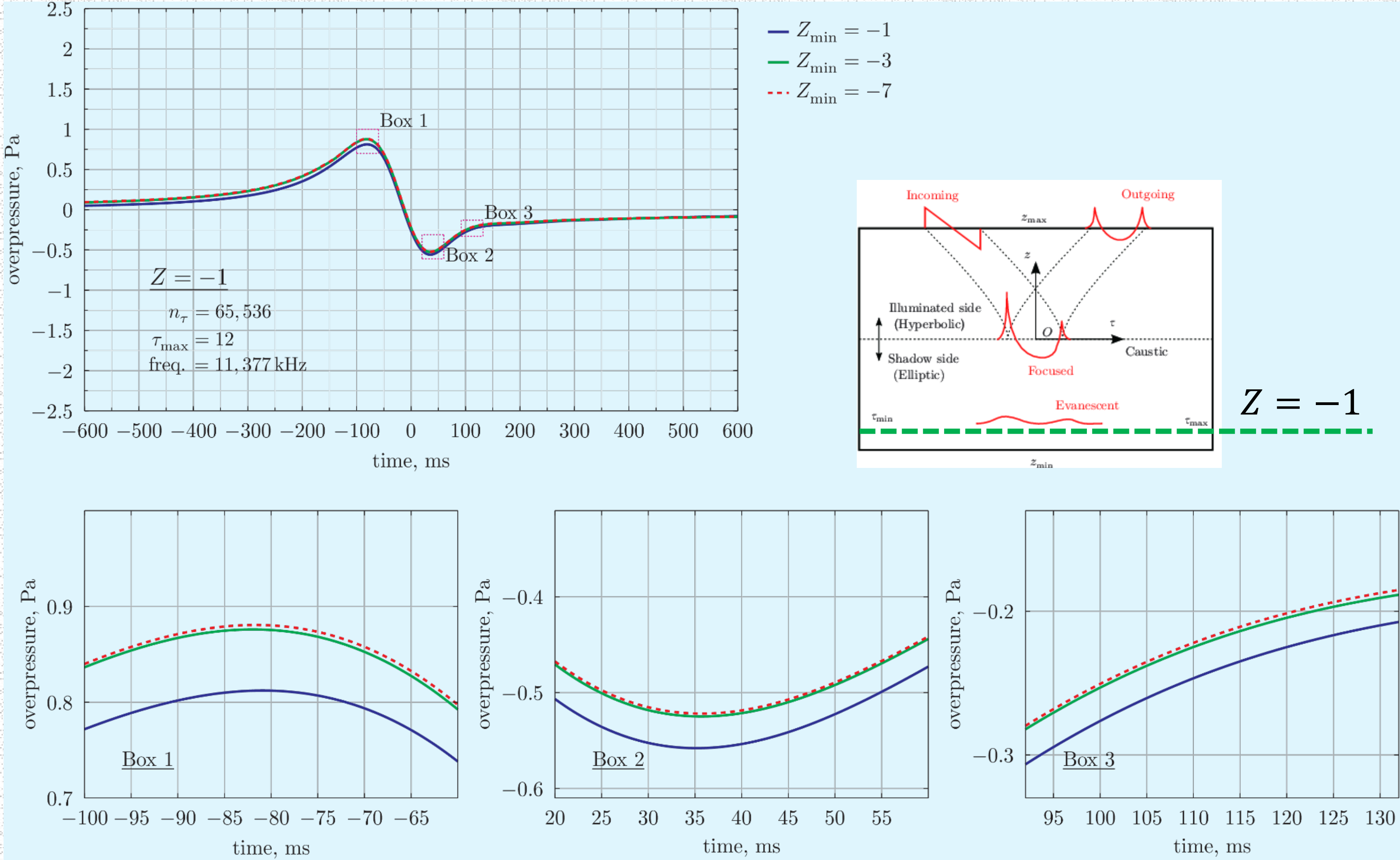


Case1, Optional, Variable Domain Size in *Z*

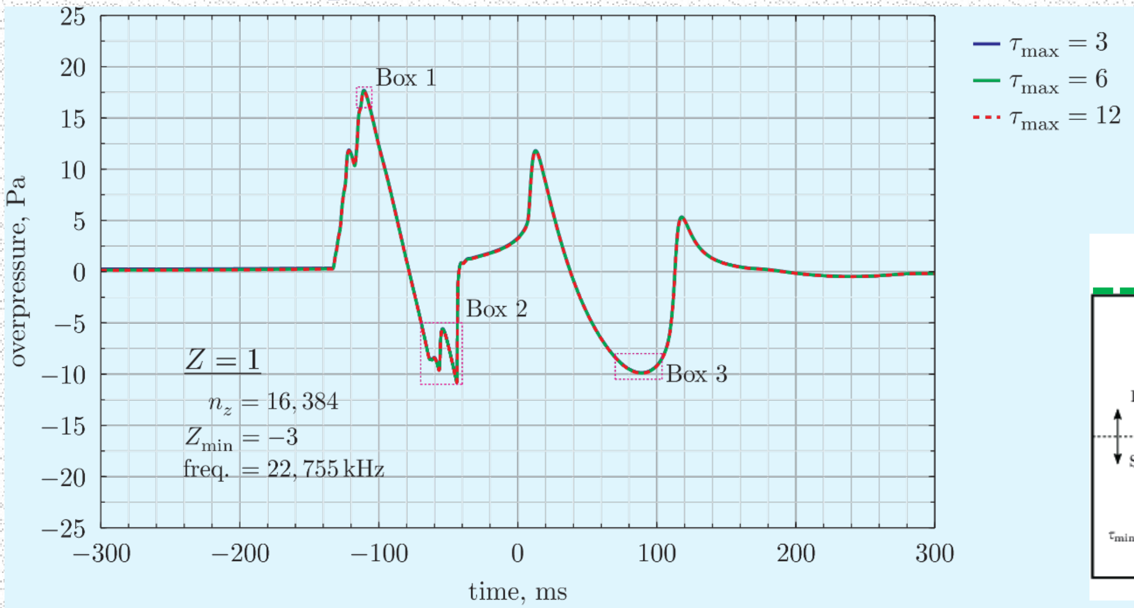


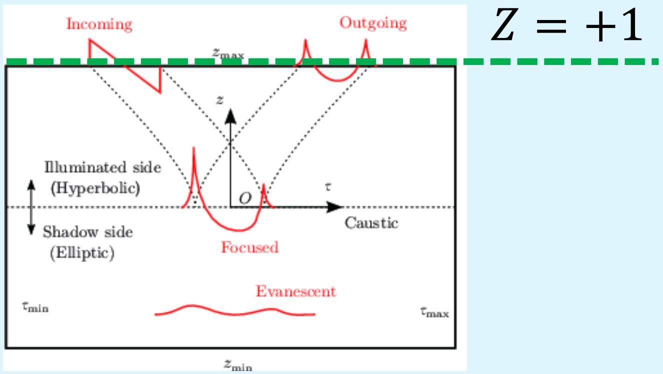
$Z = 0$

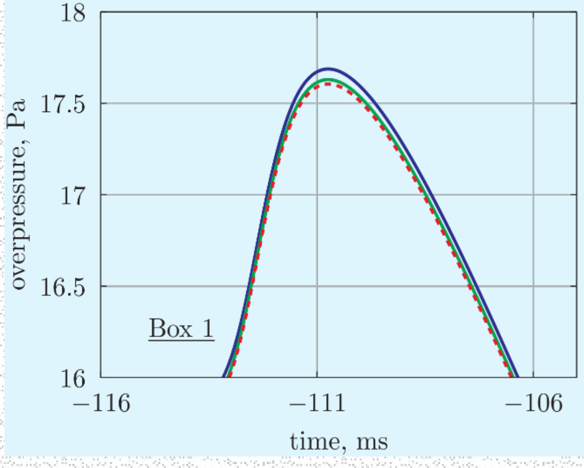
Case1, Optional, Variable Domain Size in Z

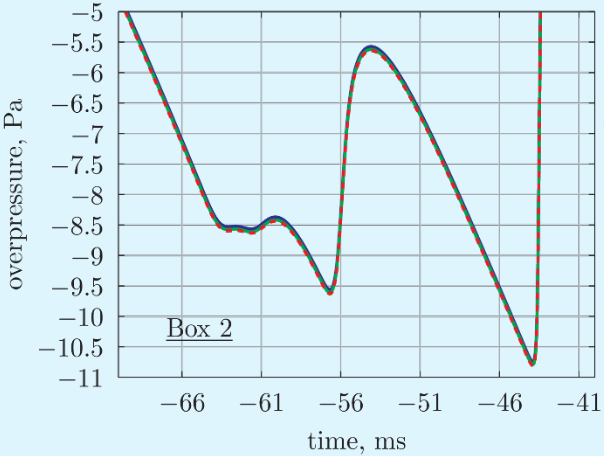


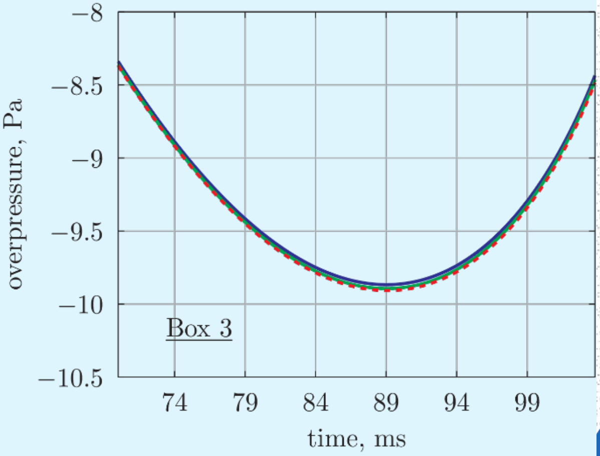
Case1, Optional, Variable Domain Size in τ



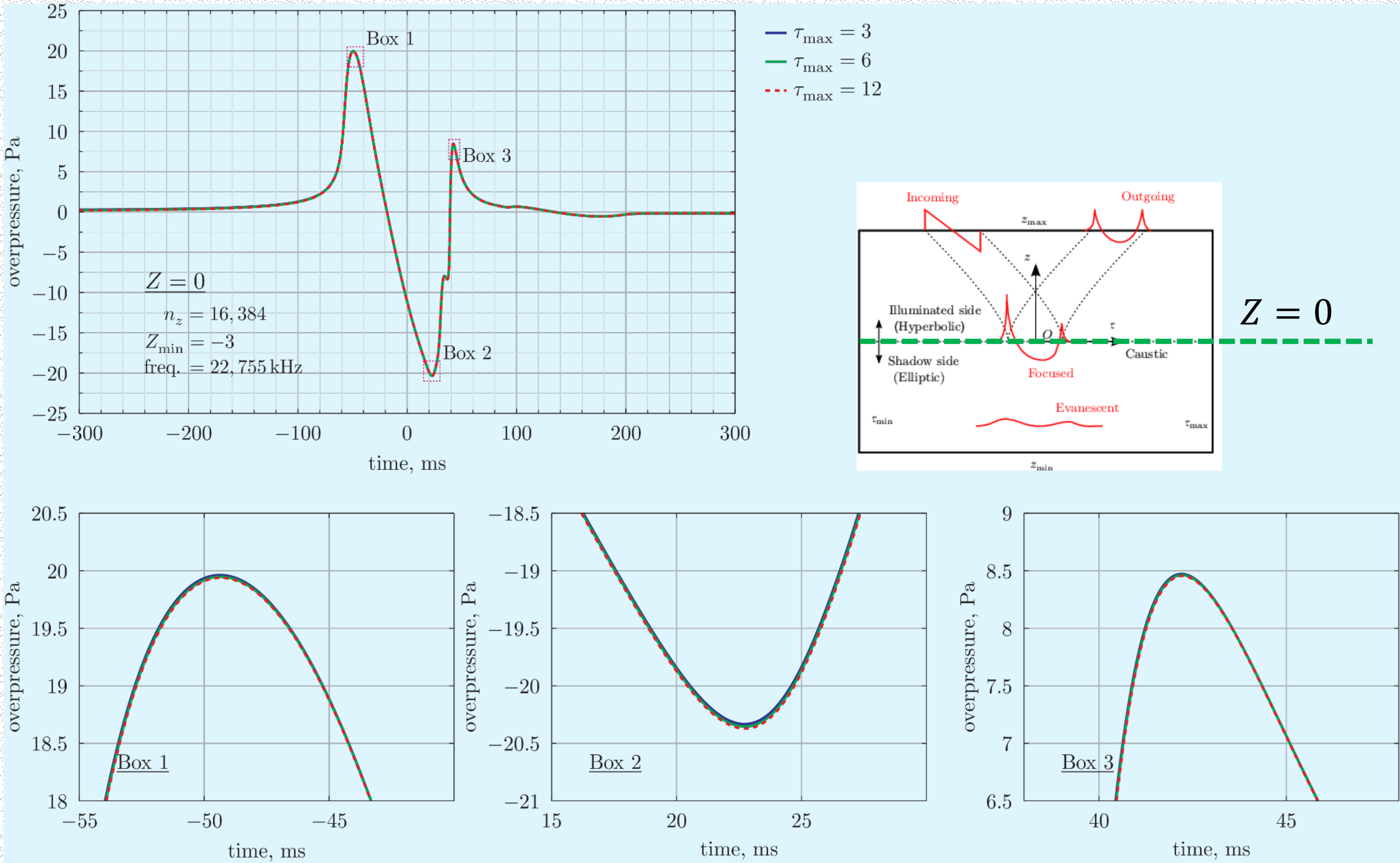




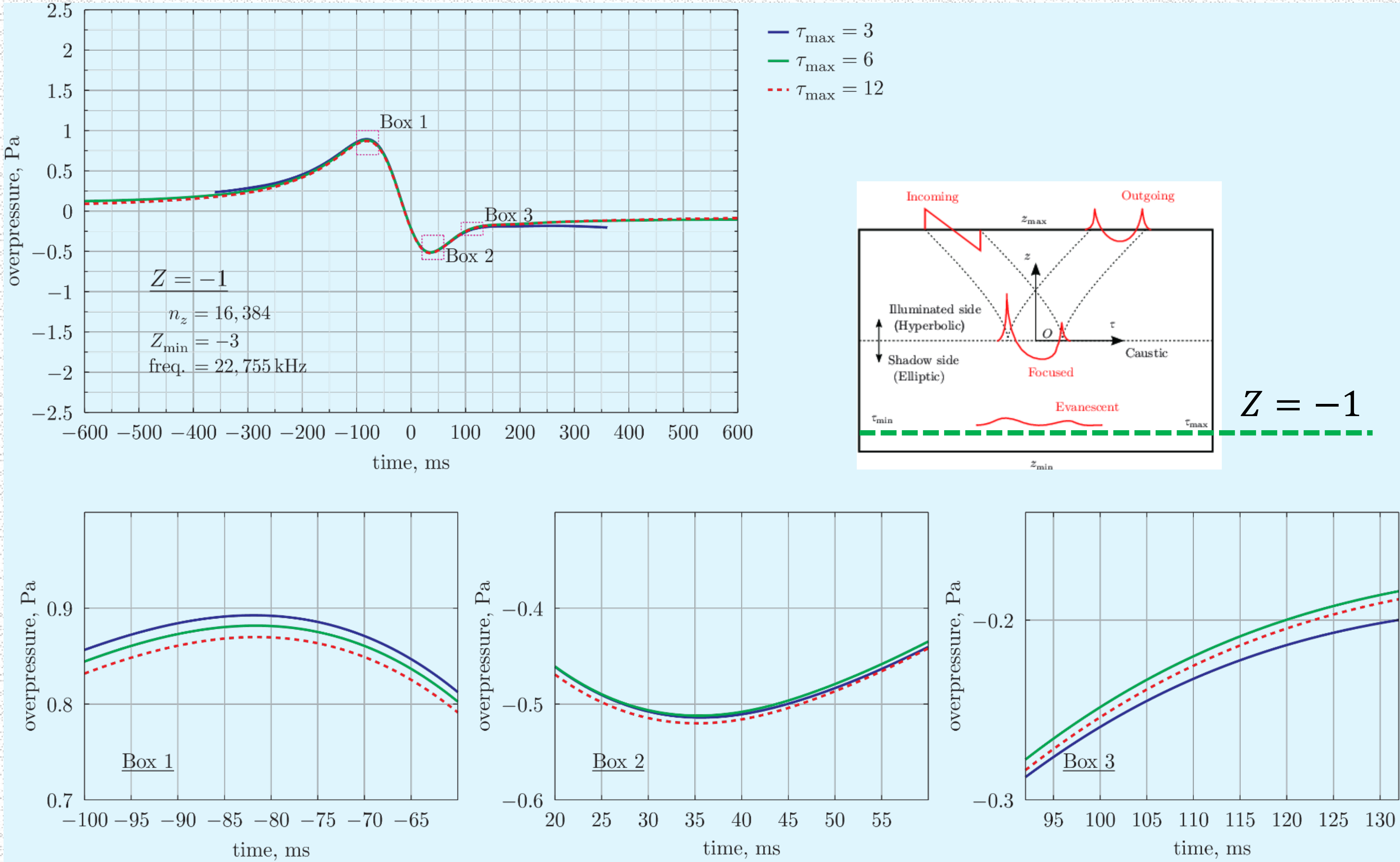




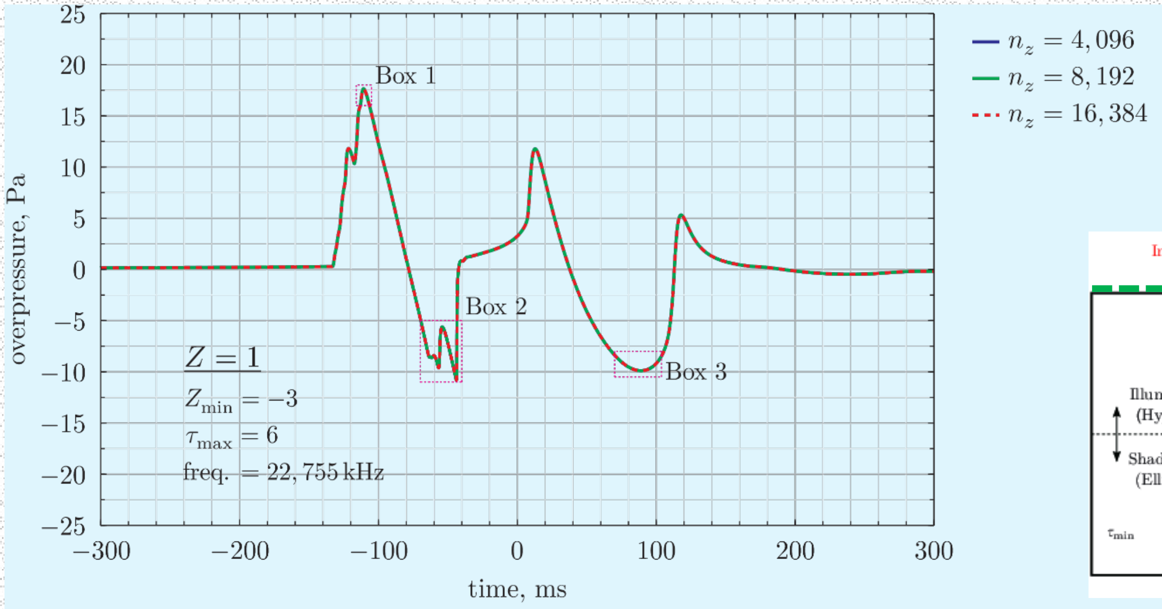
Case1, Optional, Variable Domain Size in τ

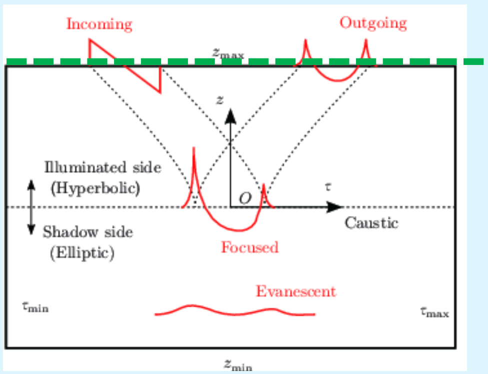


Case1, Optional, Variable Domain Size in τ

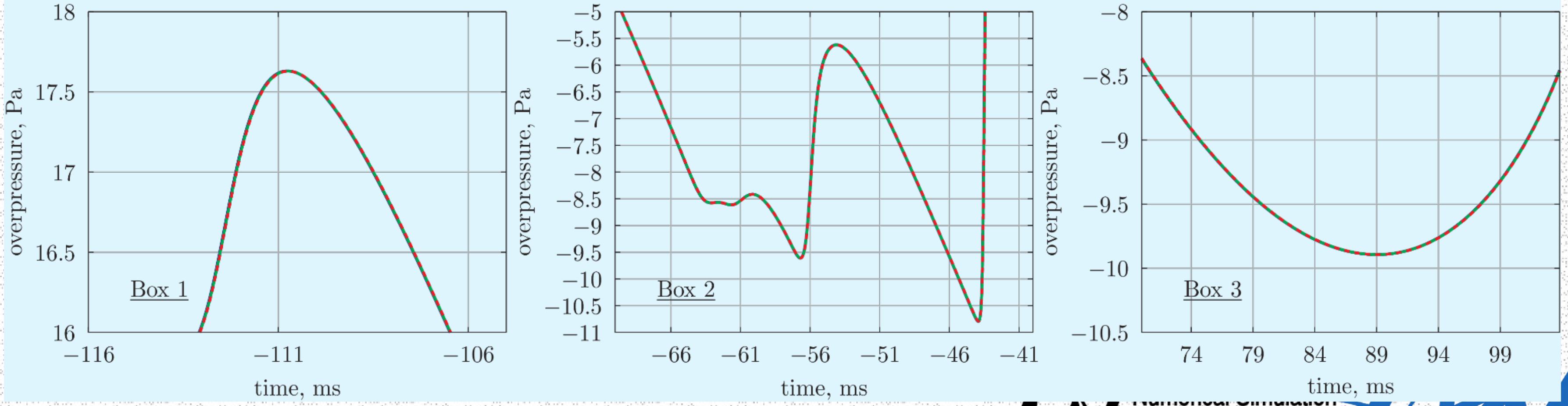


Case1, Optional, Variable Resolution in *Z*

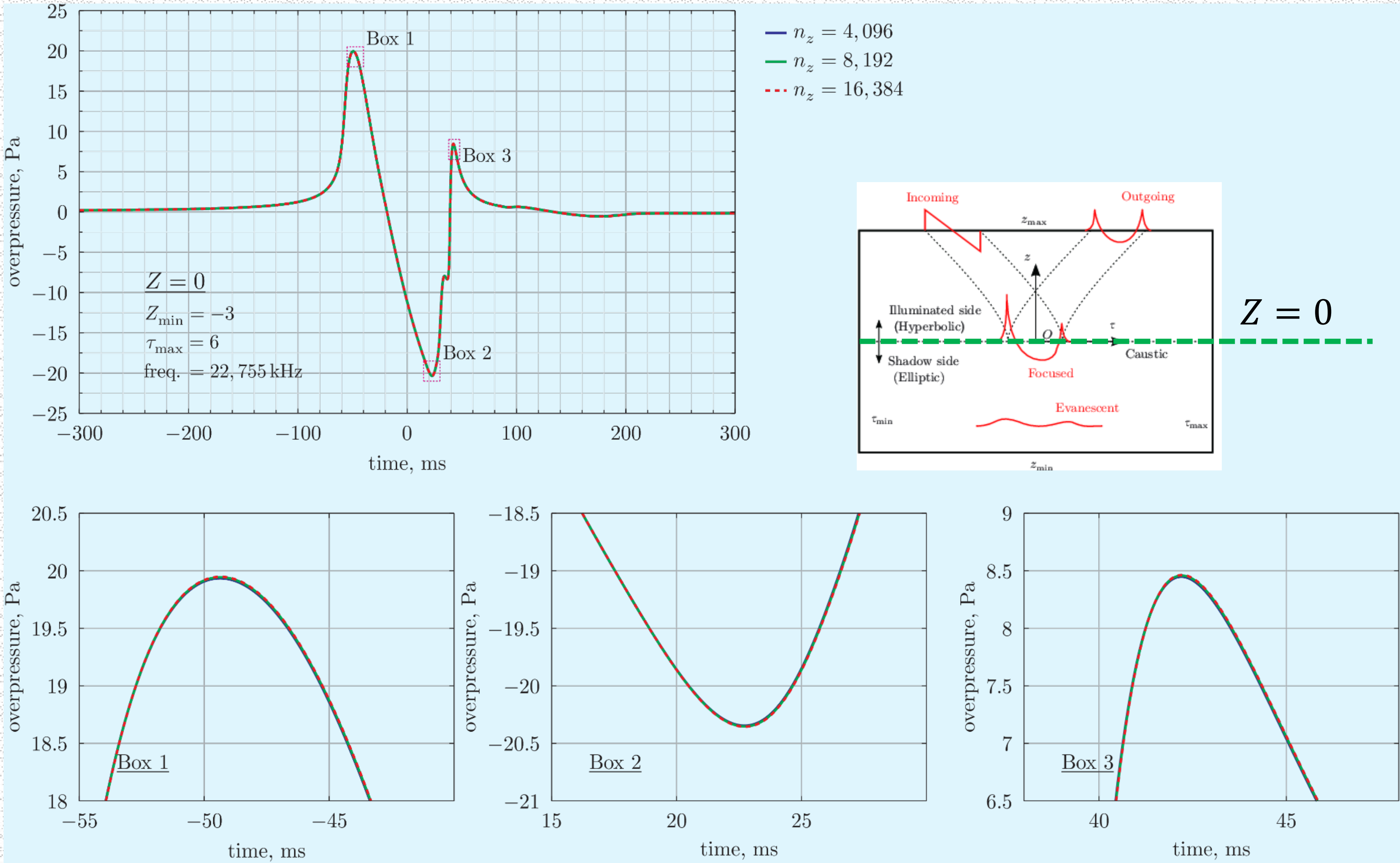




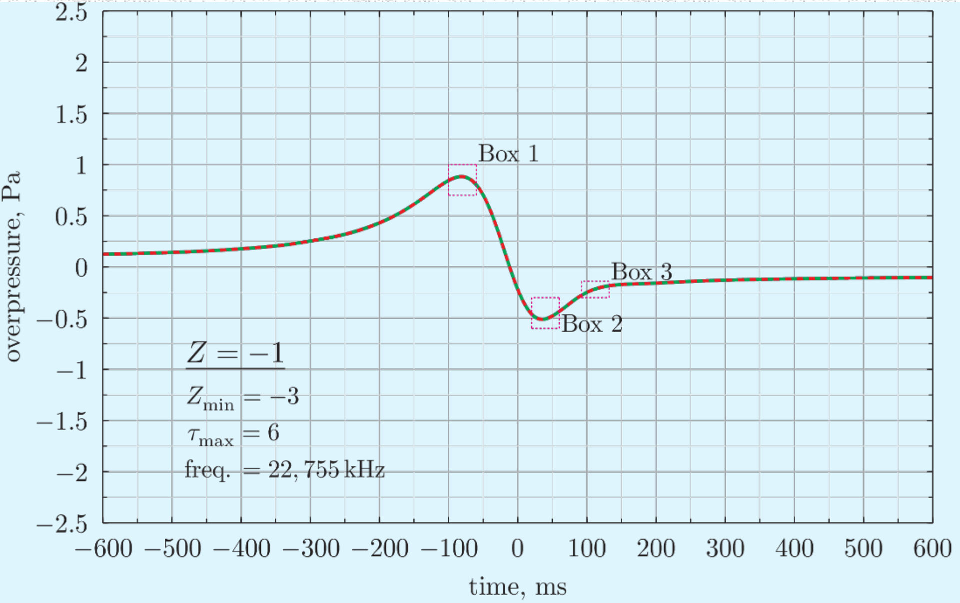
$Z = +1$

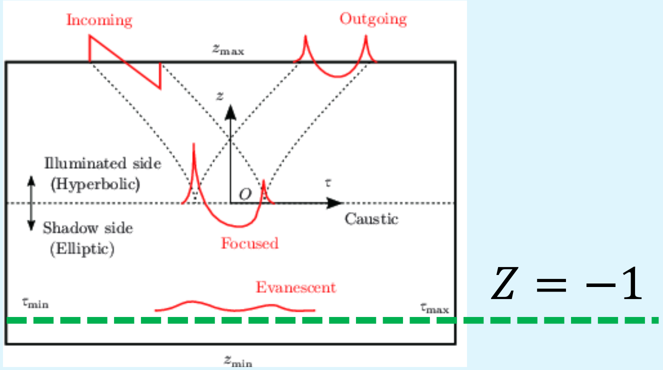


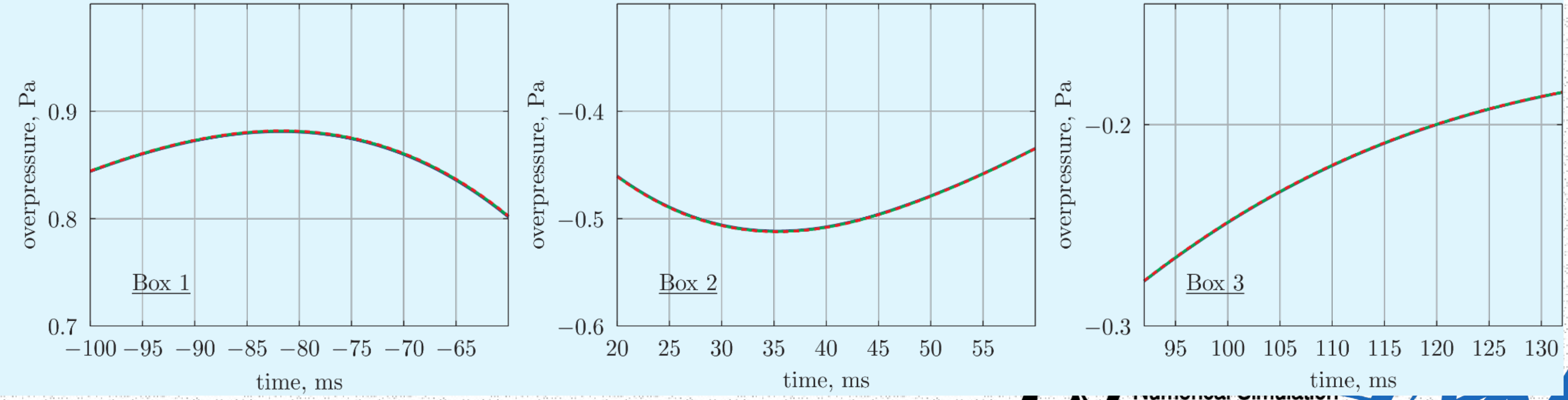
Case1, Optional, Variable Resolution in *Z*



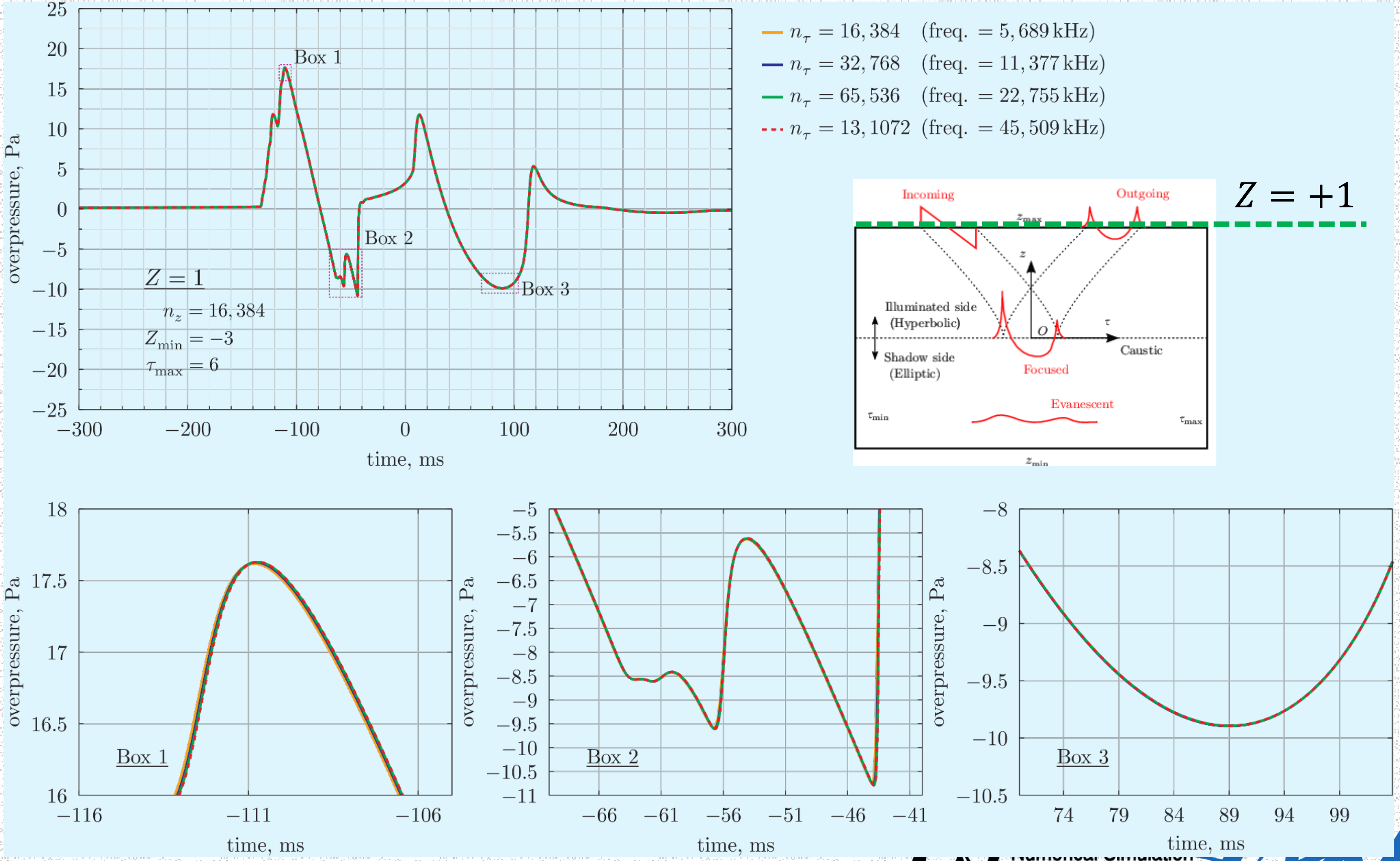
Case1, Optional, Variable Resolution in Z





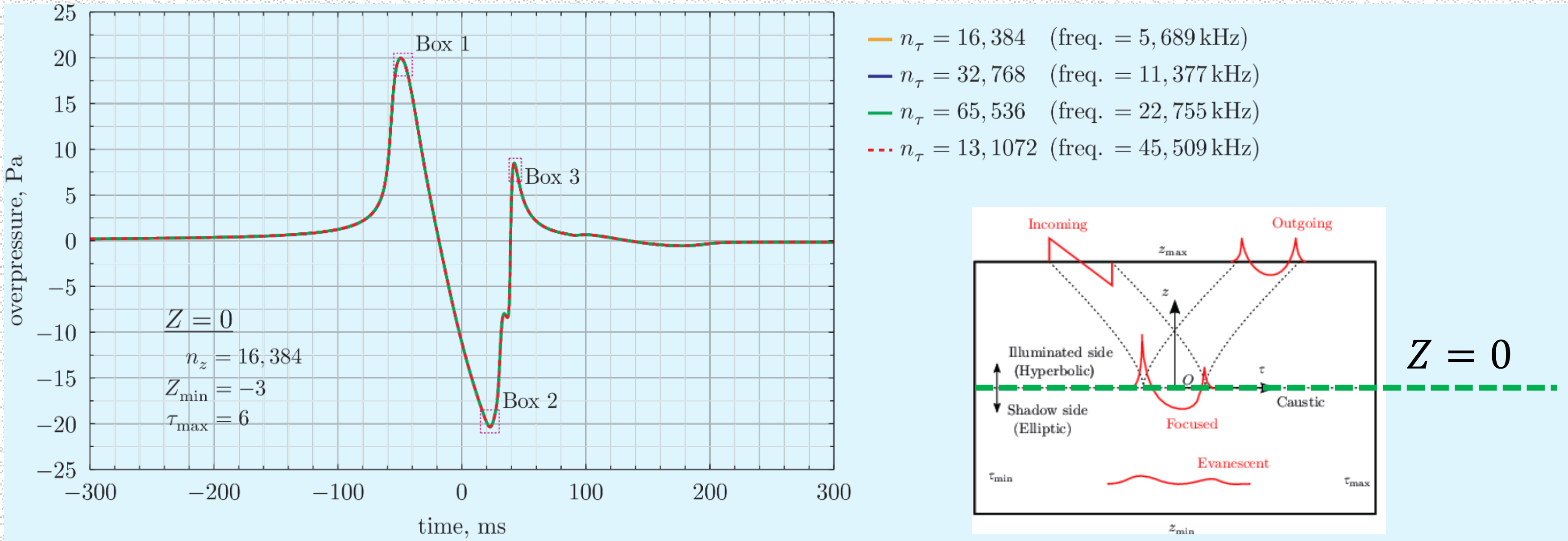


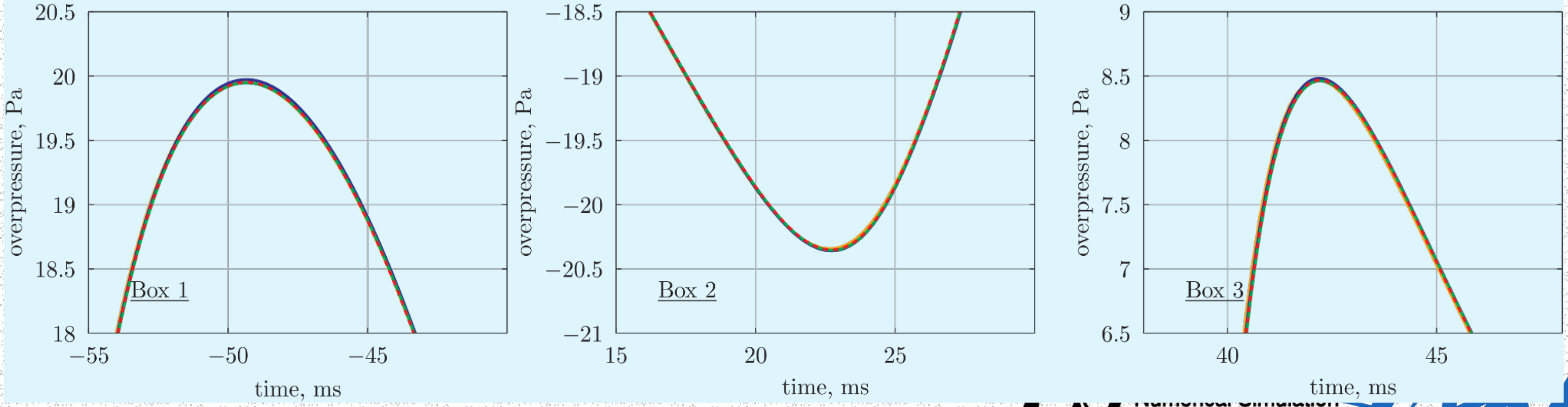
Case1, Optional, Variable Resolution in τ



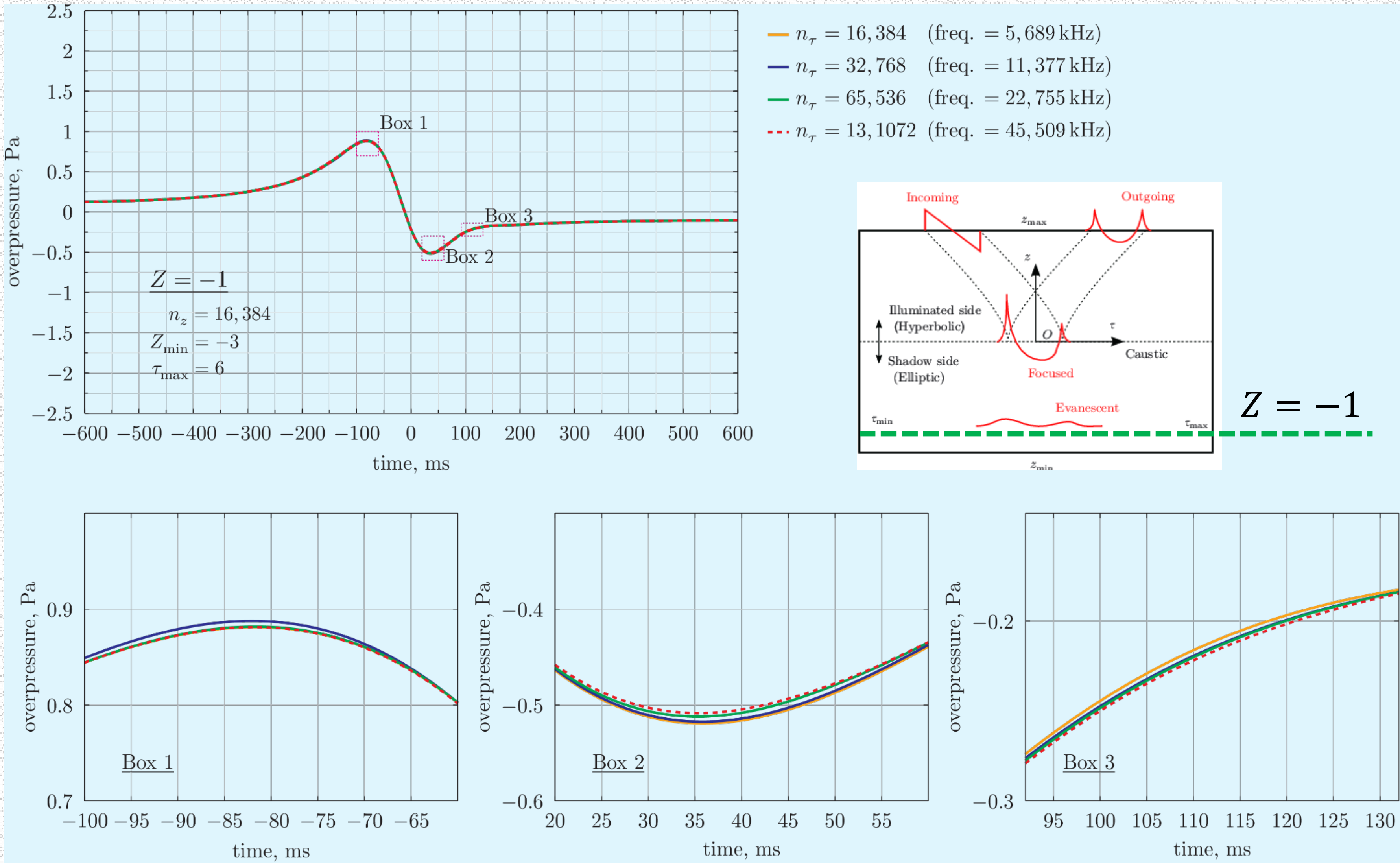
Numerical Simulation Research Unit

Case1, Optional, Variable Resolution in τ

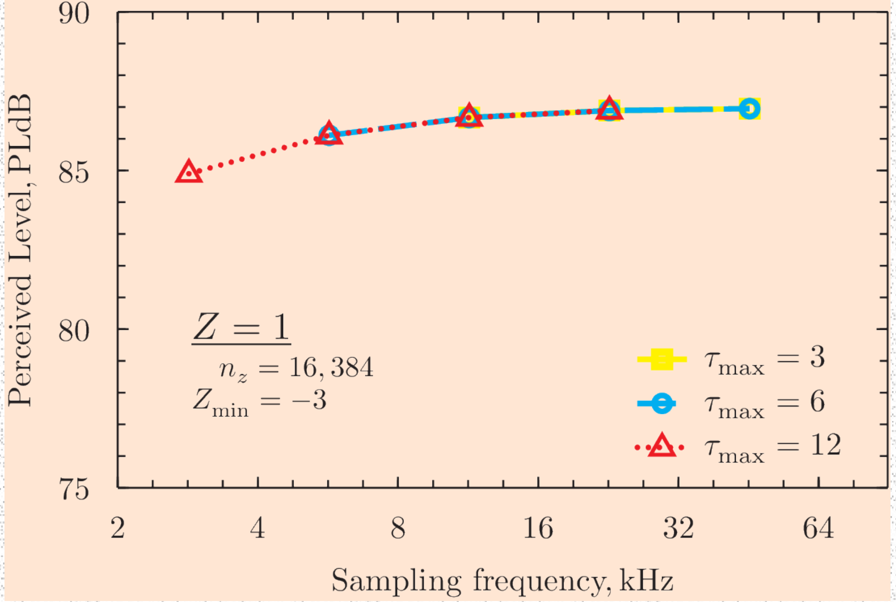


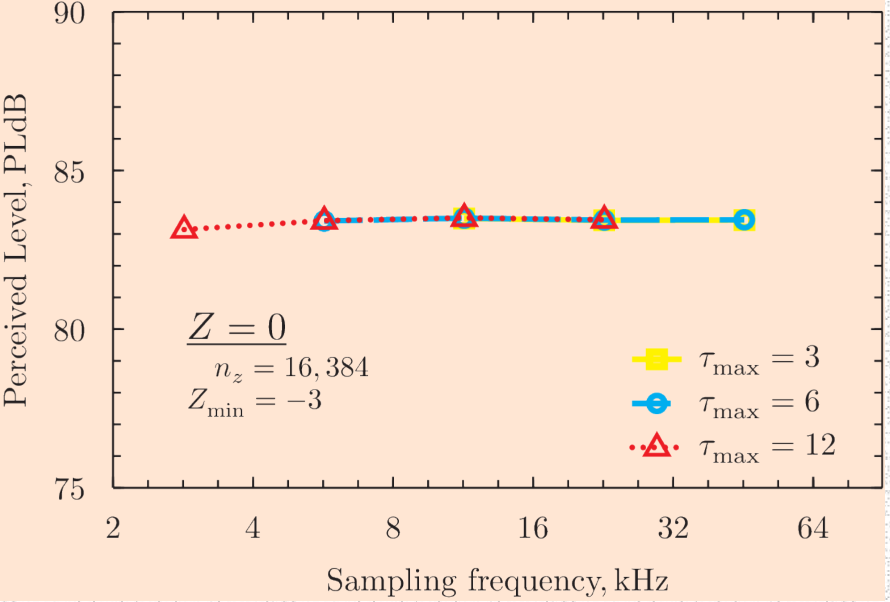


Case1, Optional, Variable Resolution in τ



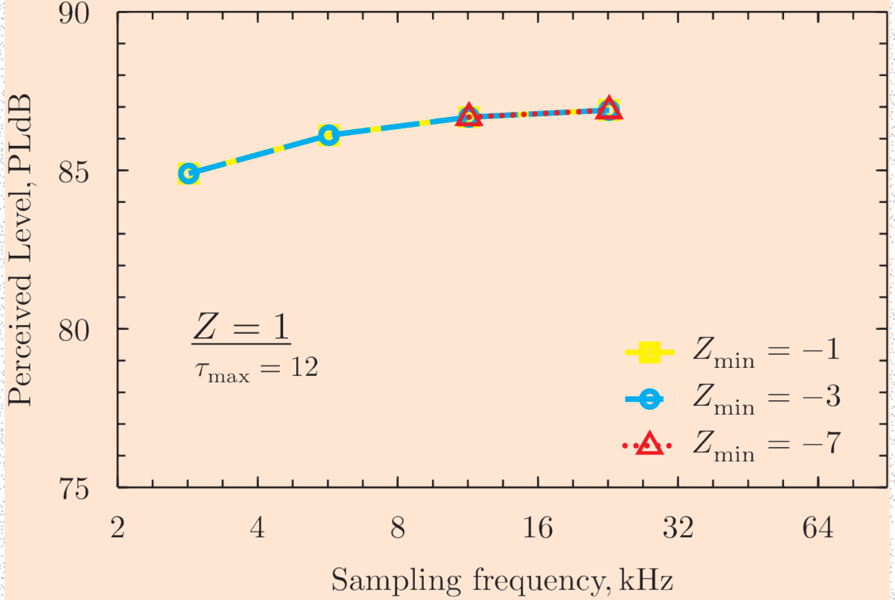
Case1, Optional, Fixed Domain size in Z

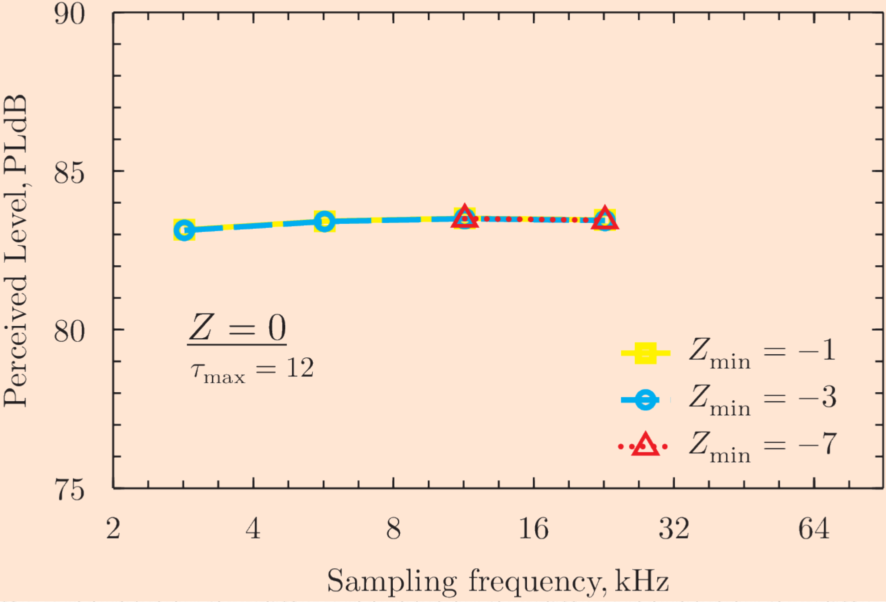




$Z = -1$, N/A

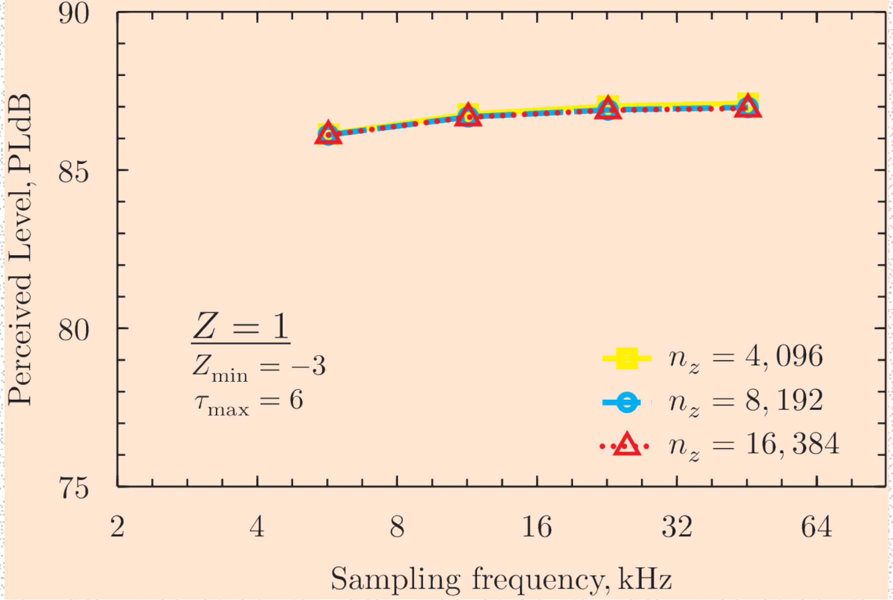
Case1, Optional, Fixed Domain size in τ

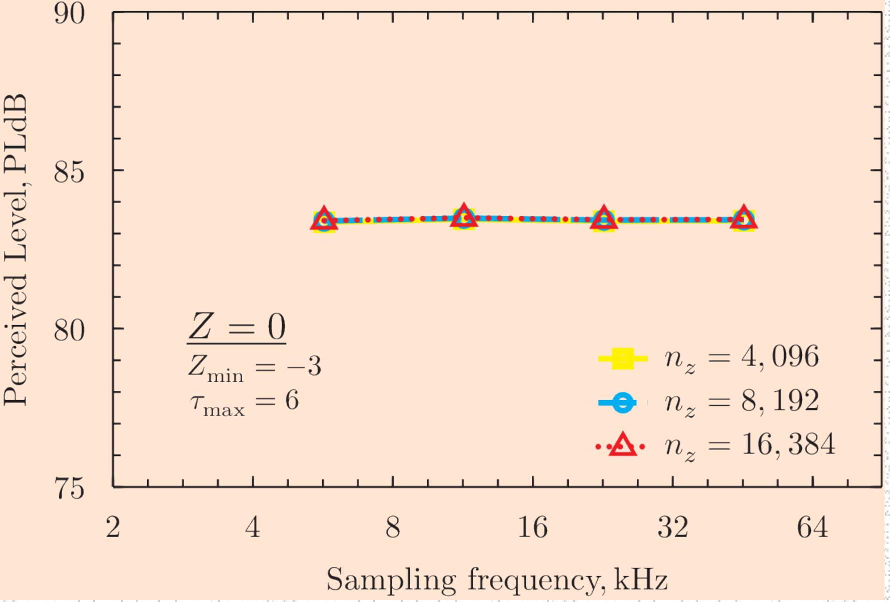




$Z = -1$, N/A

Case1, Optional, Fixed Domain size in Z and τ





$Z = -1$, N/A

Summary

- ✓Case 1, required & Case 2, required:
  - ✓ Addition of buffer region on both side should be tried when calculating loudness. (Sometimes very important, sometimes no need.)

- ✓Case 1, optional
  - ✓ Determining delta-tangent ray is the key point to perform the lossy NTE analysis.

Thank you for your attention!

Any questions?

Numerical Simulation
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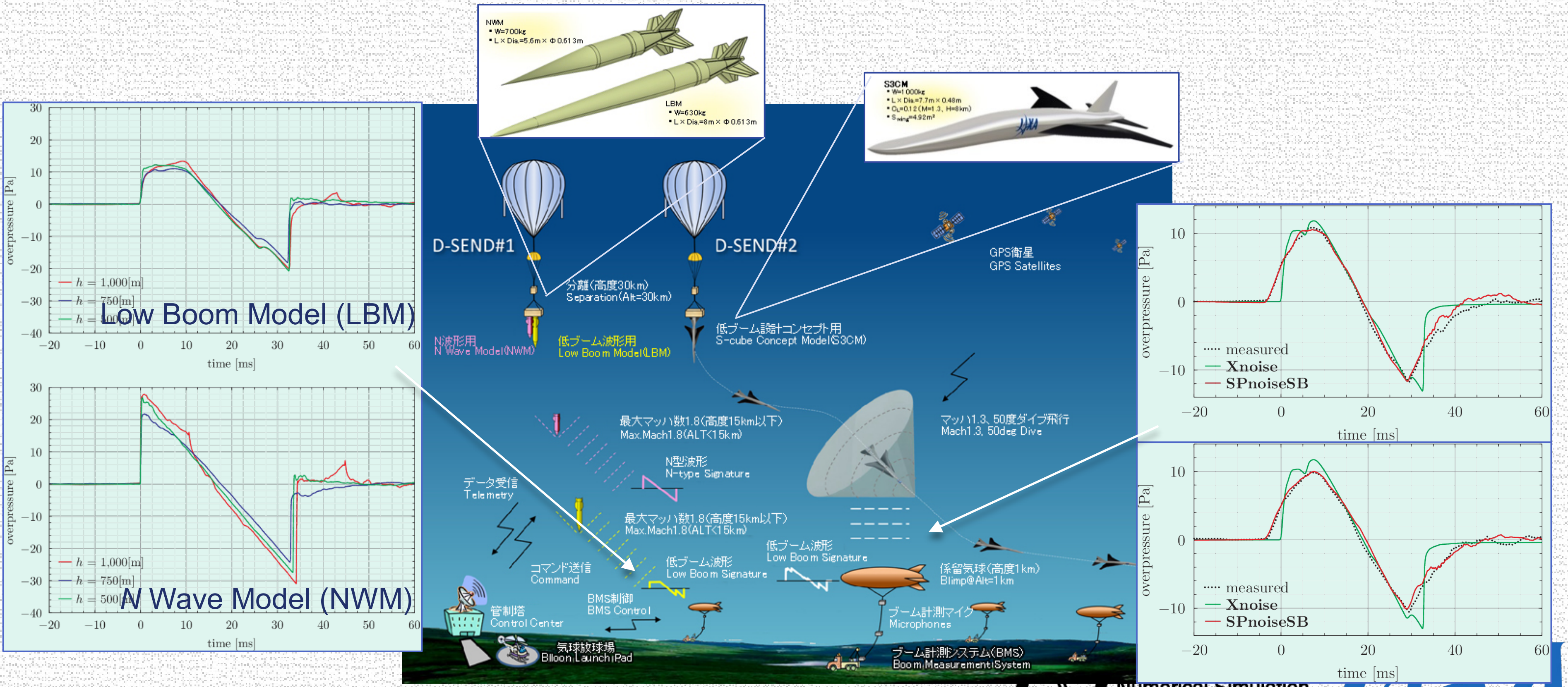
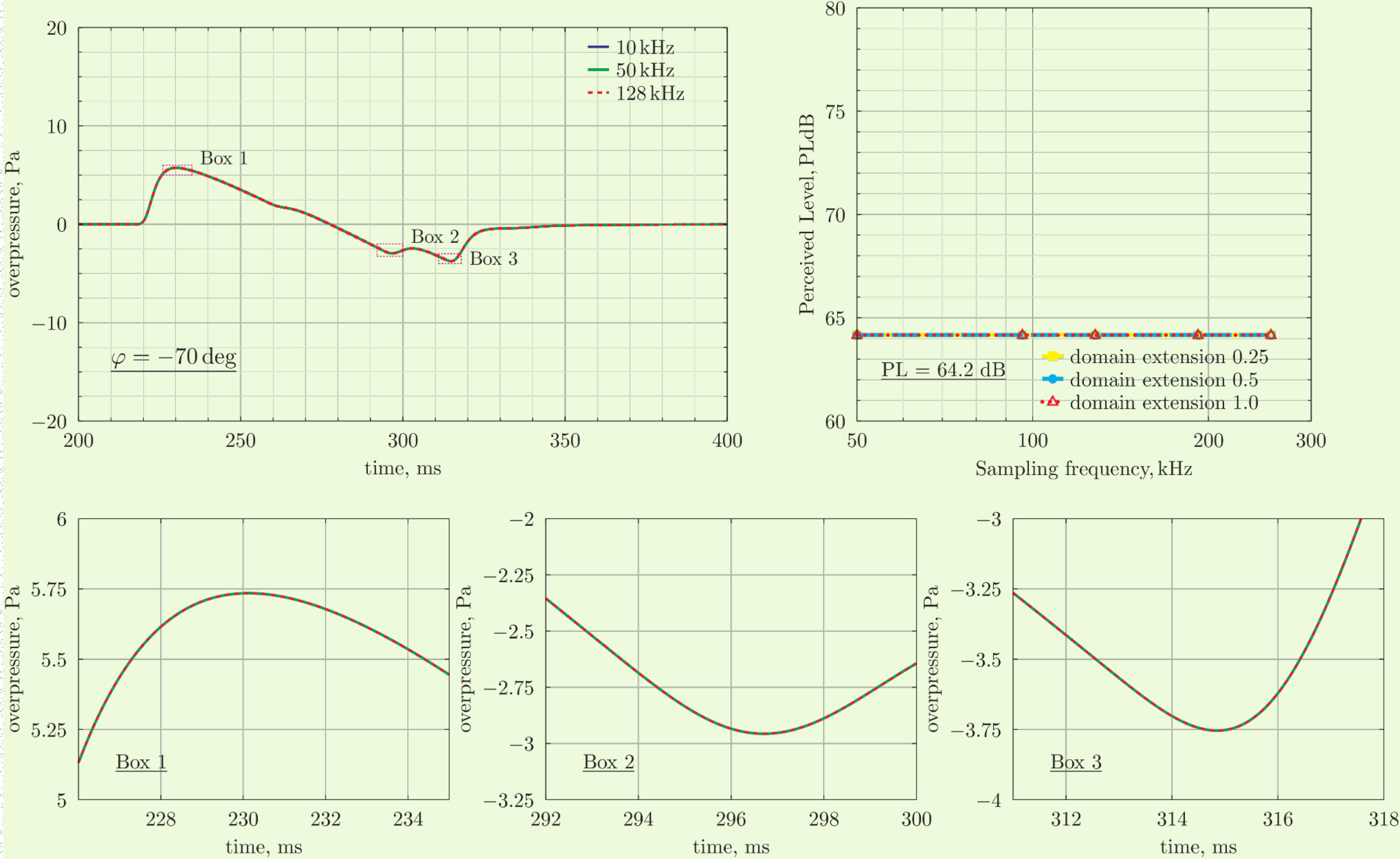
Appendix

D-SEND project in JAXA

- ✓ Demonstration of JAXA’s low-boom design concept
- ✓ D-SEND#1 flight test was successfully performed in 2011 (Bottom left)
- ✓ D-SEND#2 flight test demonstrated our design concept (Bottom right)

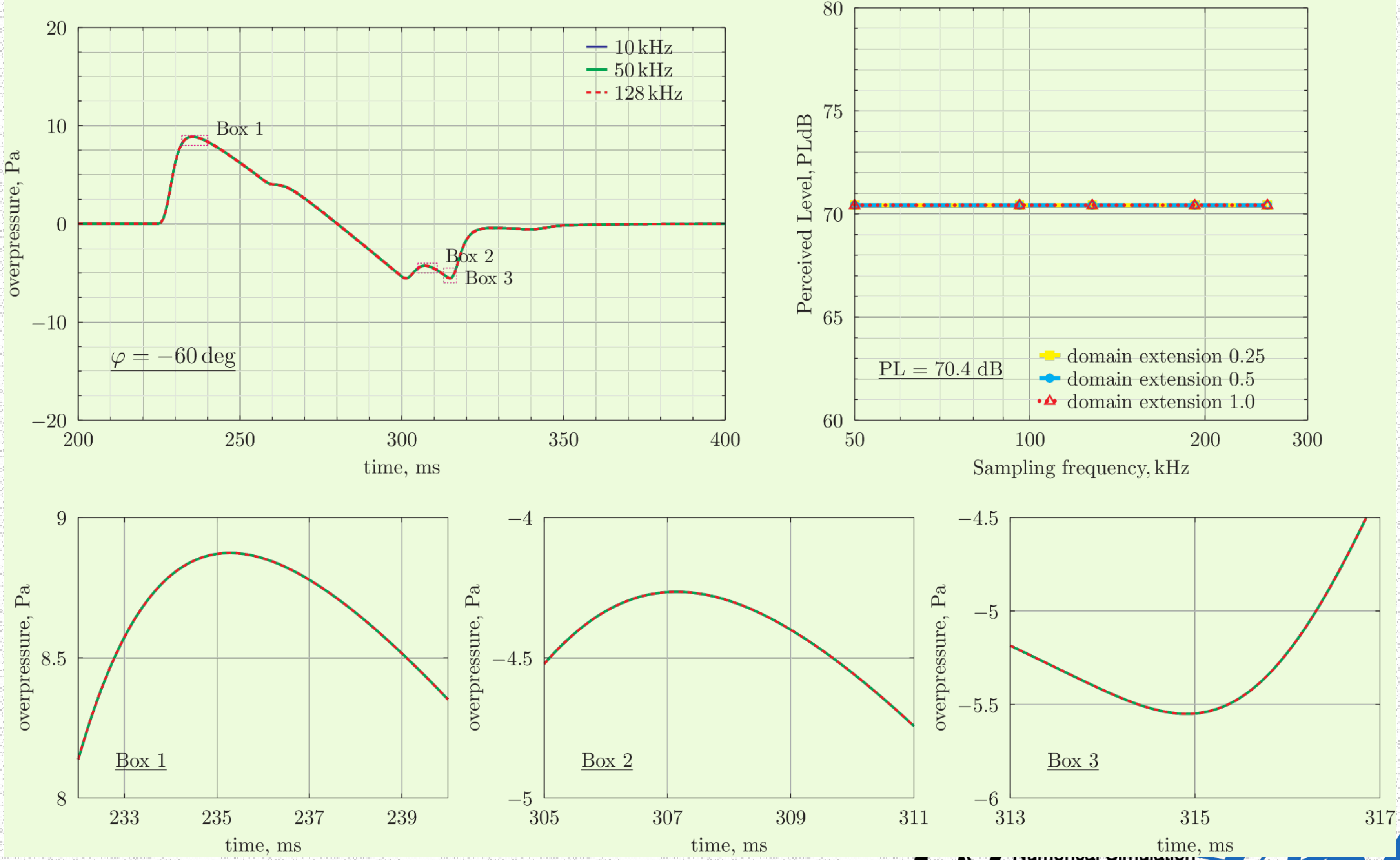


Case 1, Required, $\varphi = -70$ deg

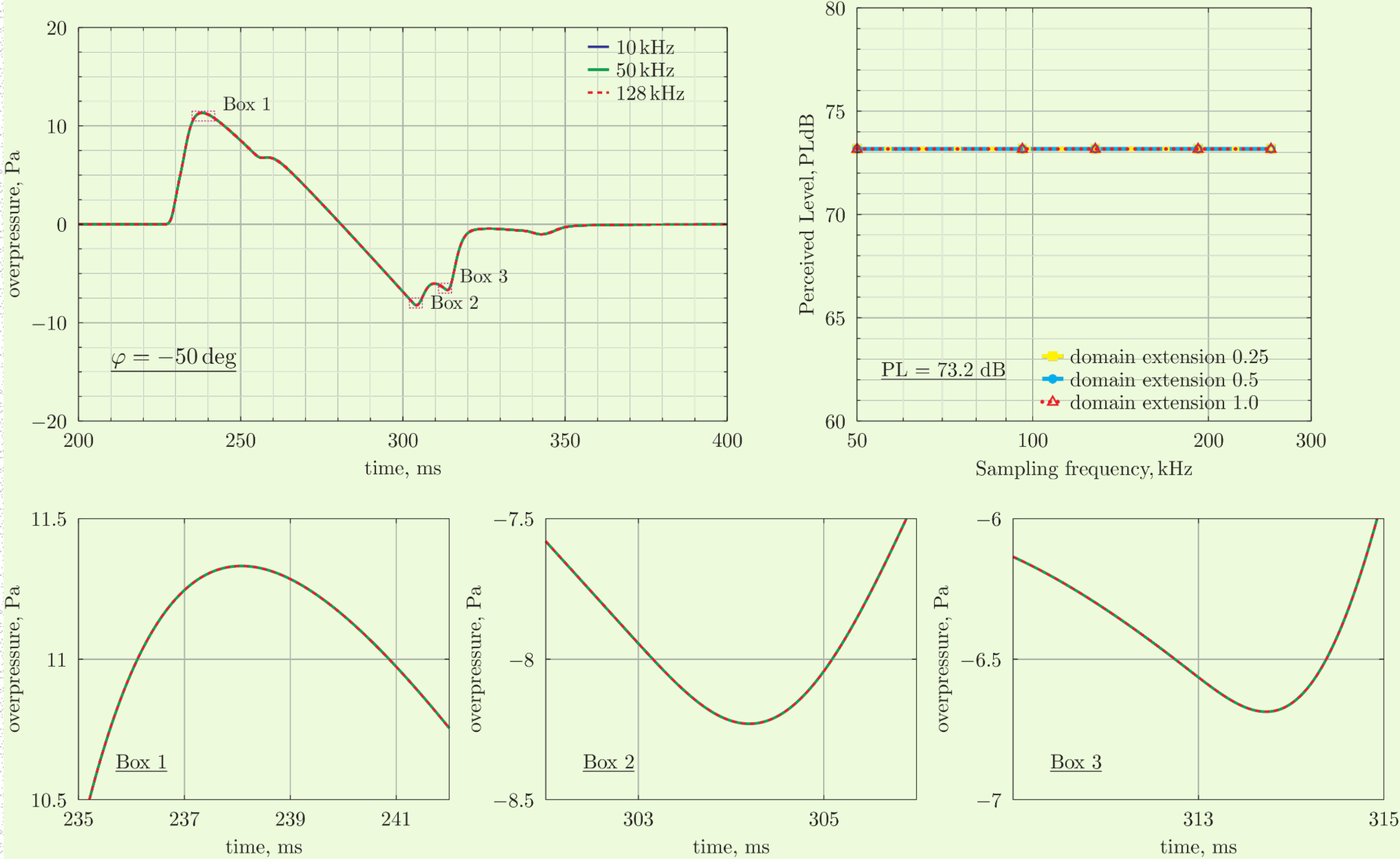


Research Unit

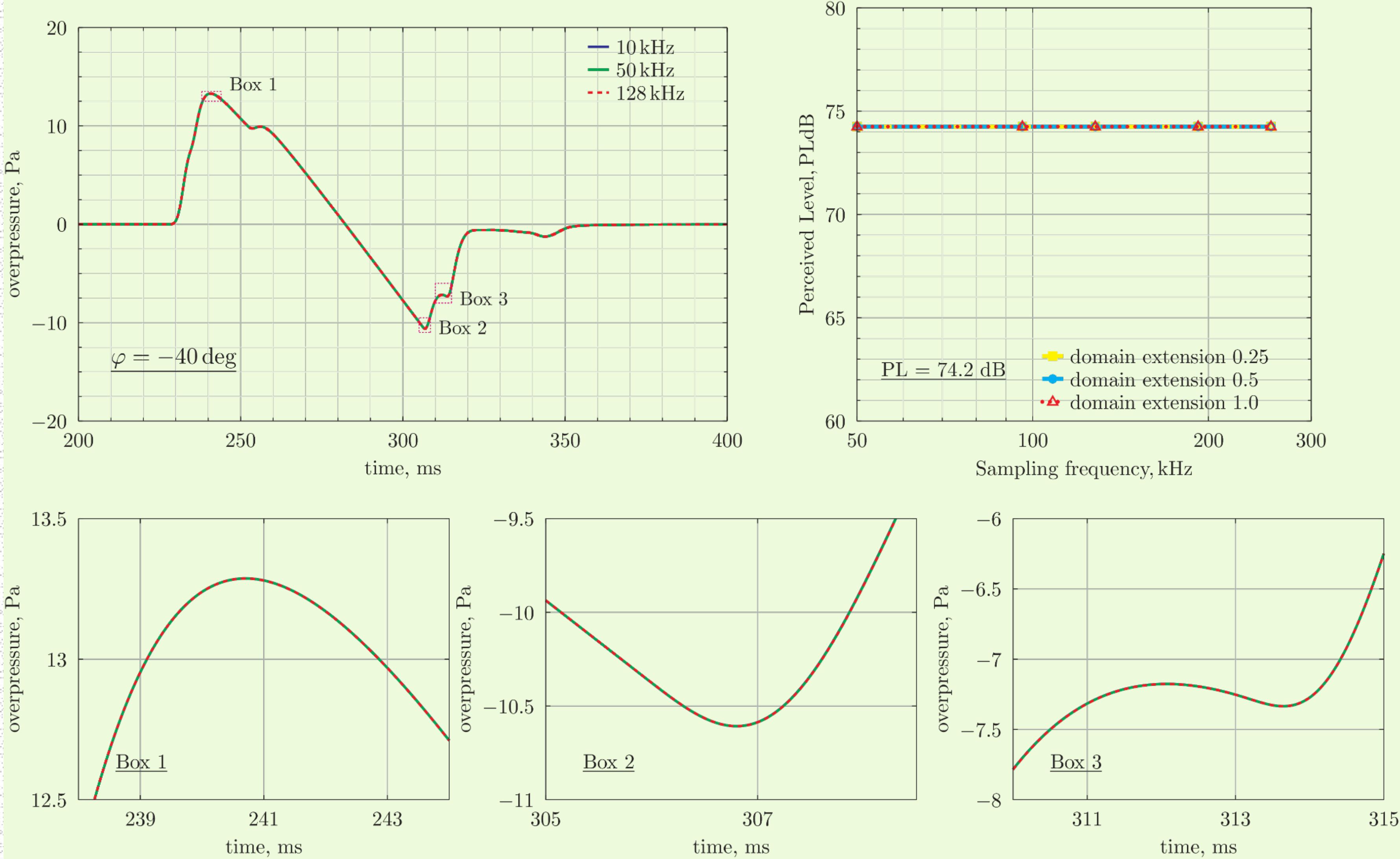
Case 1, Required, $\varphi = -60$ deg



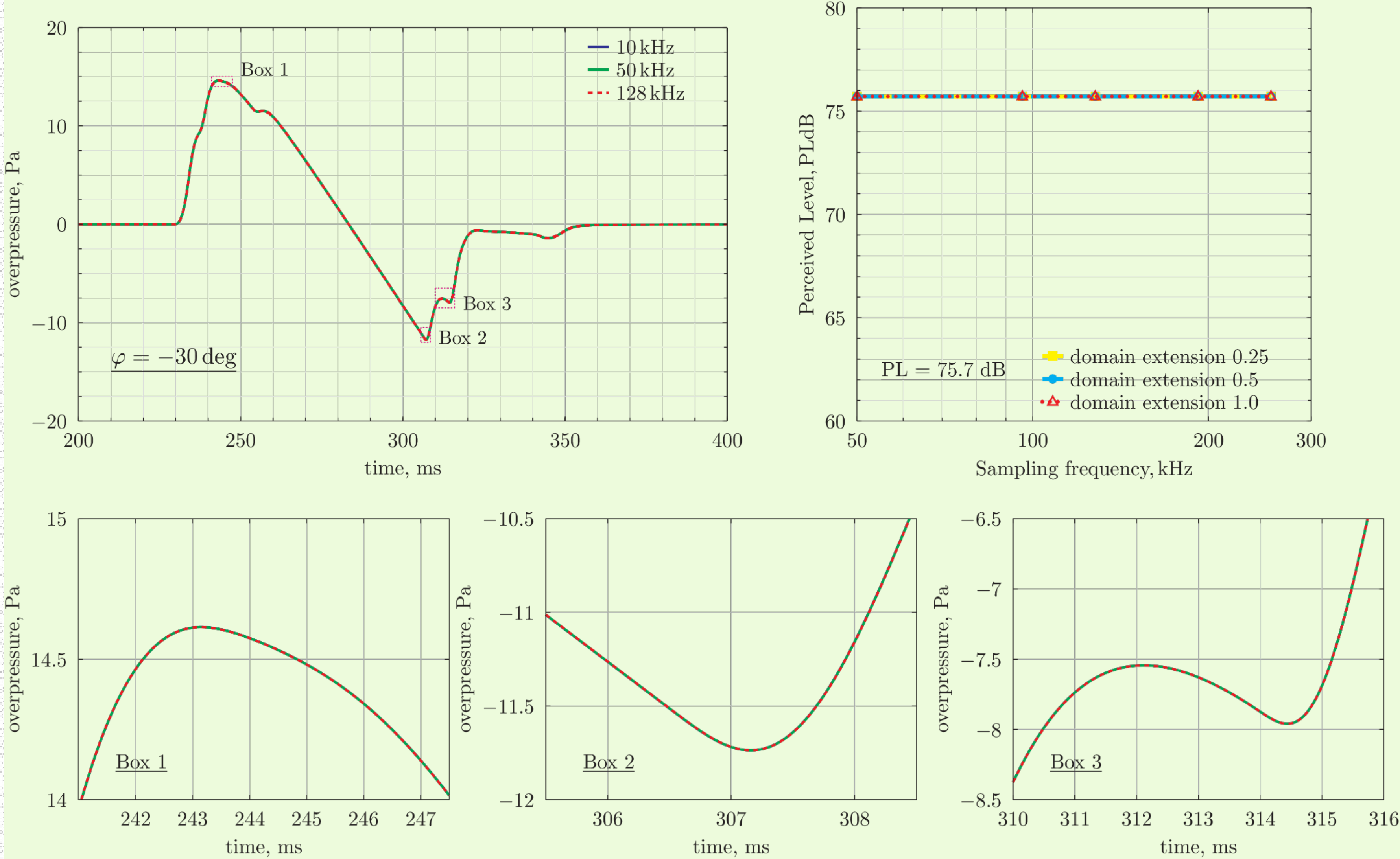
Case 1, Required, $\varphi = -50$ deg



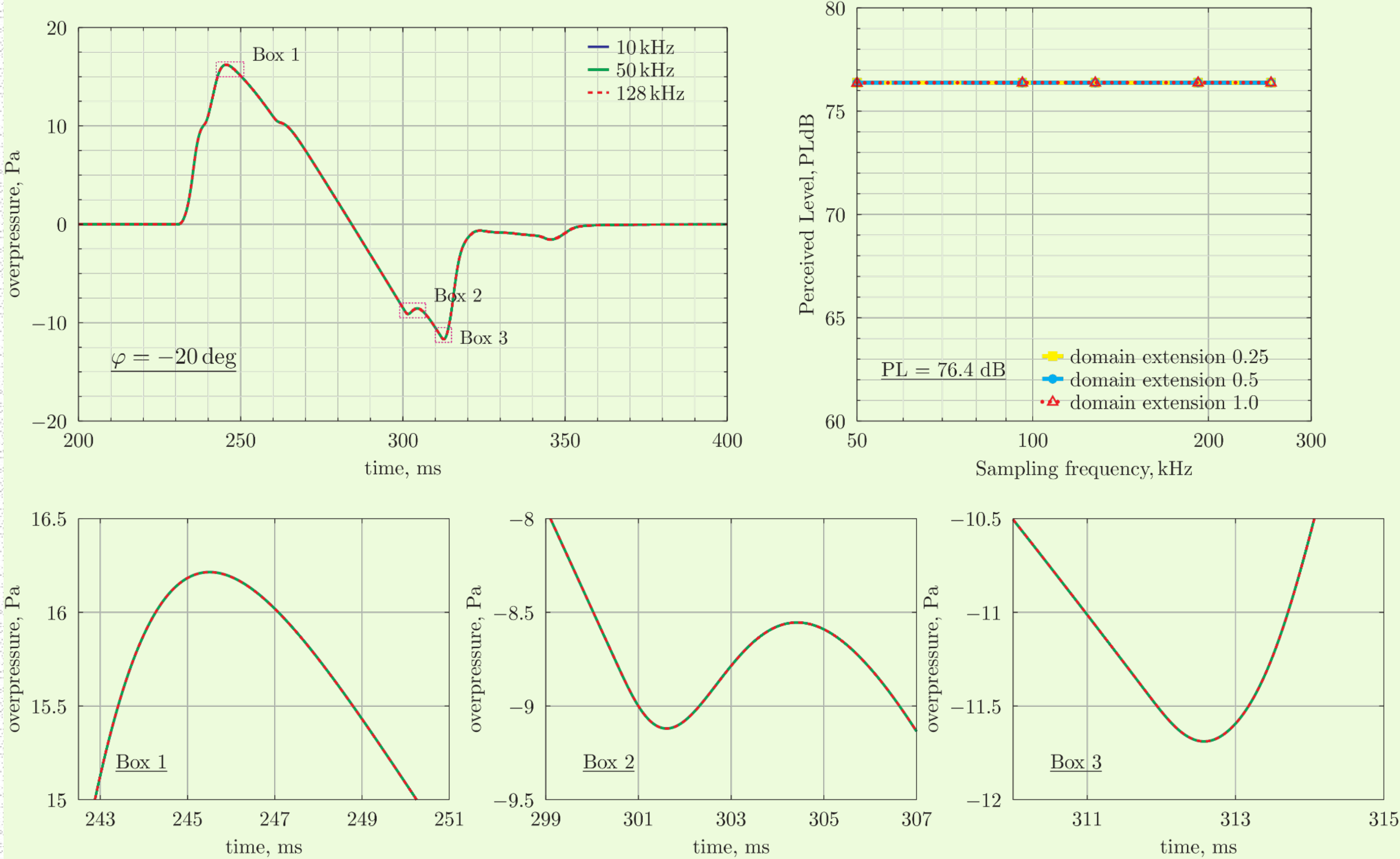
Case 1, Required, $\varphi = -40$ deg



Case 1, Required, $\varphi = -30$ deg

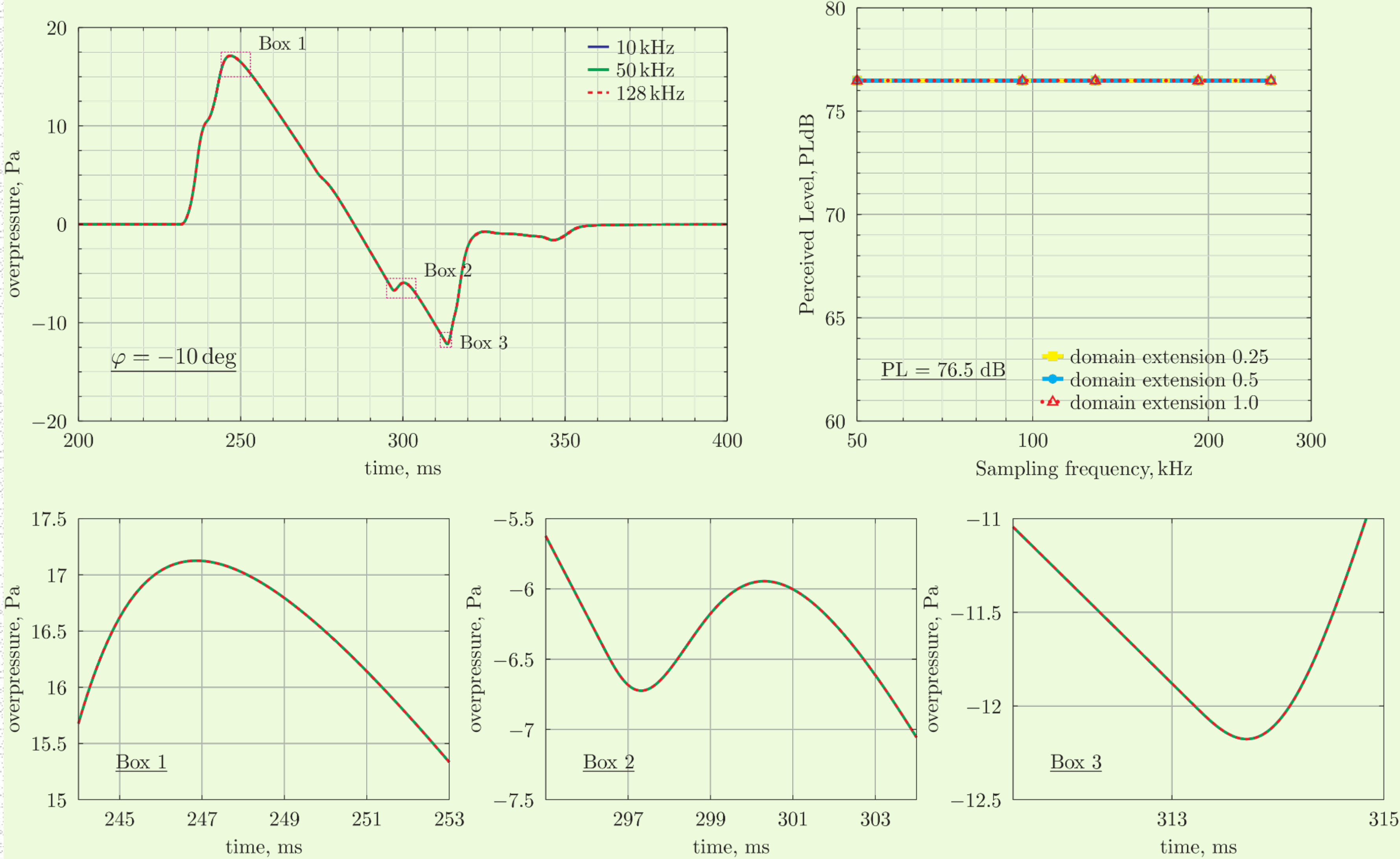


Case 1, Required, $\varphi = -20$ deg

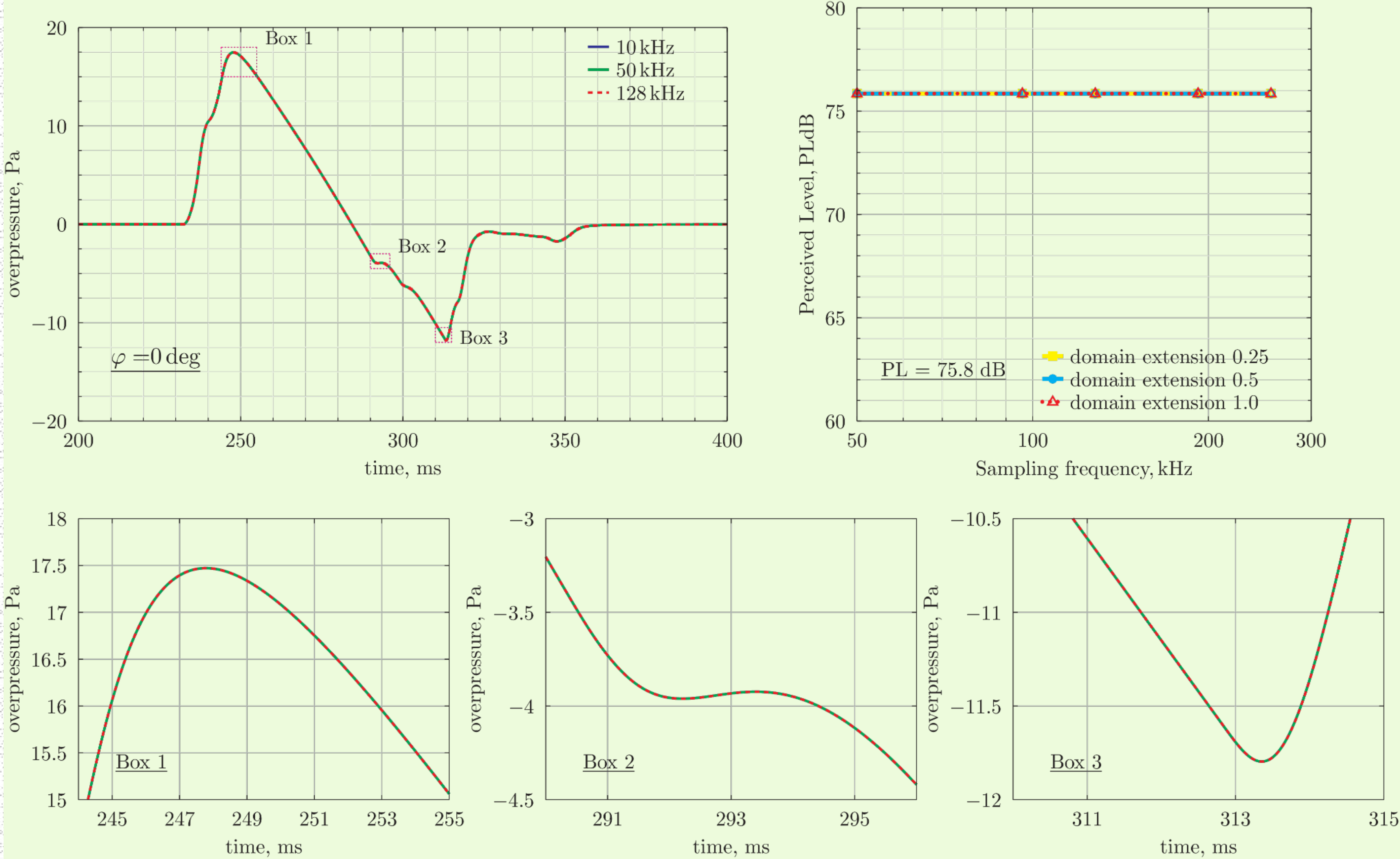


Research Unit

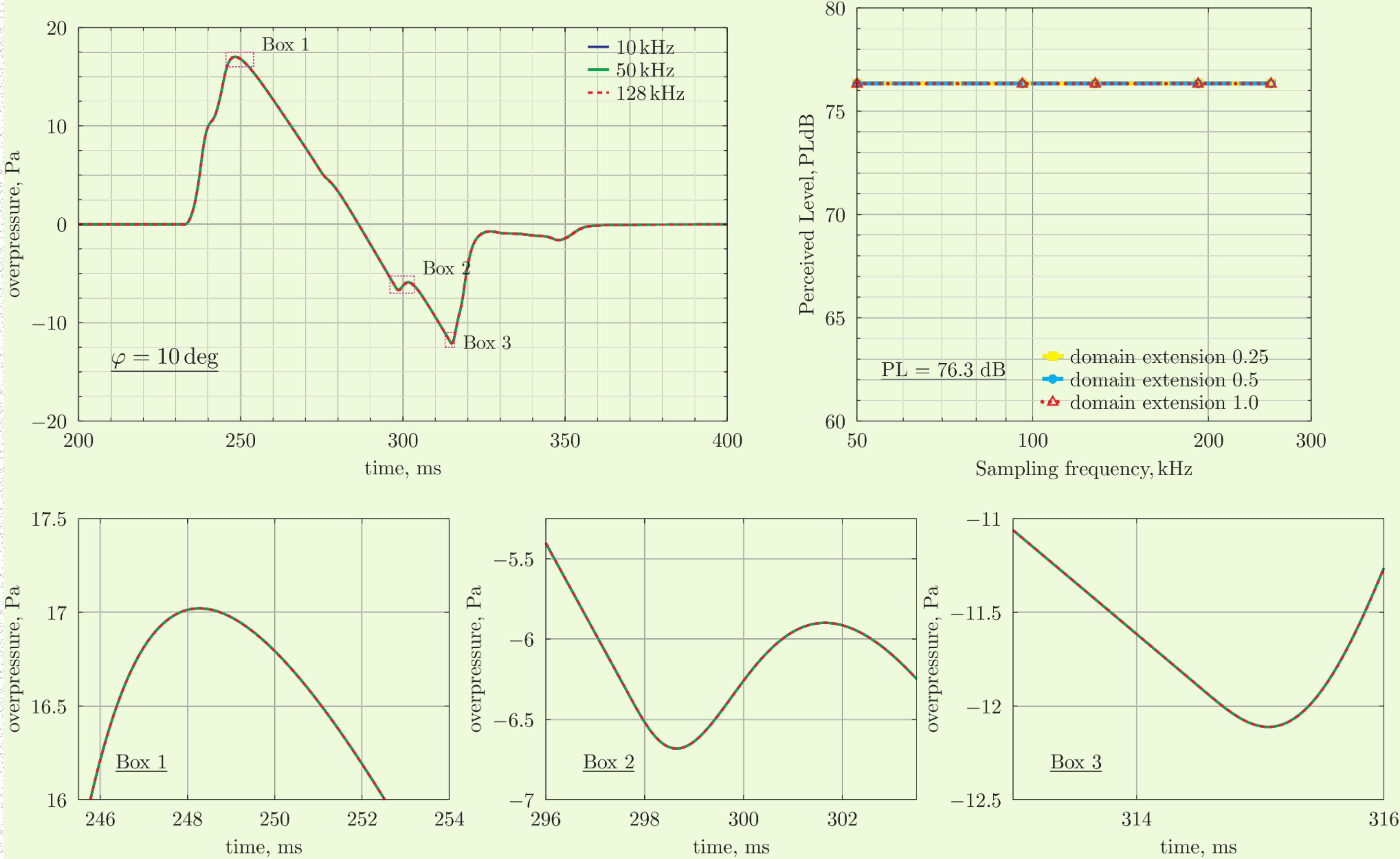
Case 1, Required, $\varphi = -10$ deg



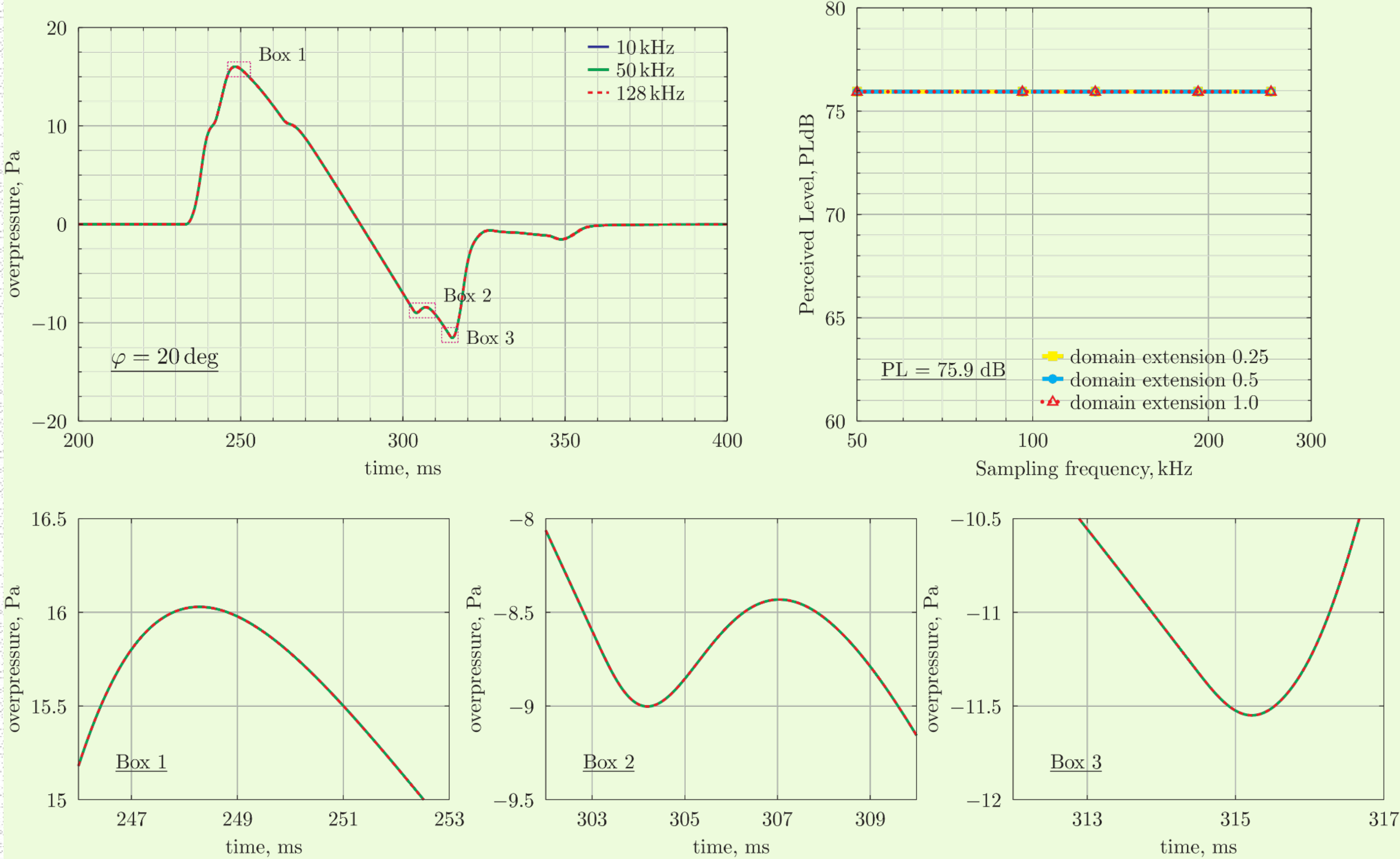
Case 1, Required, $\varphi = 0$ deg



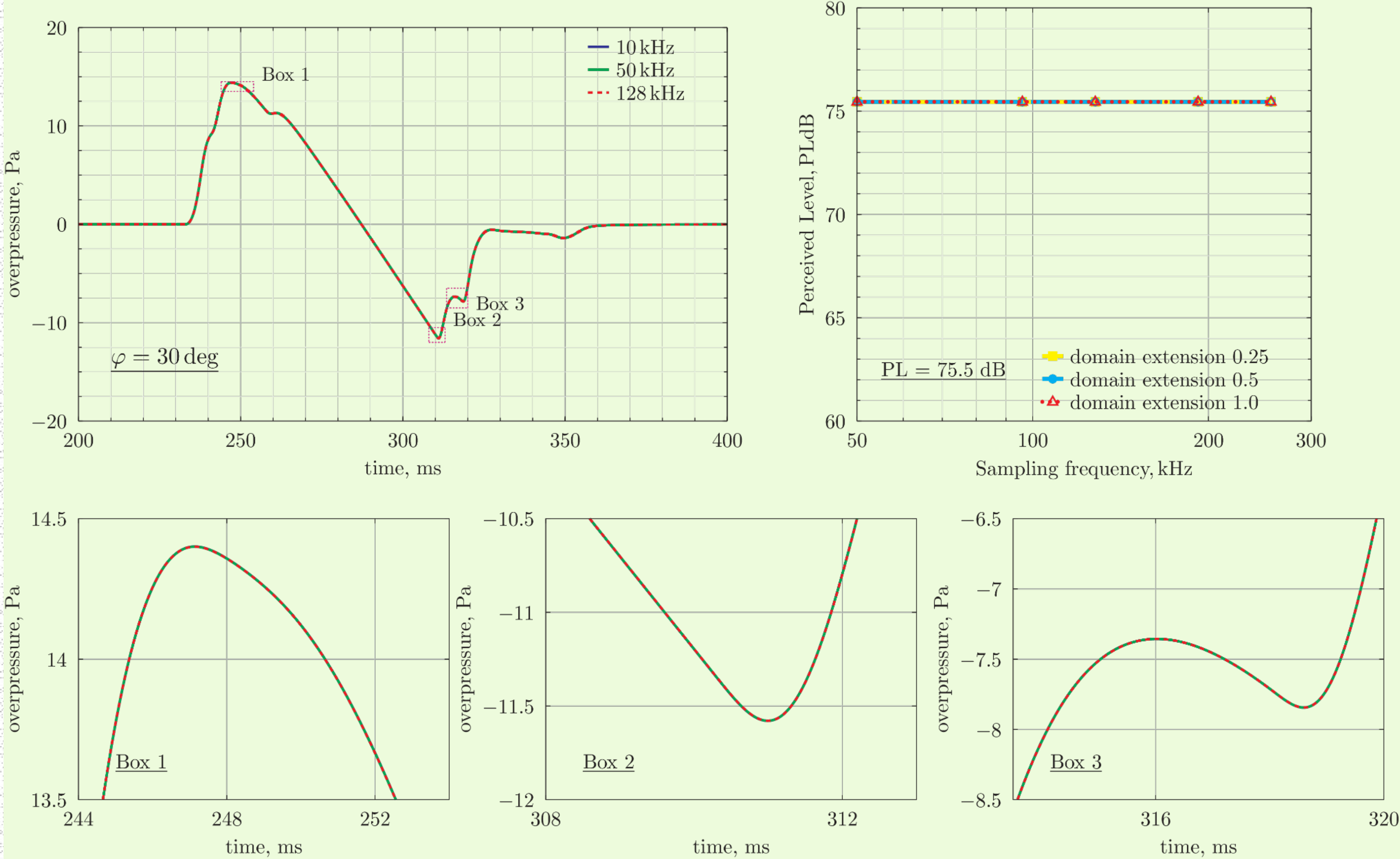
Case 1, Required, $\varphi = 10$ deg



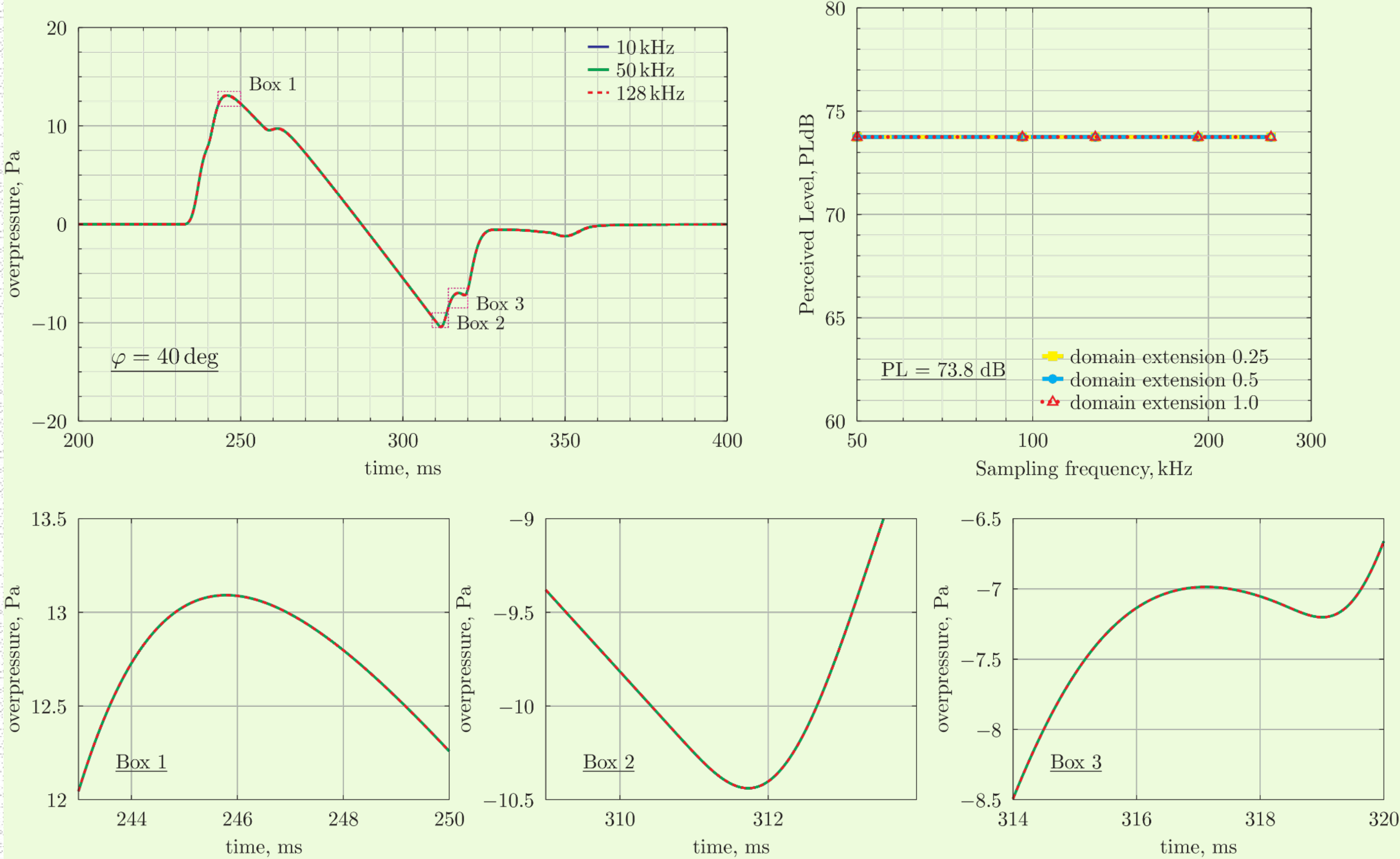
Case 1, Required, $\varphi = 20$ deg



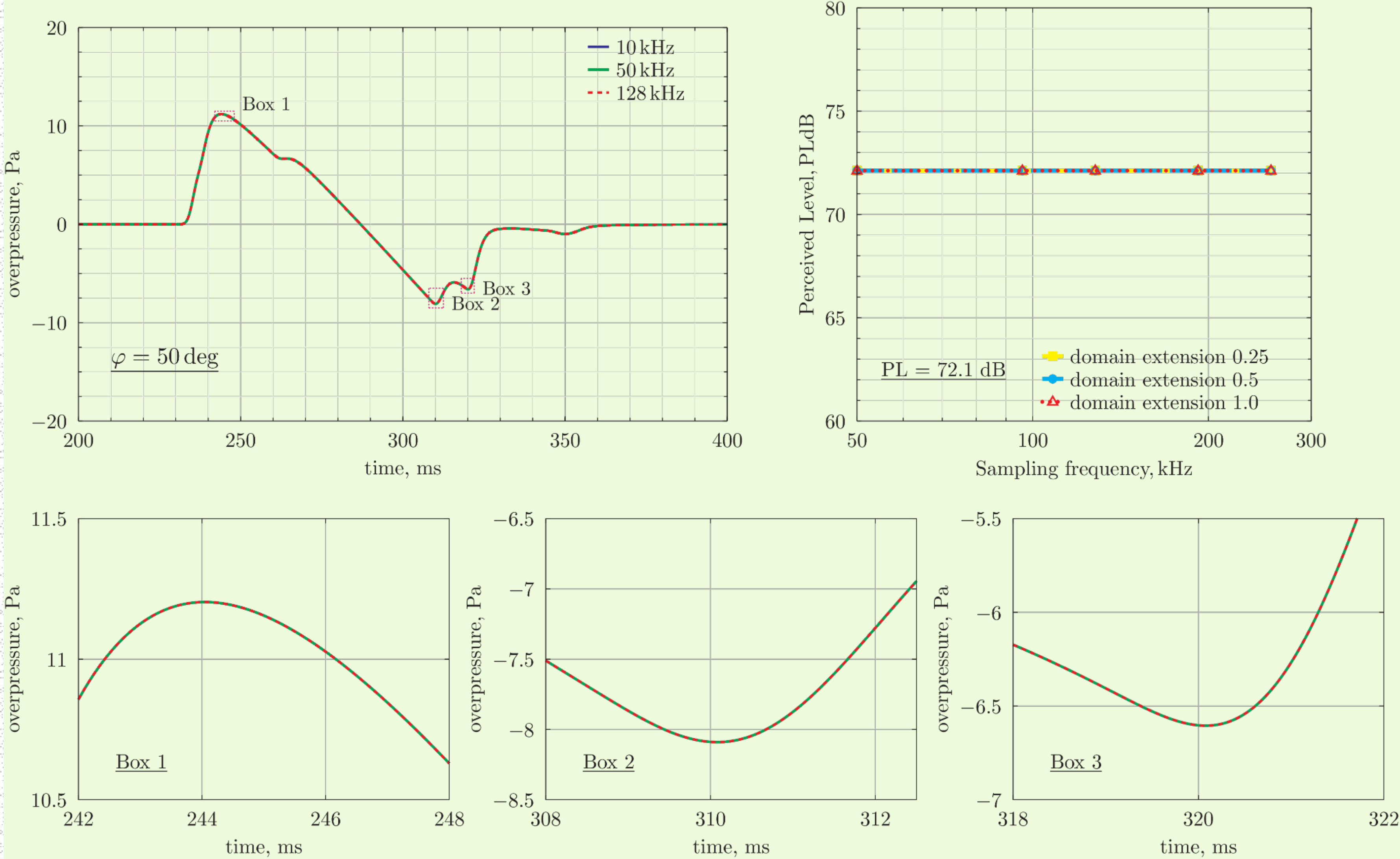
Case 1, Required, $\varphi = 30$ deg



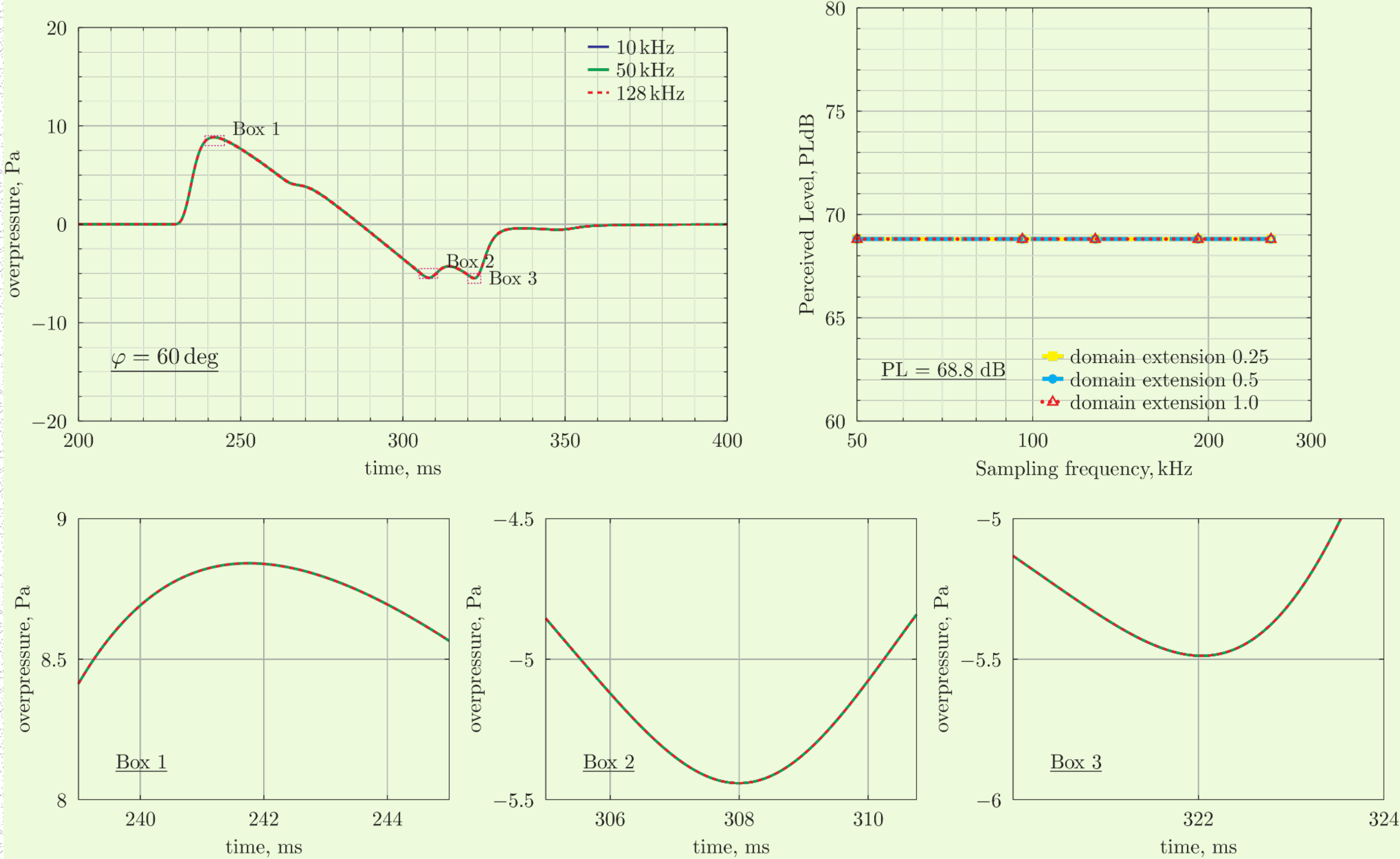
Case 1, Required, $\varphi = 40$ deg



Case 1, Required, $\varphi = 50$ deg

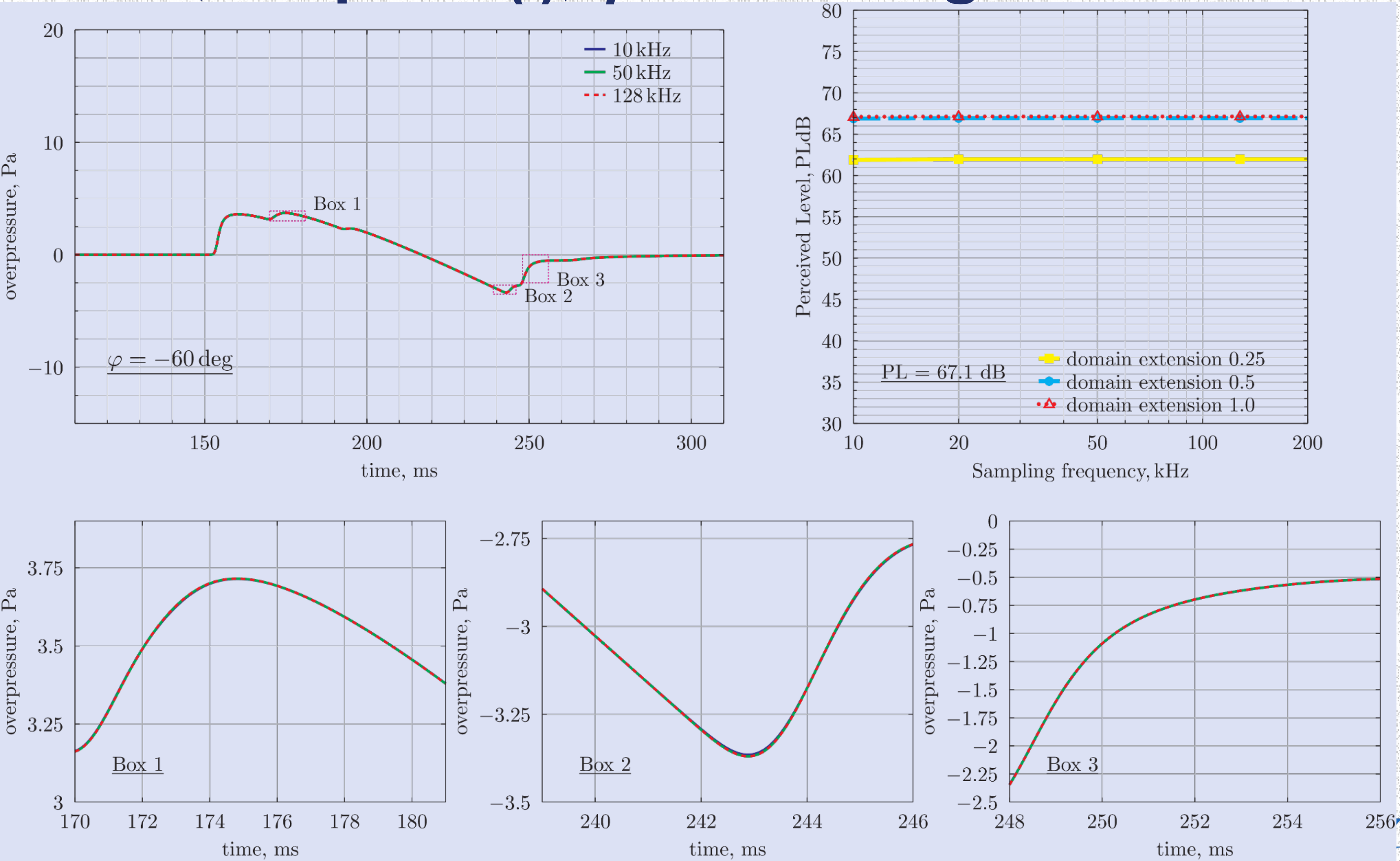


Case 1, Required, $\varphi = 60$ deg

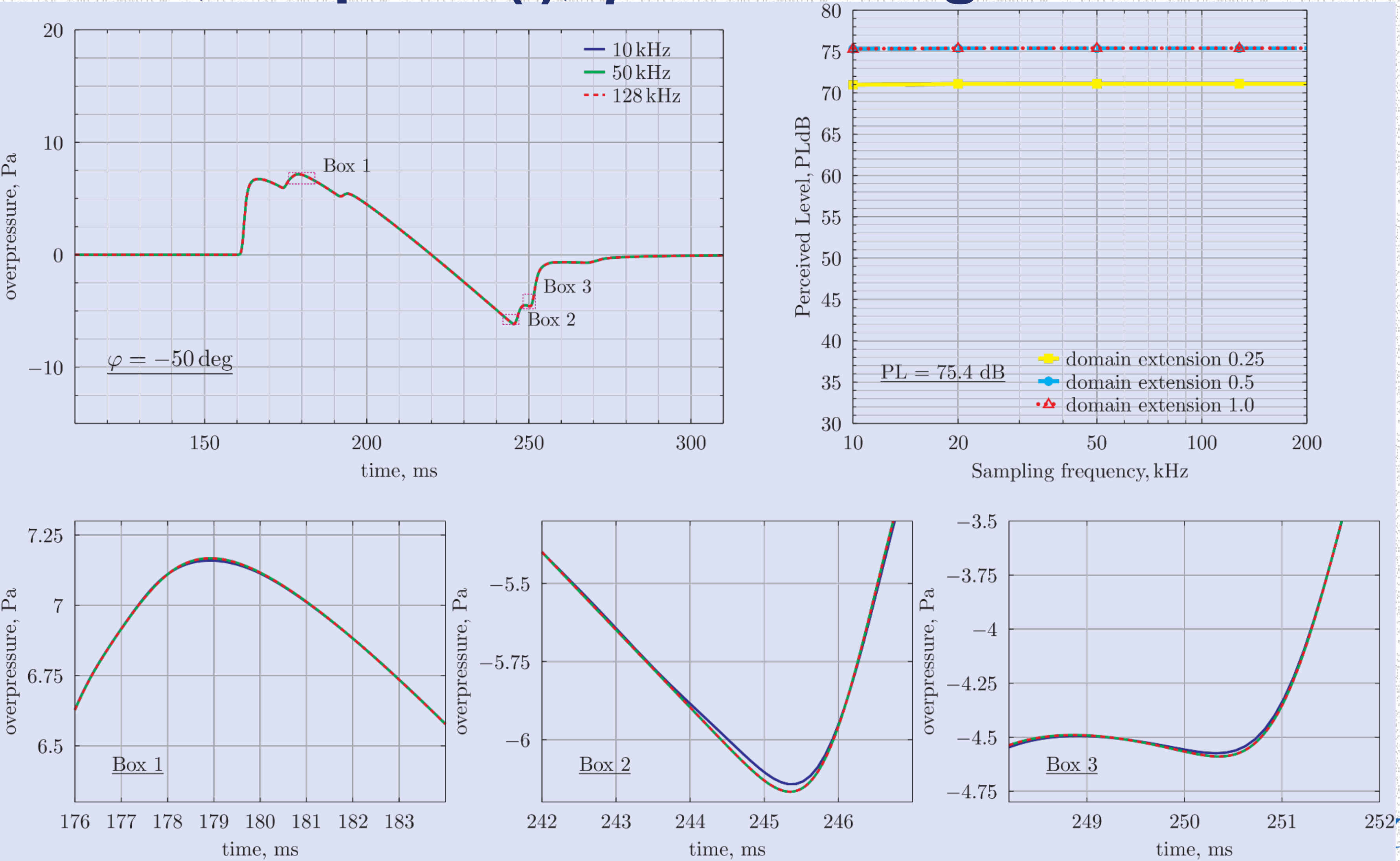


Research Unit

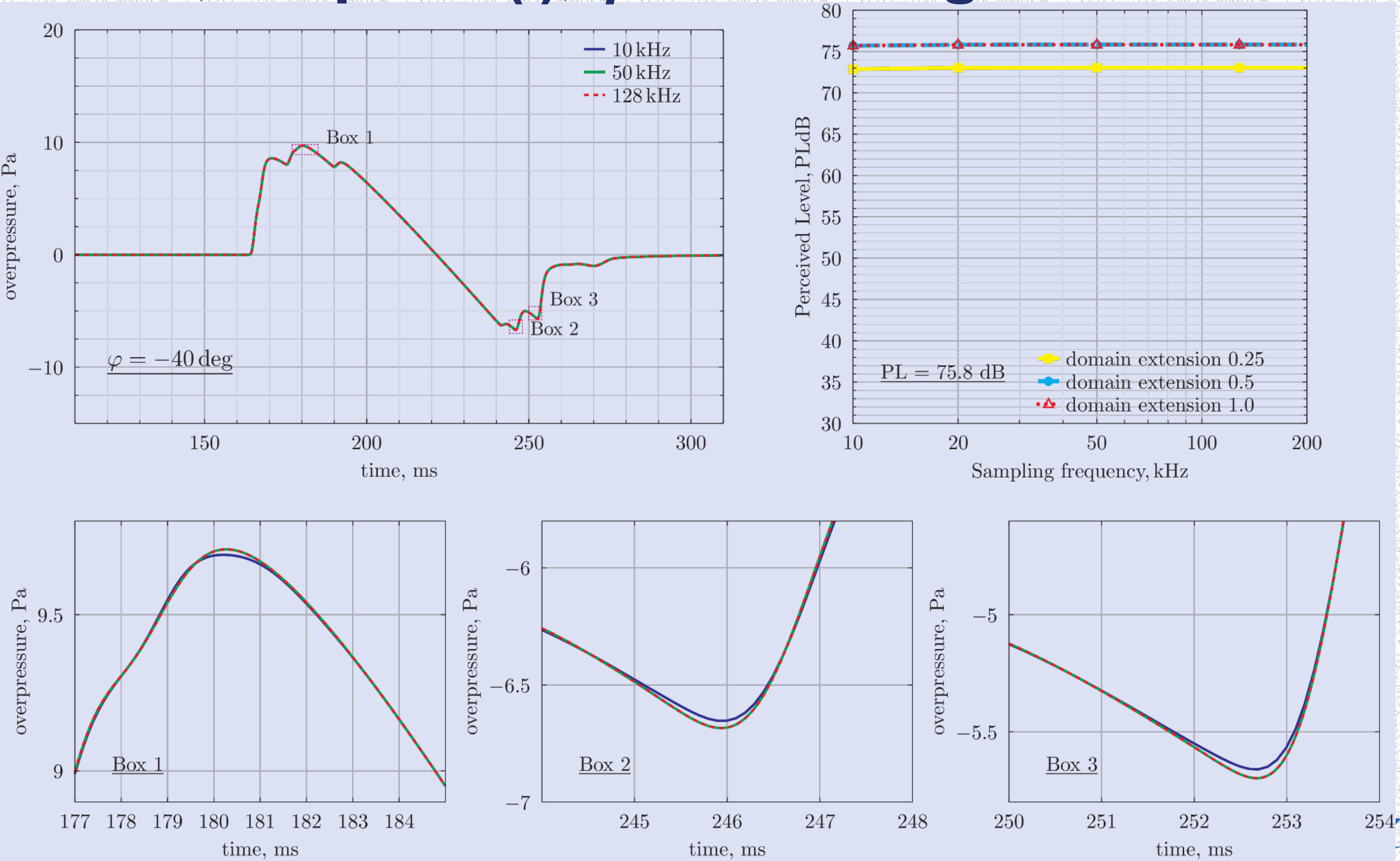
Case 2, Required(i), $\varphi = -60$ deg



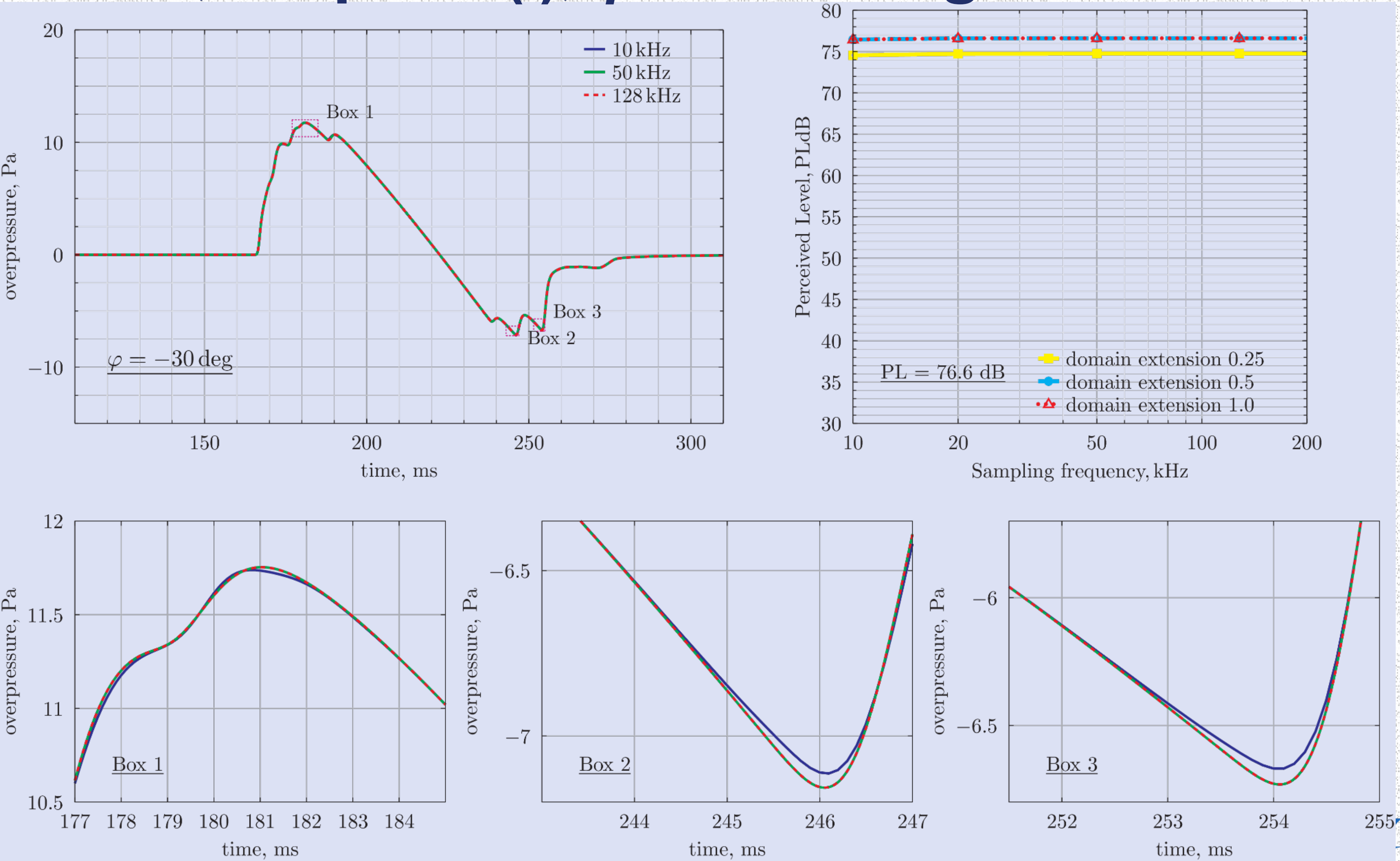
Case 2, Required(i), $\varphi = -50$ deg



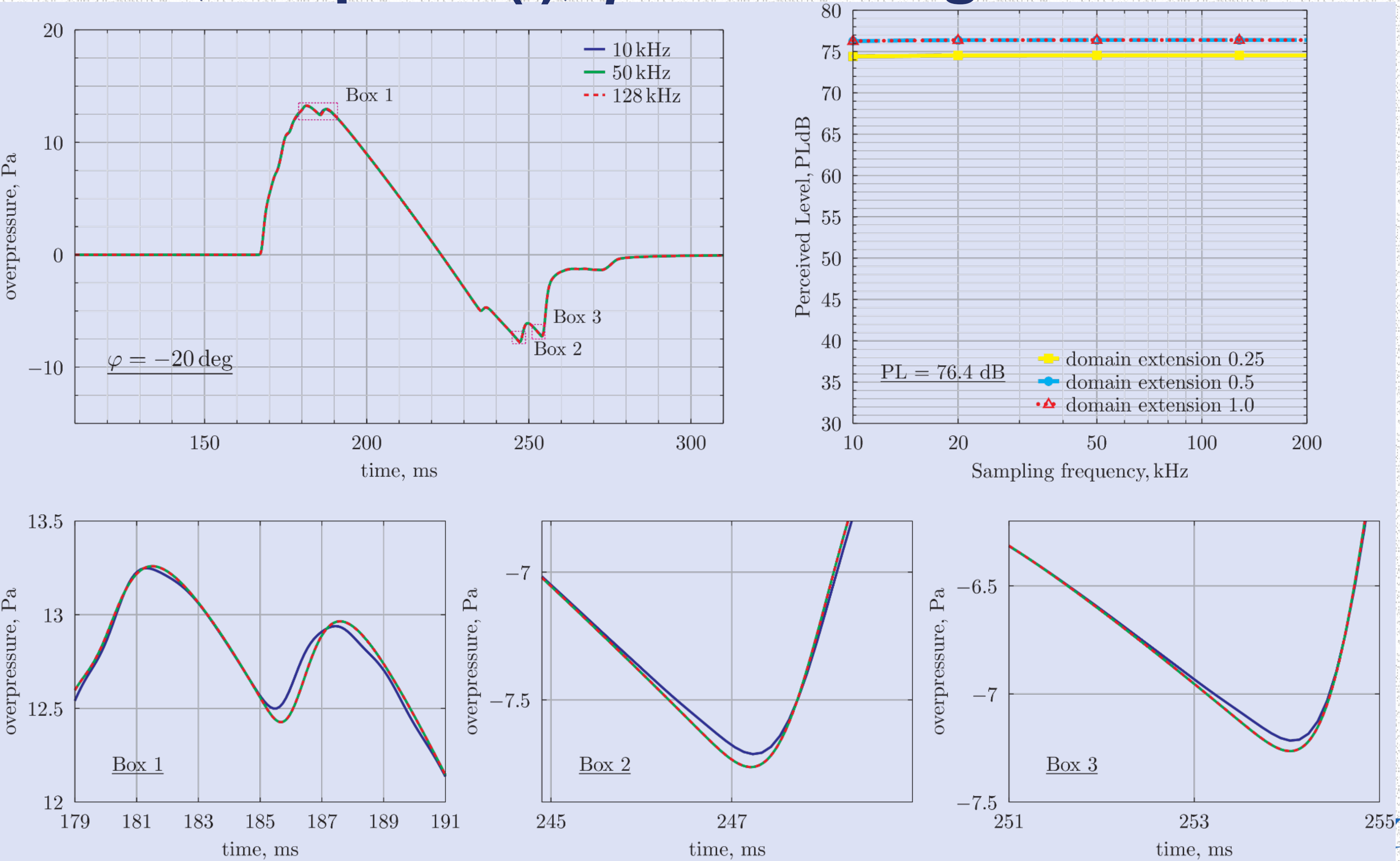
Case 2, Required(i), $\varphi = -40$ deg



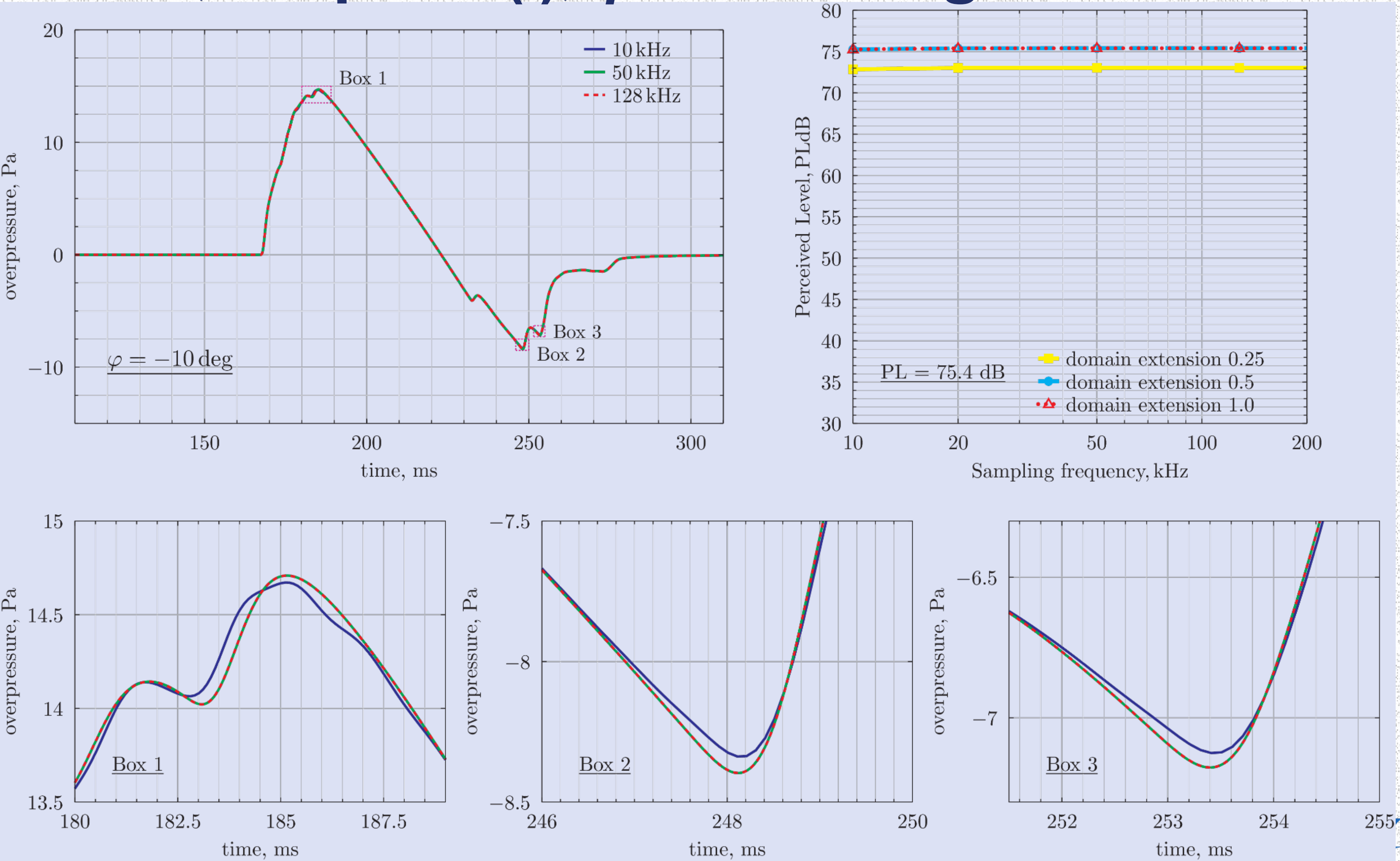
Case 2, Required(i), $\varphi = -30$ deg



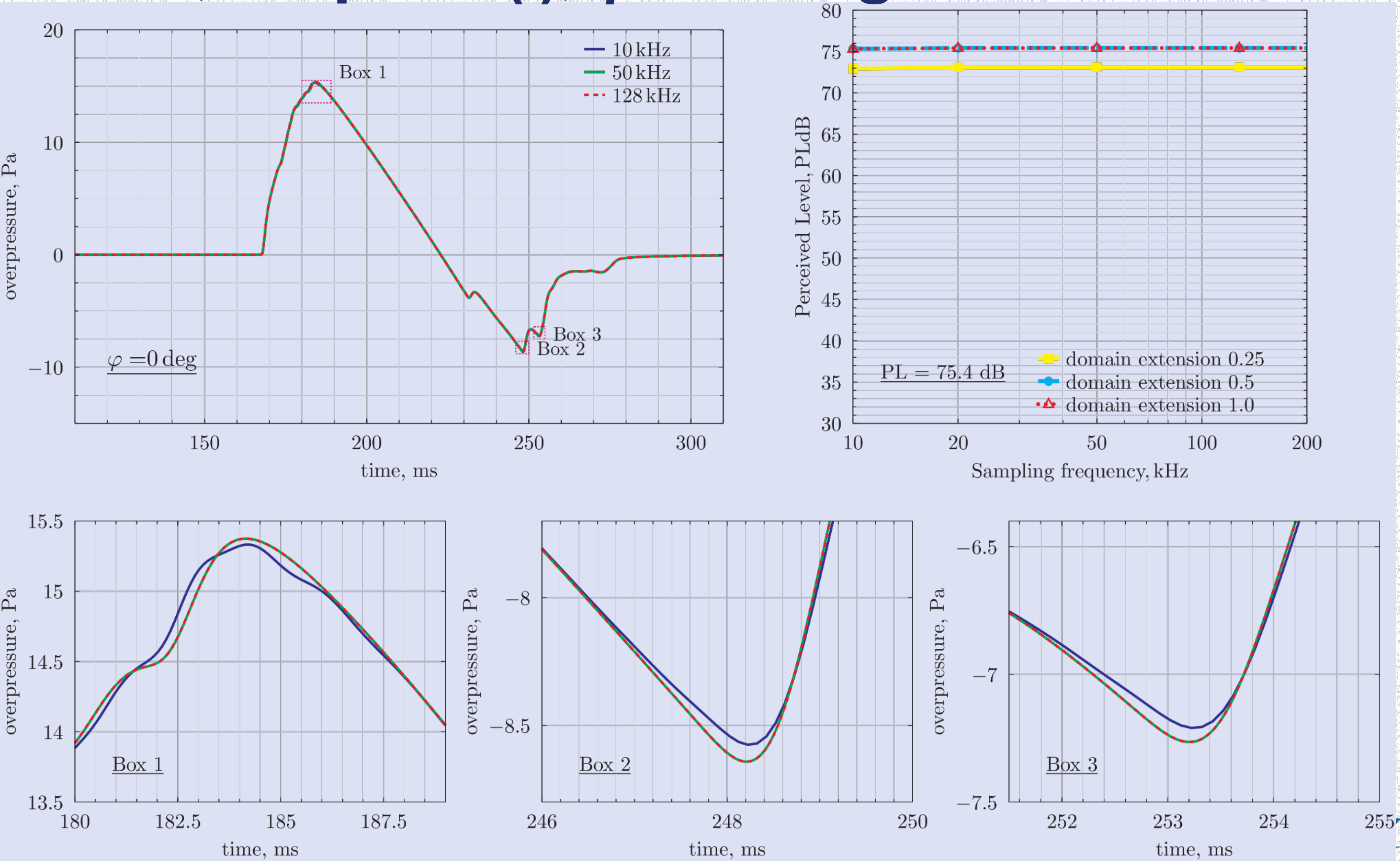
Case 2, Required(i), $\varphi = -20$ deg



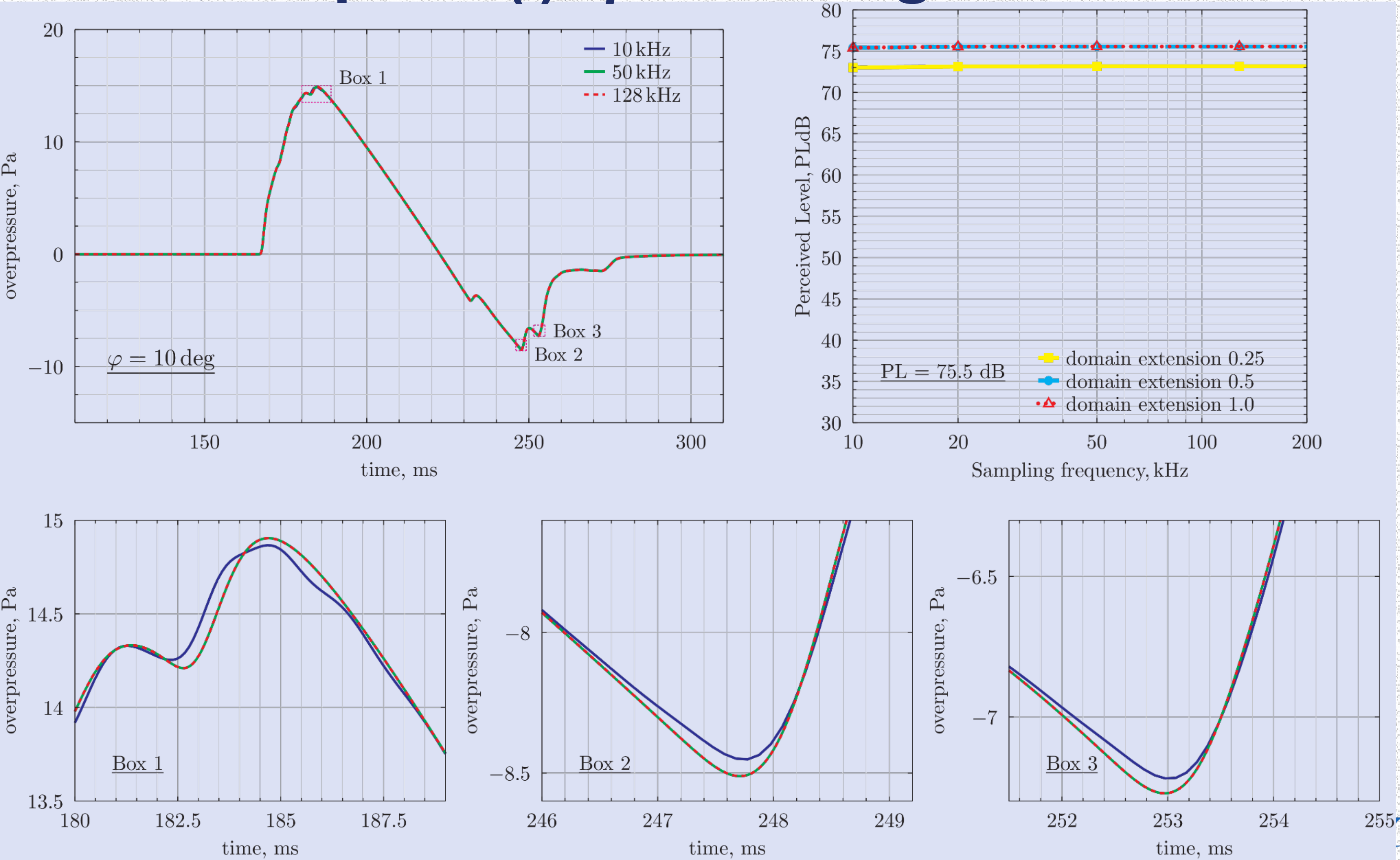
Case 2, Required(i), $\varphi = -10$ deg



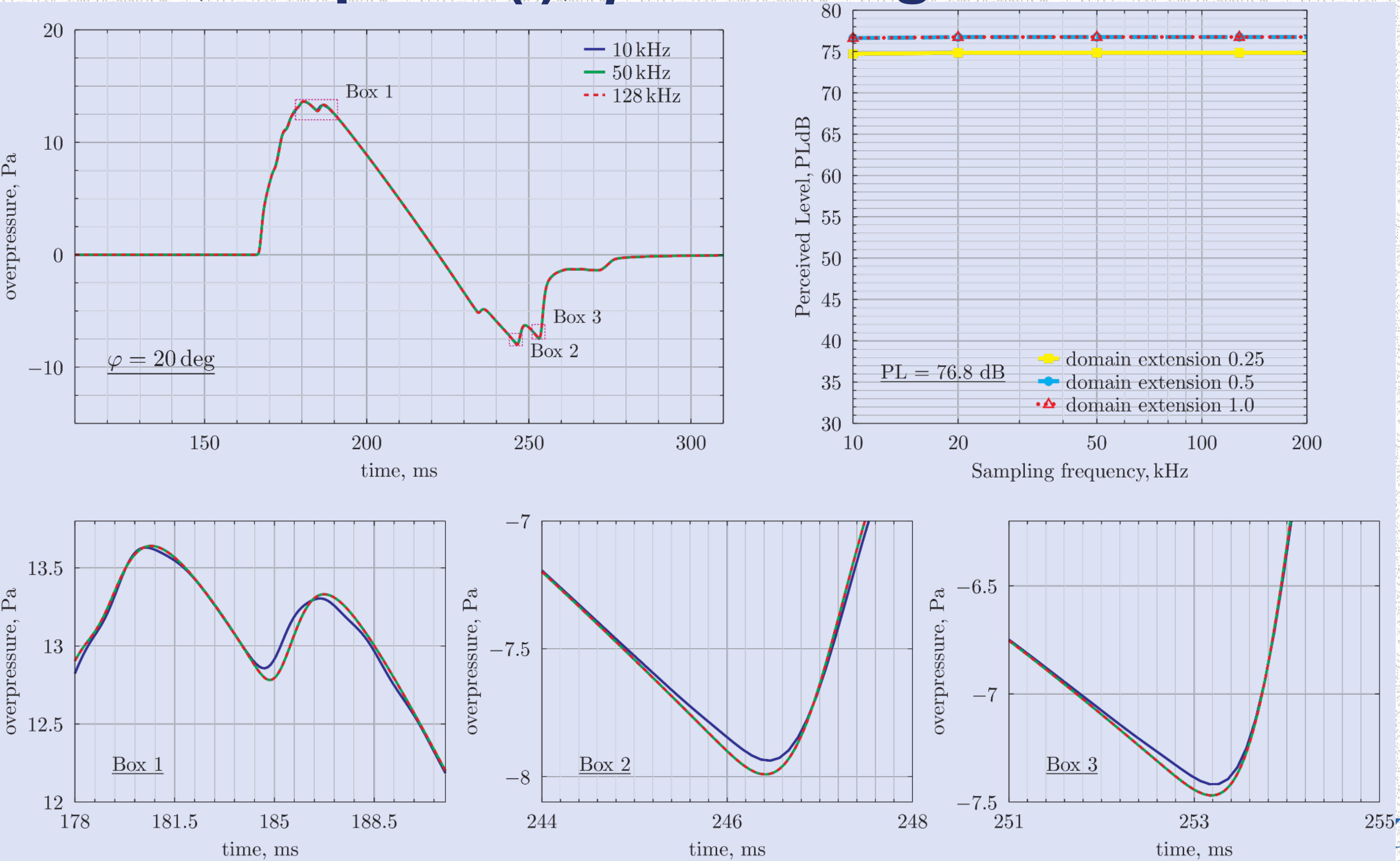
Case 2, Required(i), $\varphi = 0$ deg



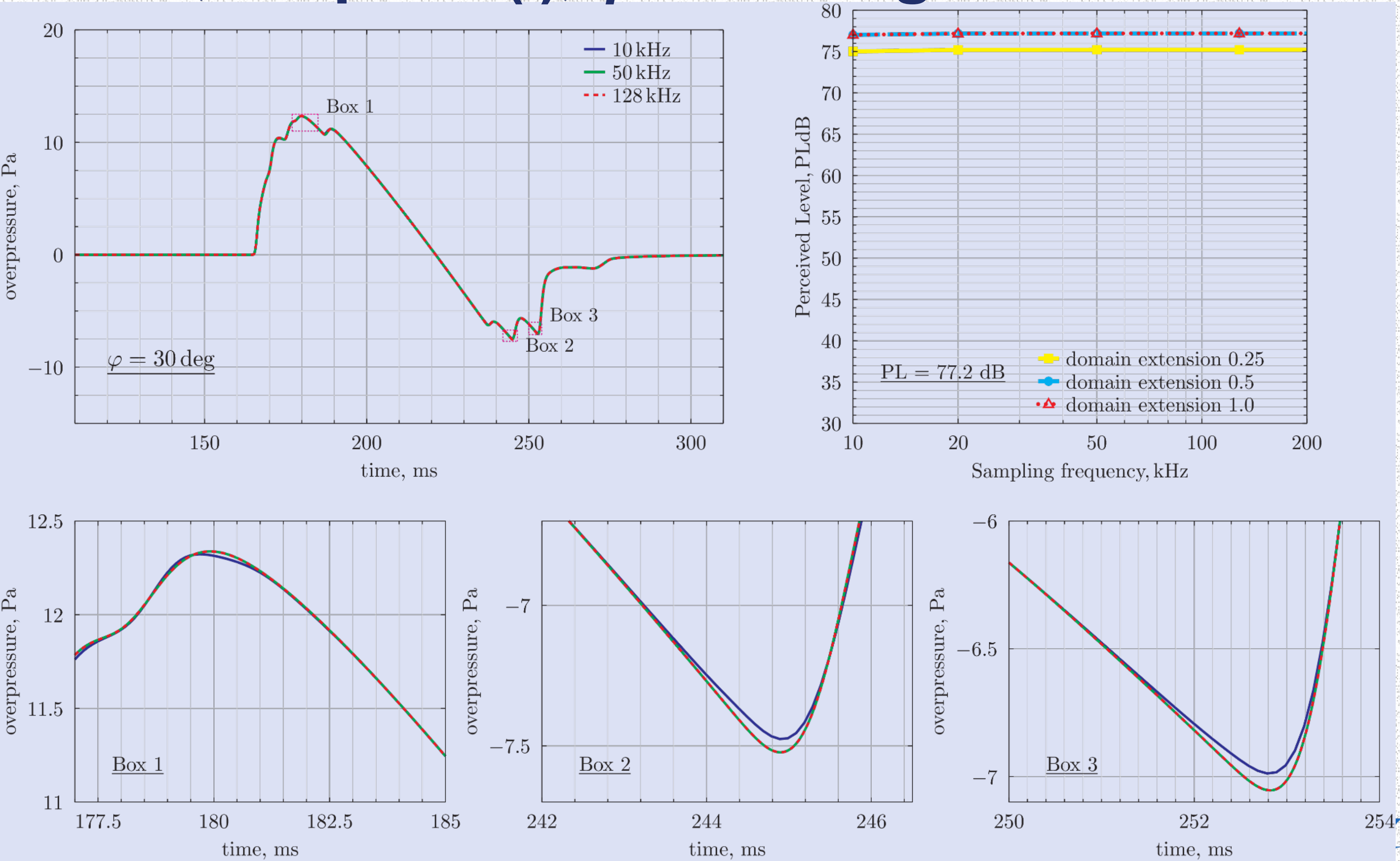
Case 2, Required(i), $\varphi = 10$ deg



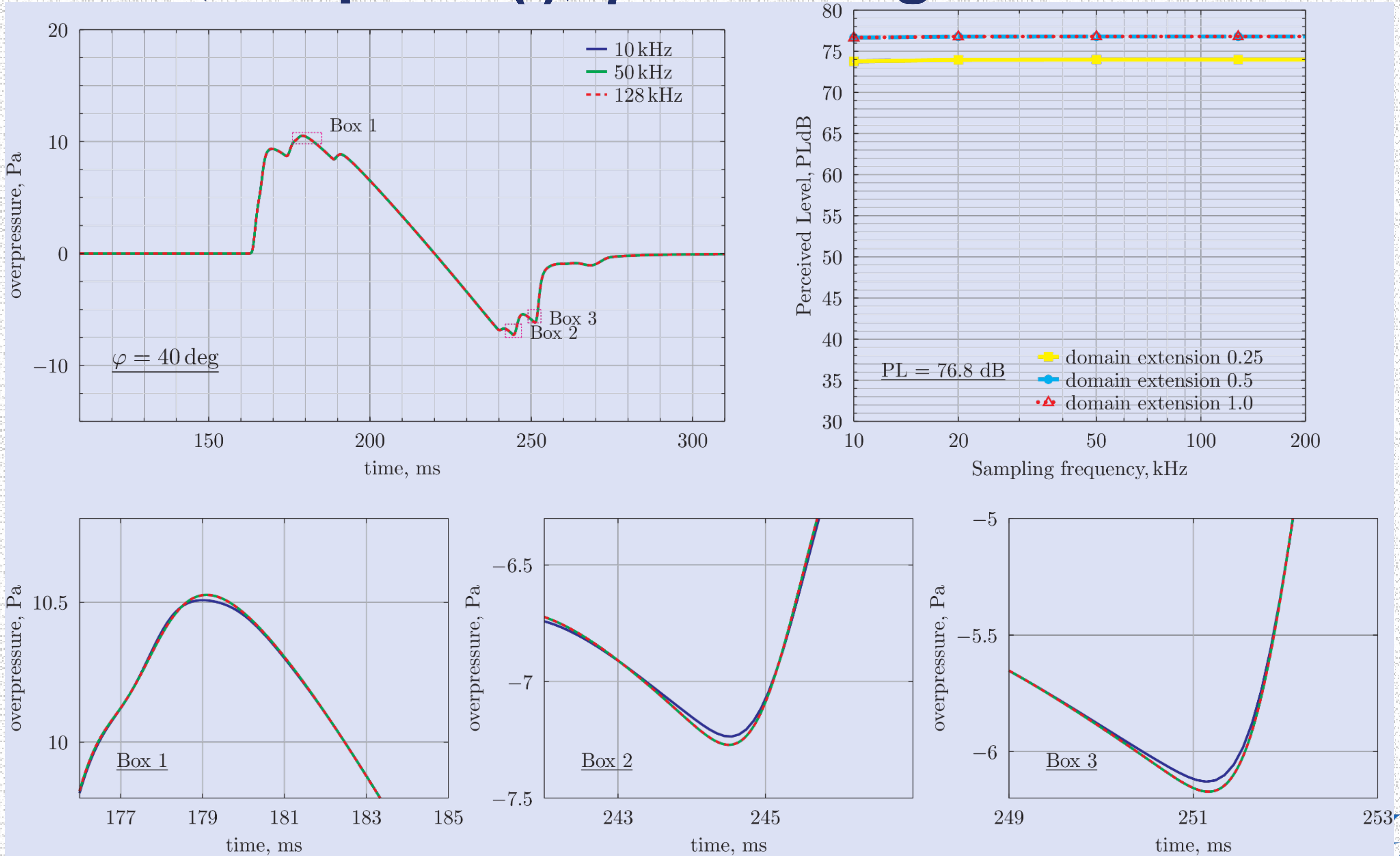
Case 2, Required(i), $\varphi = 20$ deg



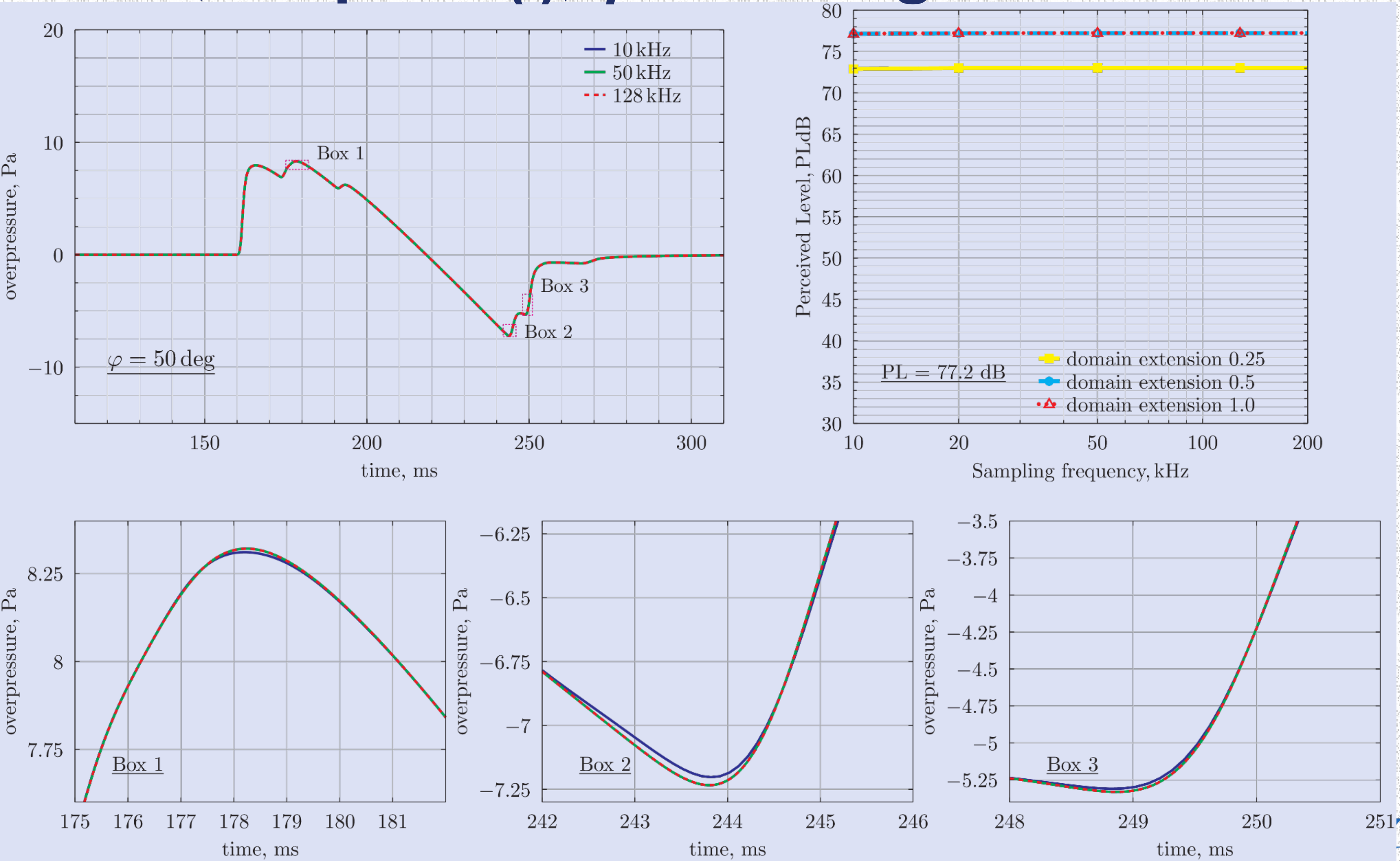
Case 2, Required(i), $\varphi = 30$ deg



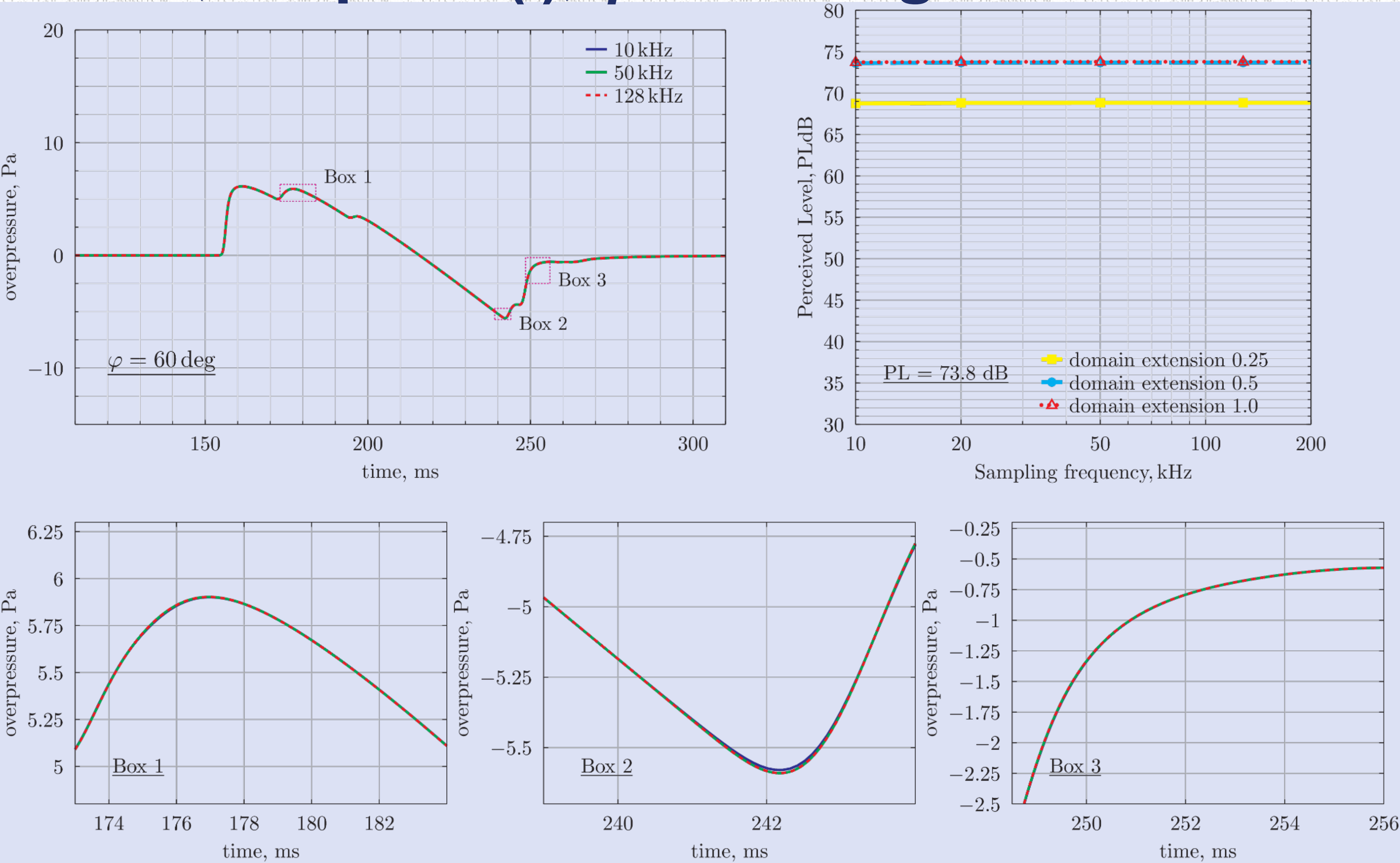
Case 2, Required(i), $\varphi = 40$ deg



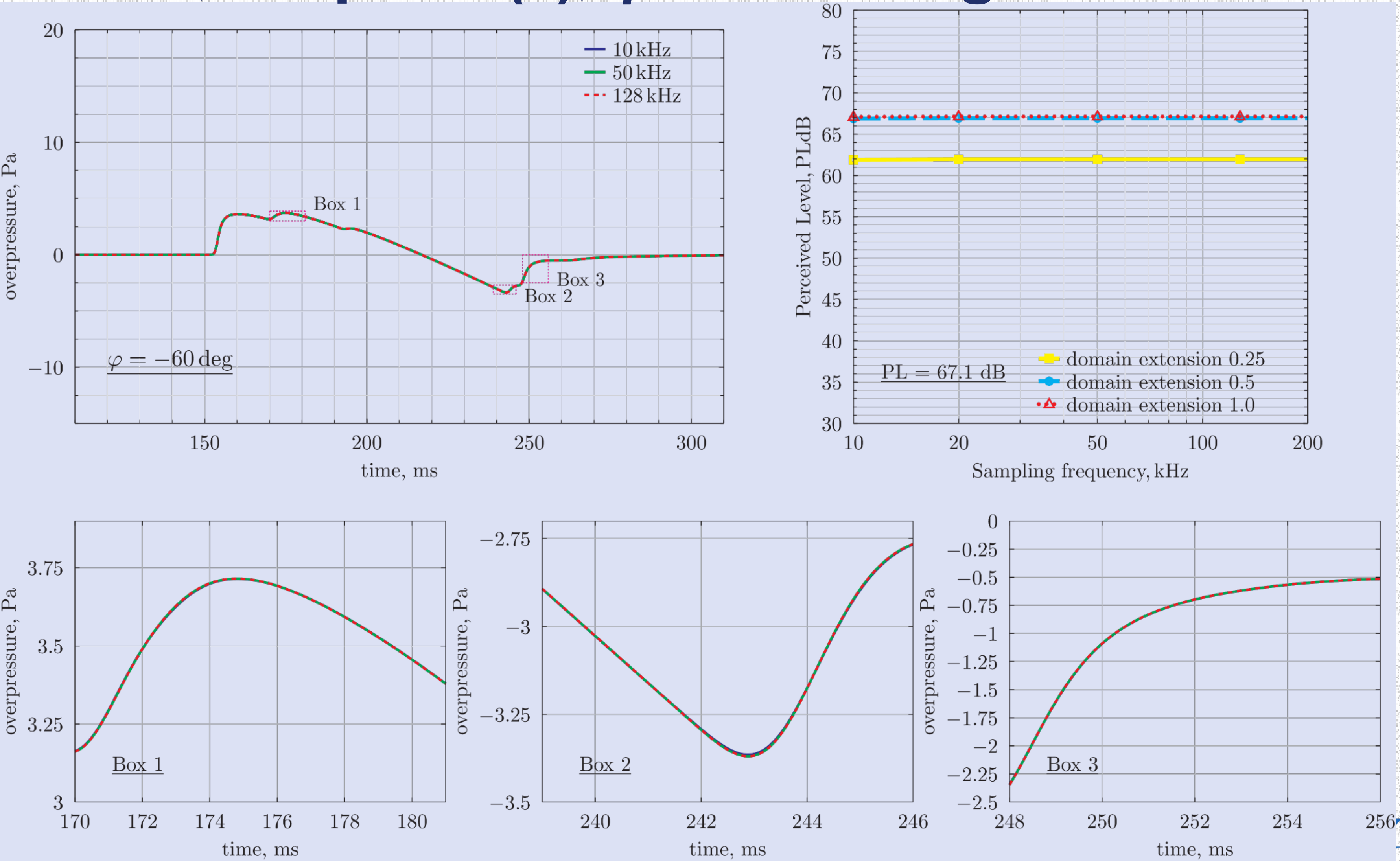
Case 2, Required(i), $\varphi = 50$ deg



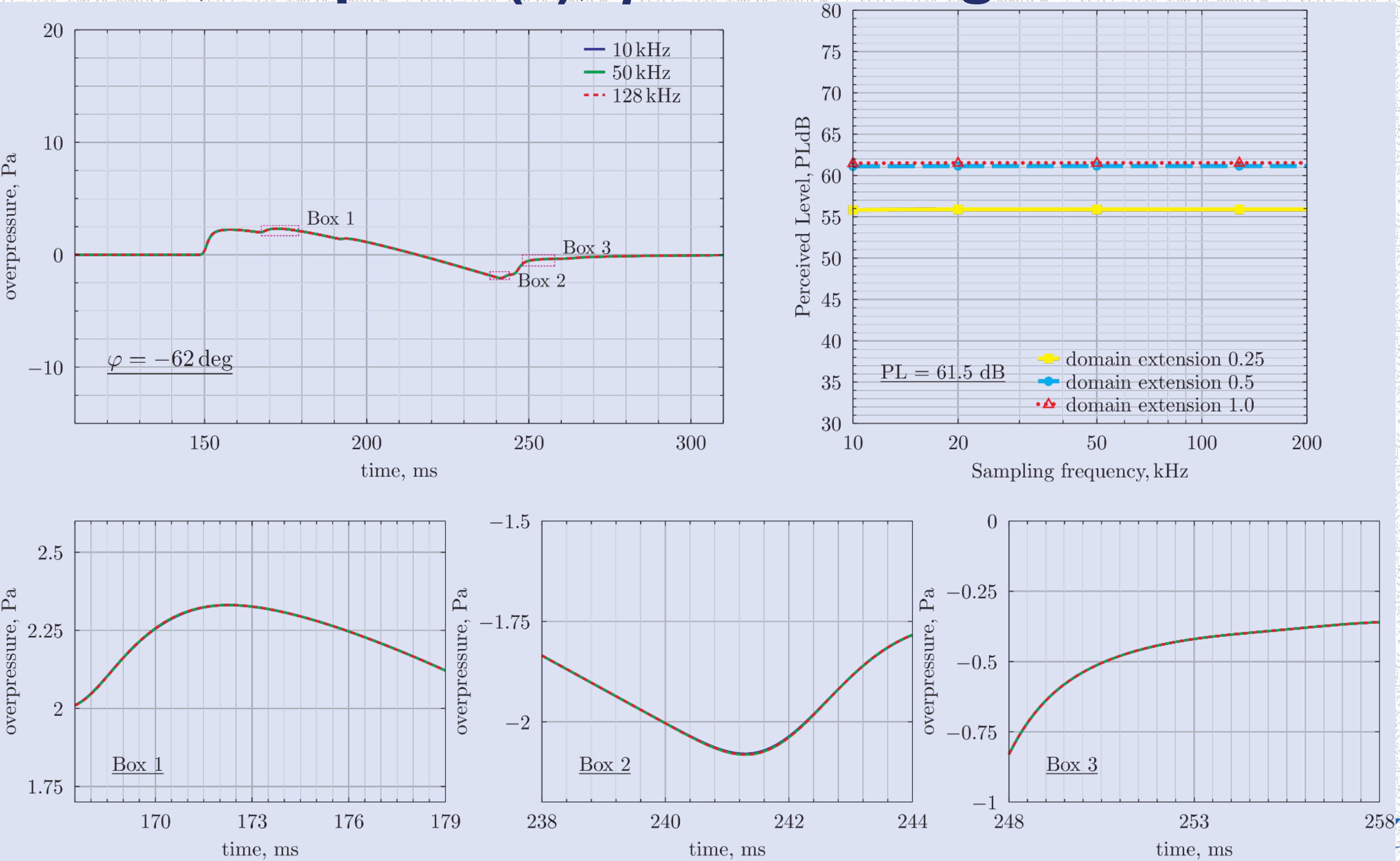
Case 2, Required(i), $\varphi = 60$ deg



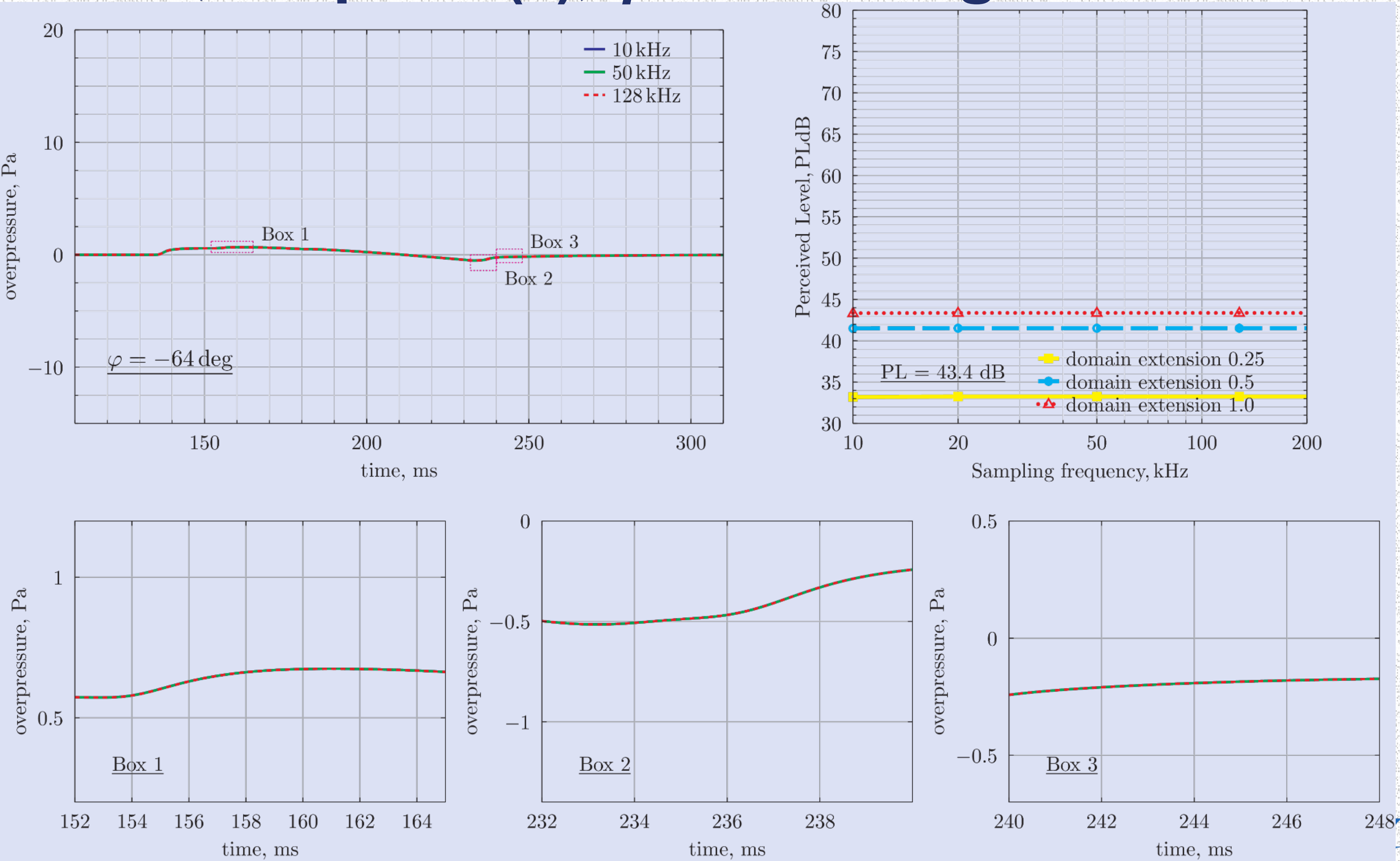
Case 2, Required(ii), $\varphi = -60$ deg



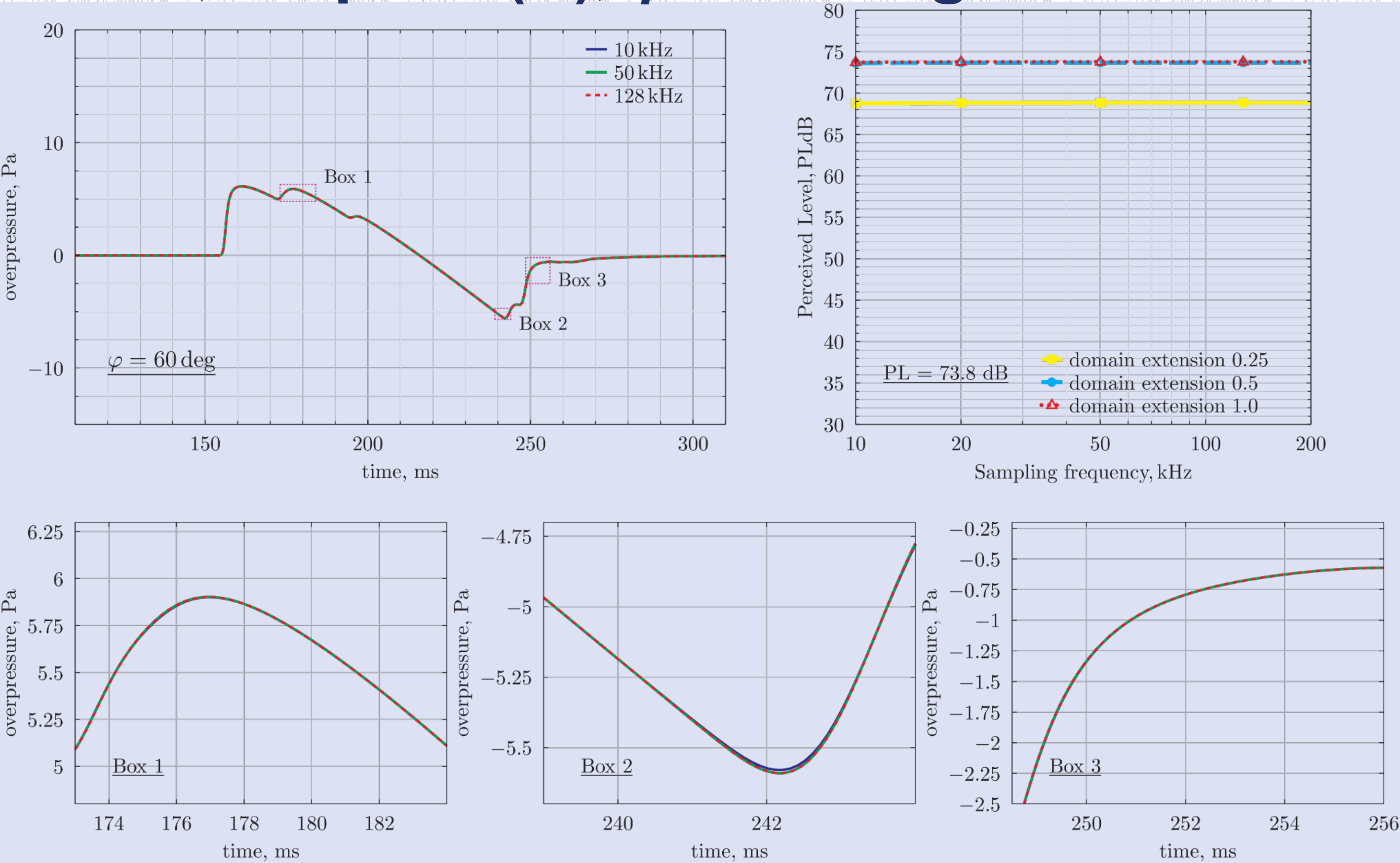
Case 2, Required(ii), $\varphi = -62$ deg



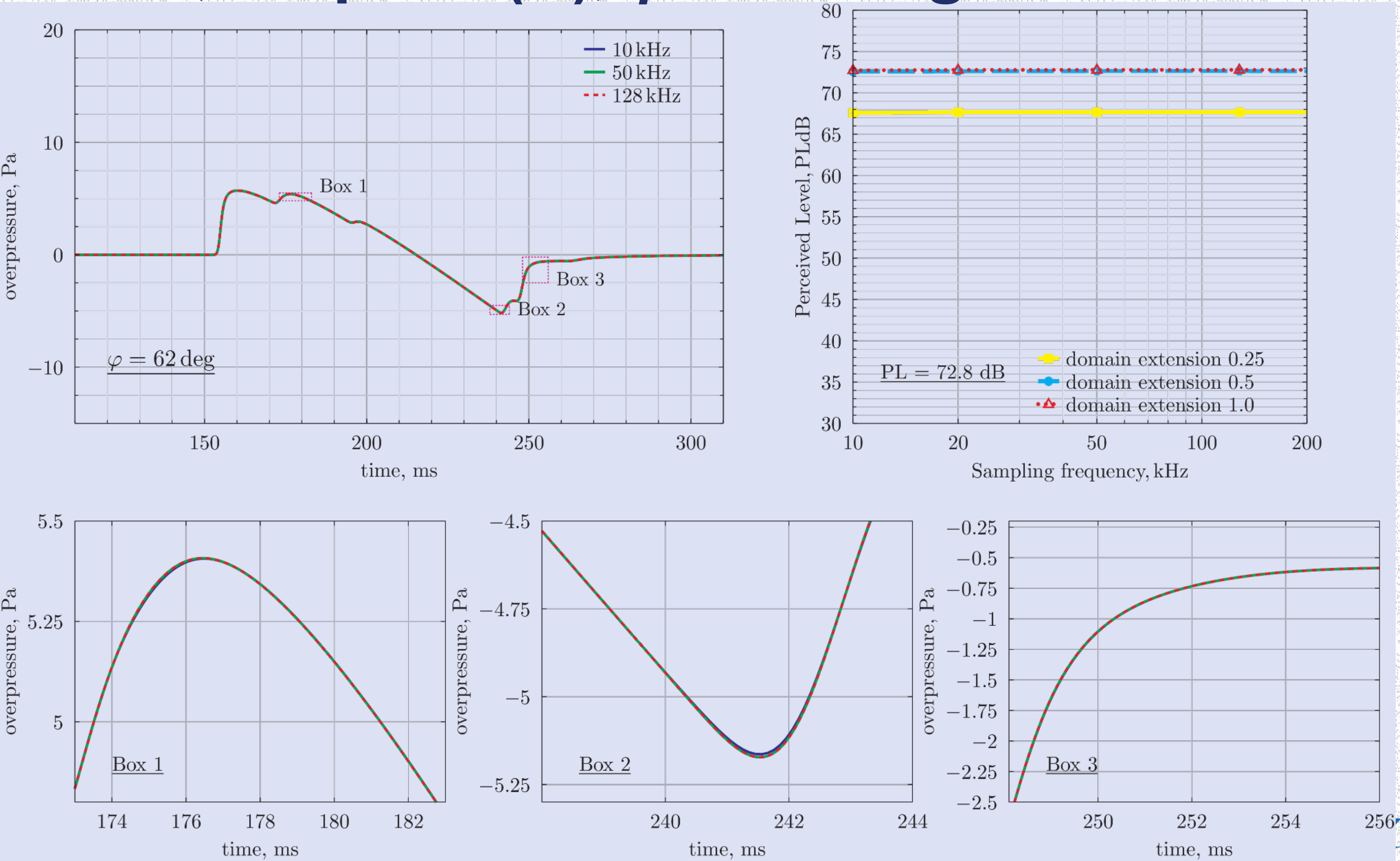
Case 2, Required(ii), $\varphi = -64$ deg



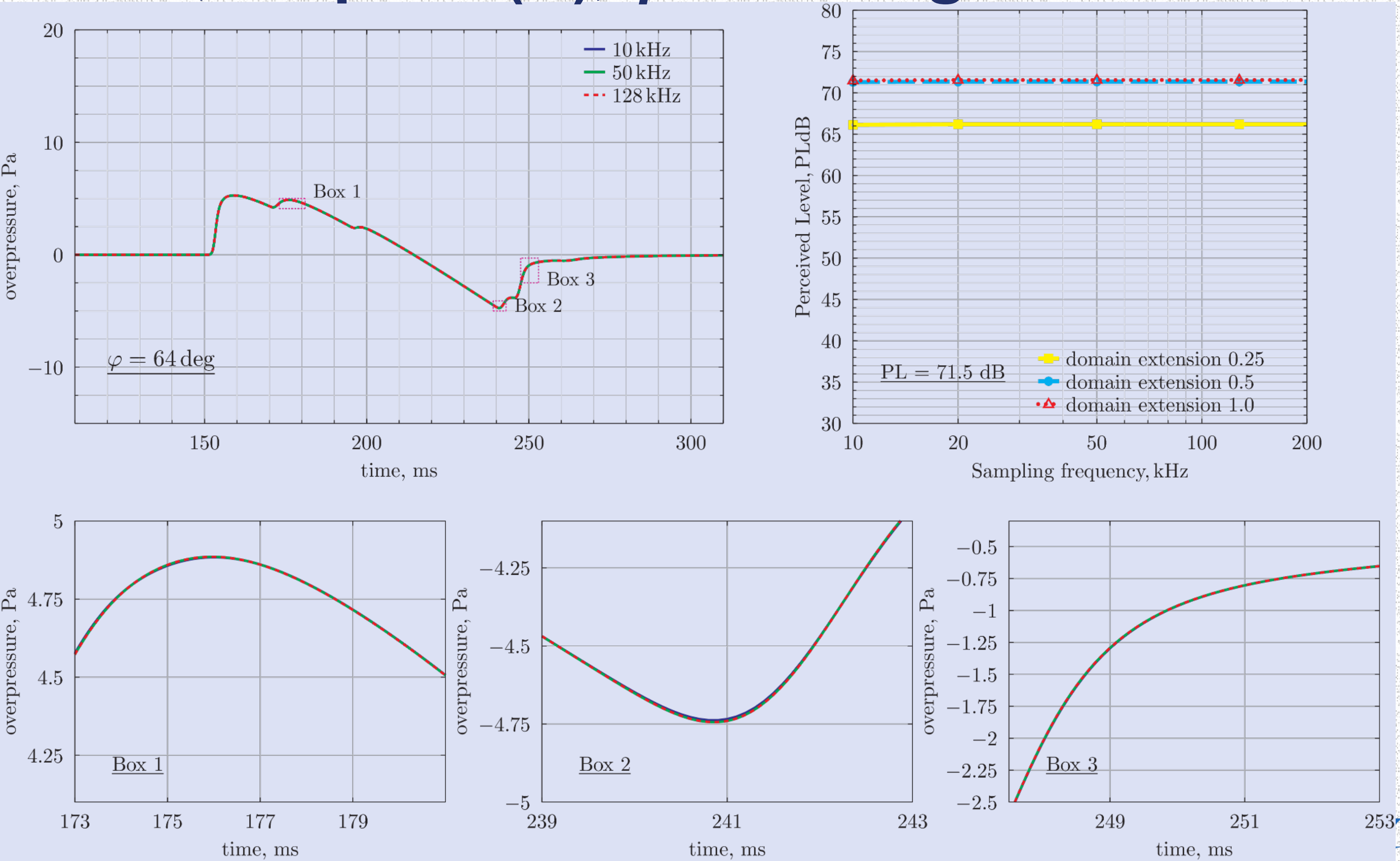
Case 2, Required(iii), $\varphi = 60$ deg



Case 2, Required(iii), $\varphi = 62$ deg

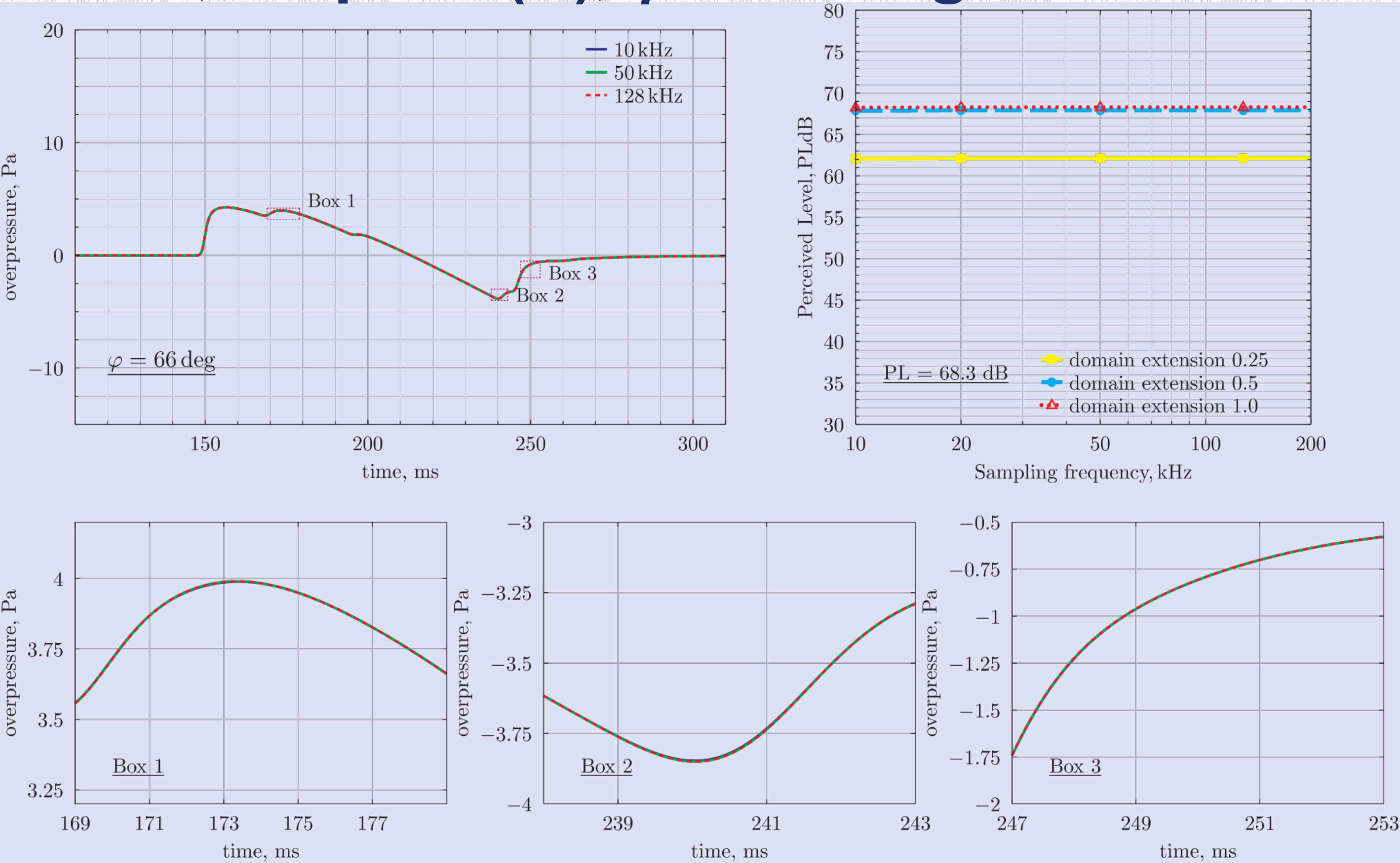


Case 2, Required(iii), $\varphi = 64$ deg

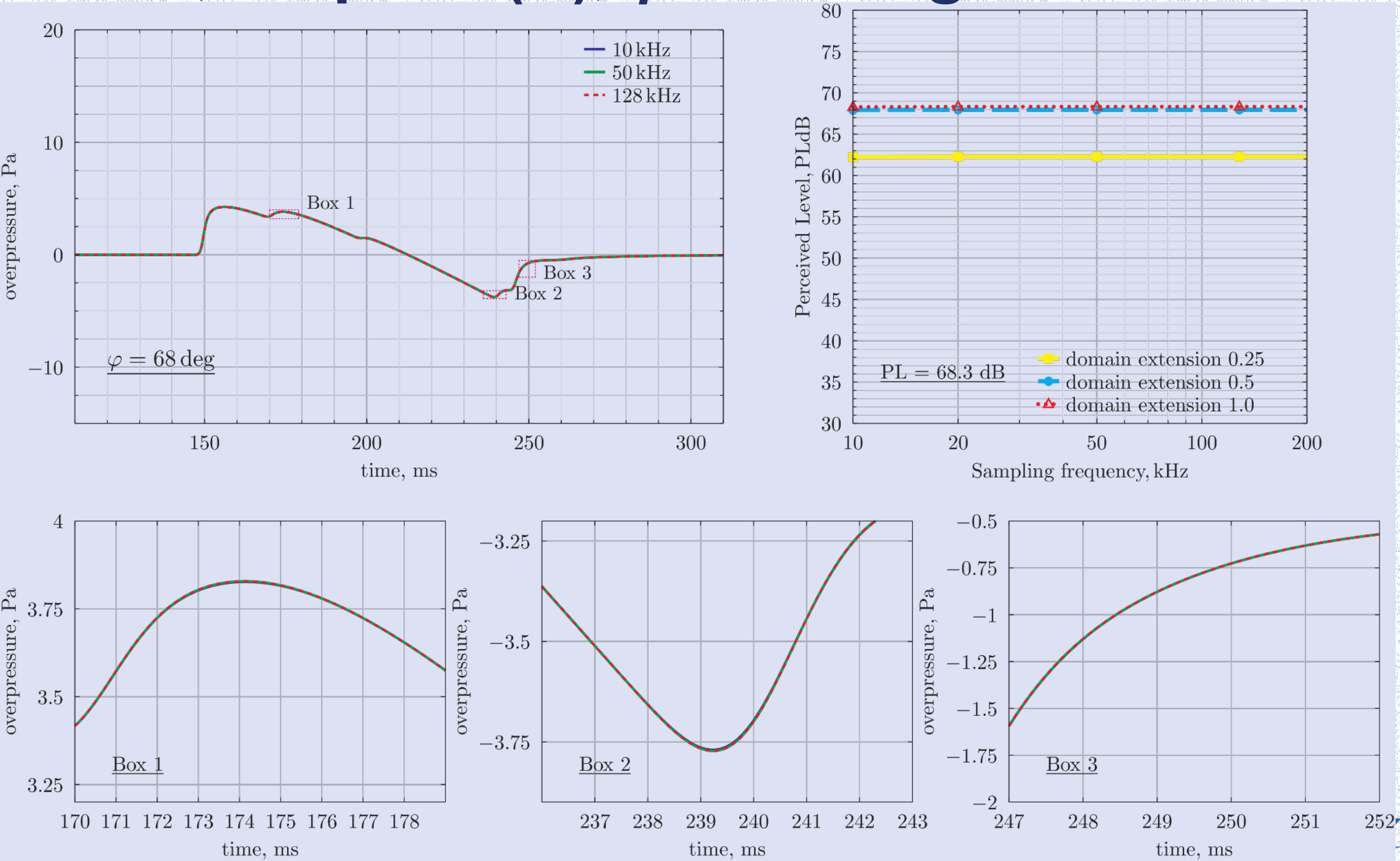


Numerical Simulation Research Unit

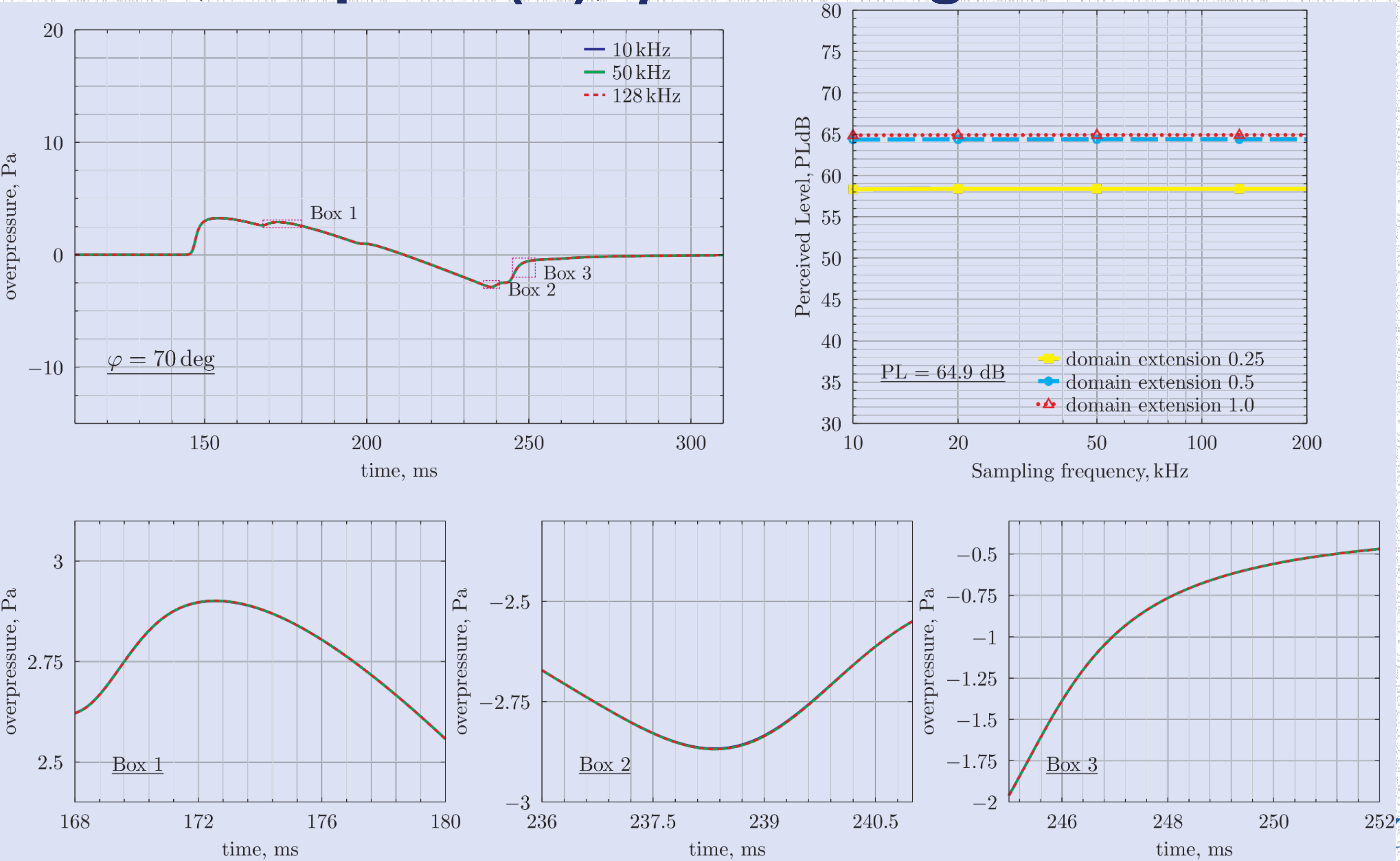
Case 2, Required(iii), $\varphi = 66$ deg



Case 2, Required(iii), $\varphi = 68$ deg



Case 2, Required(iii), $\varphi = 70$ deg



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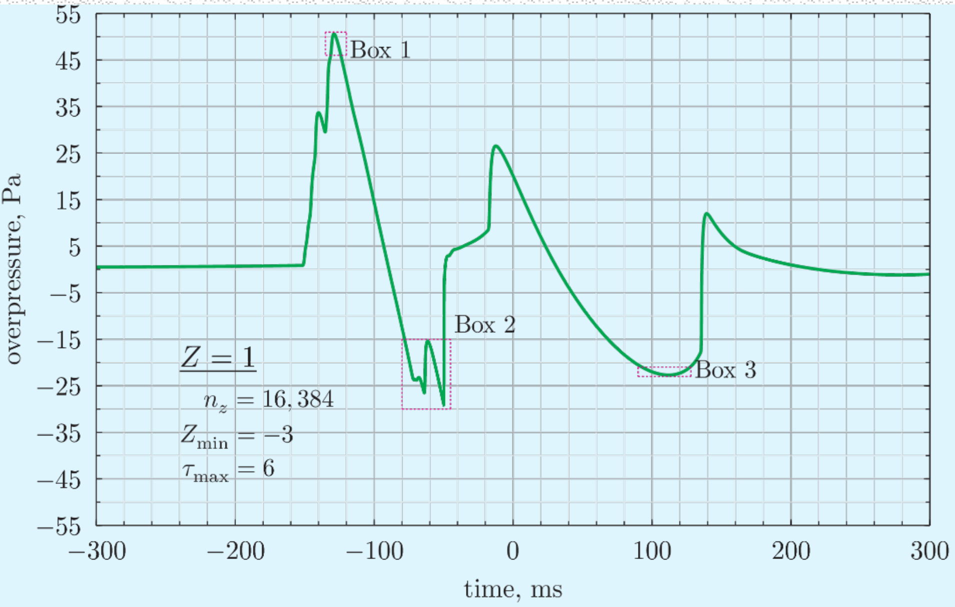
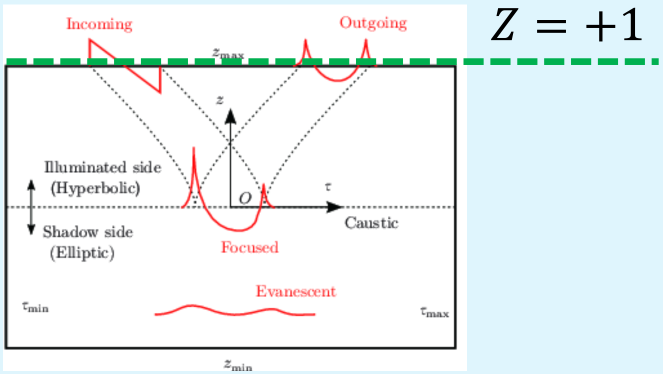
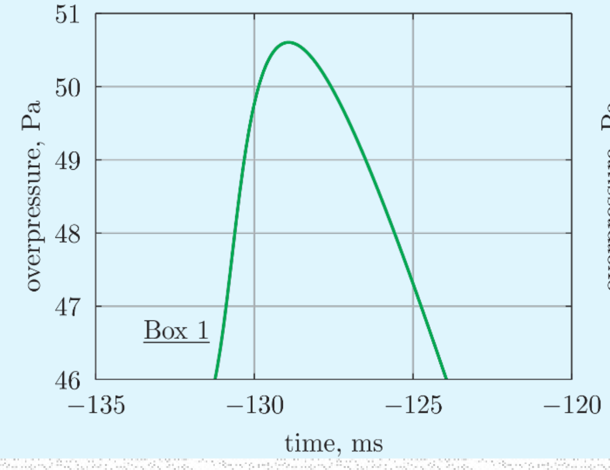
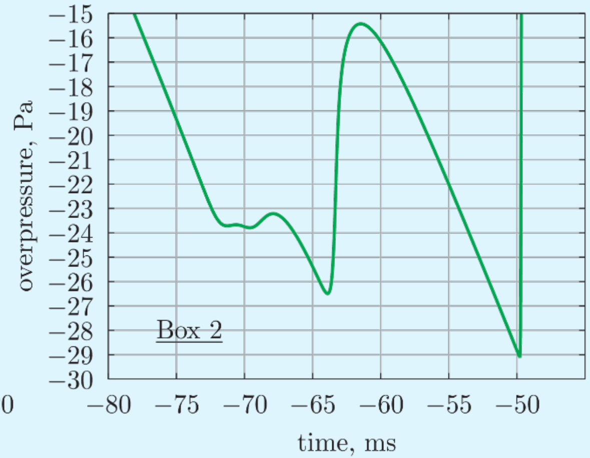
Case1, Optional, $\mathbf{n}_{\tau} = \mathbf{131,072}$

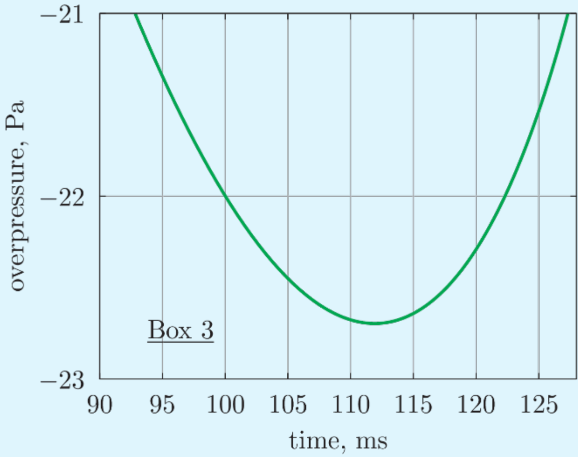


$n_\tau = 131,072$ (freq. $= 45,509$ kHz)

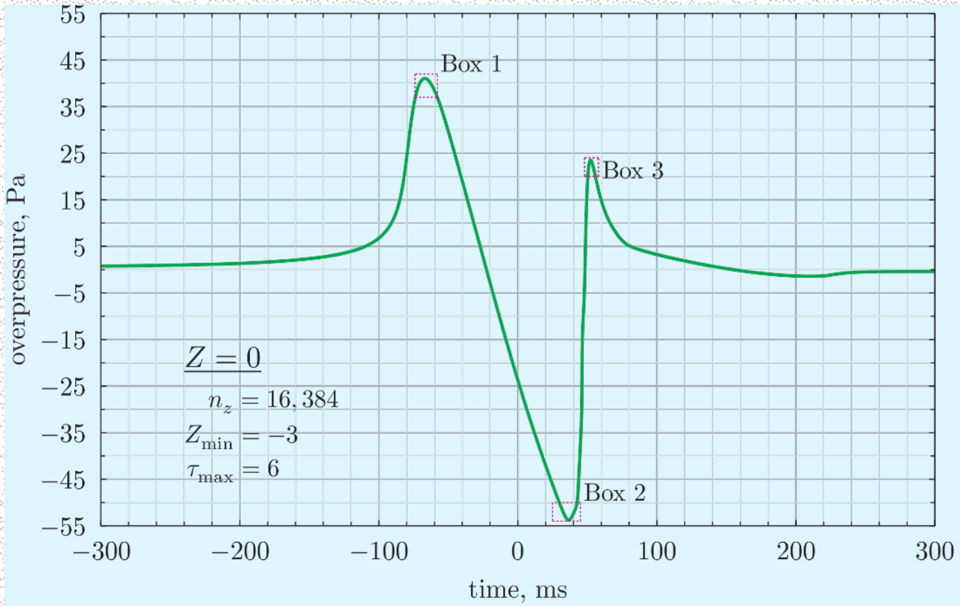


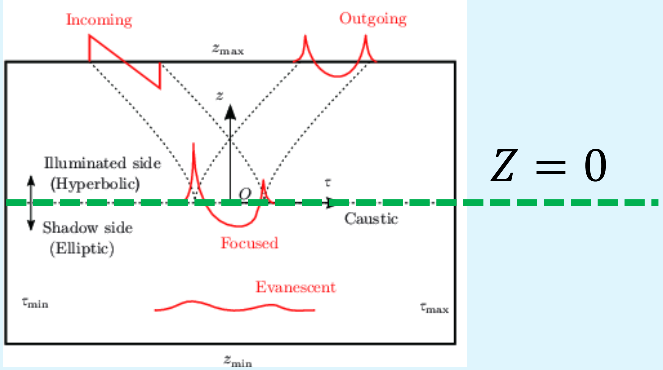


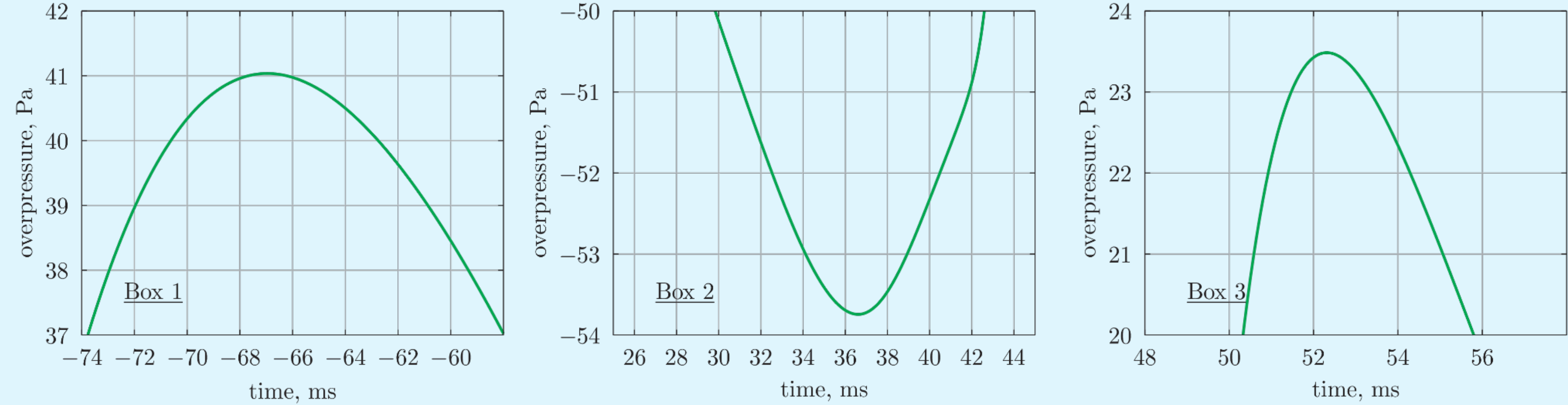




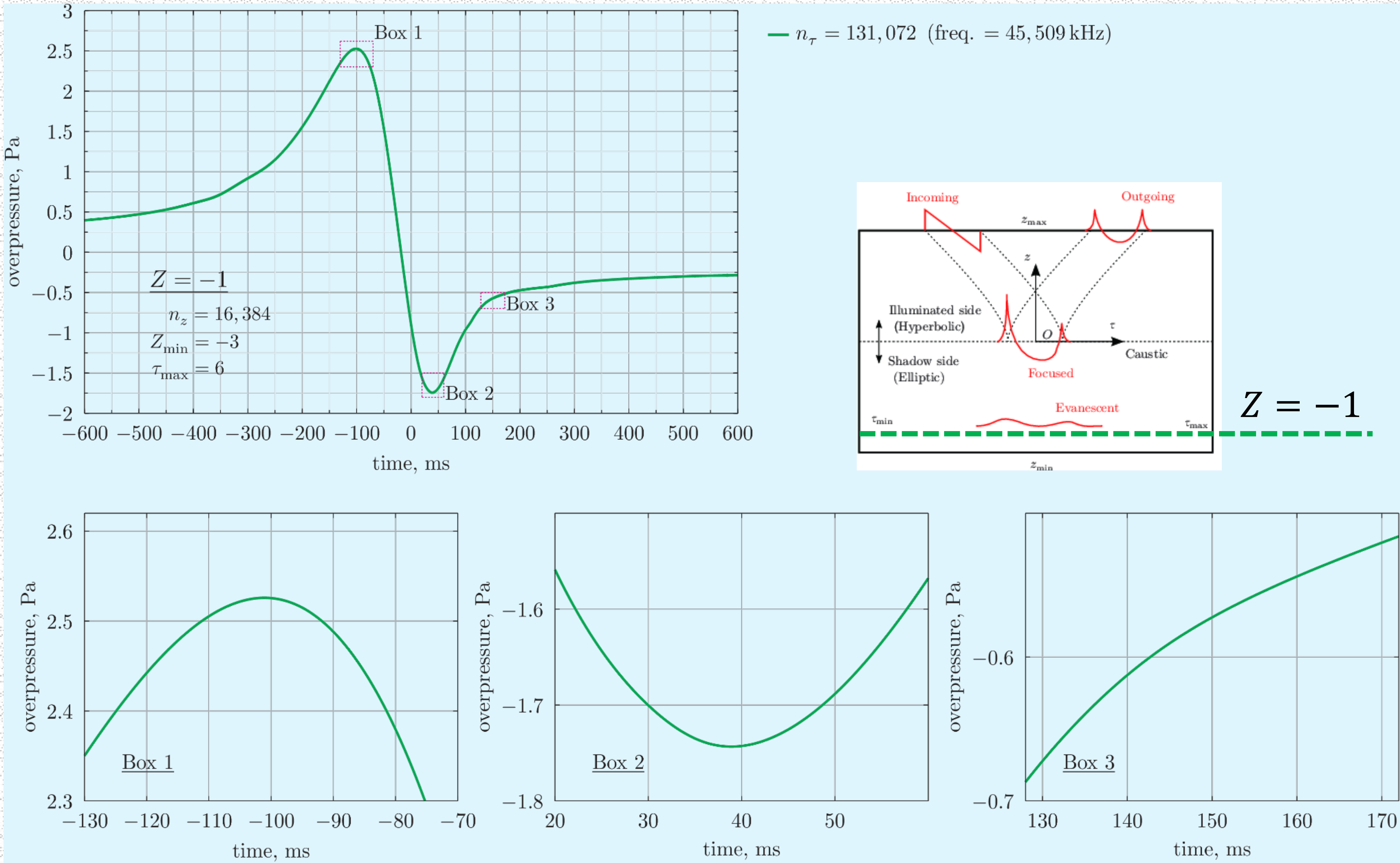
Case1, Optional, $n_\tau = 131,072$



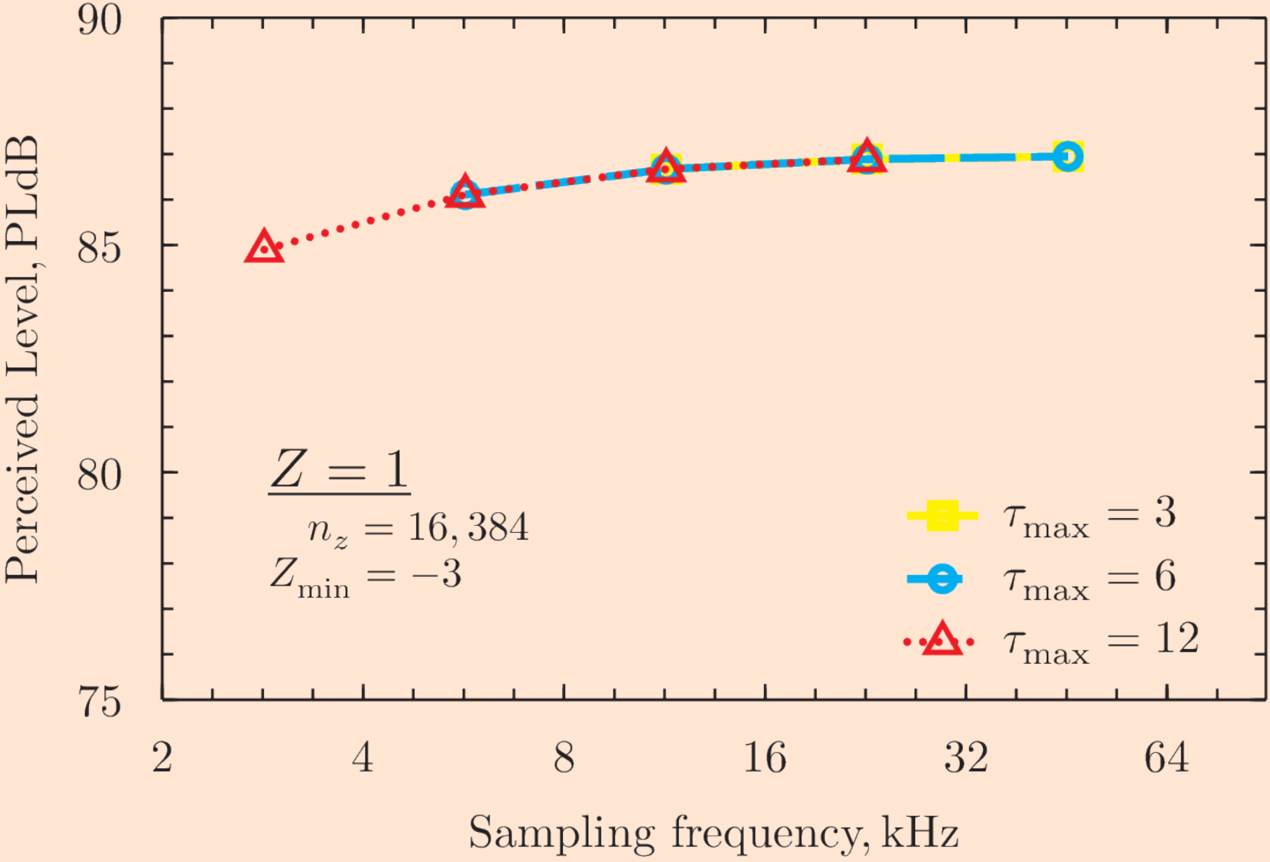




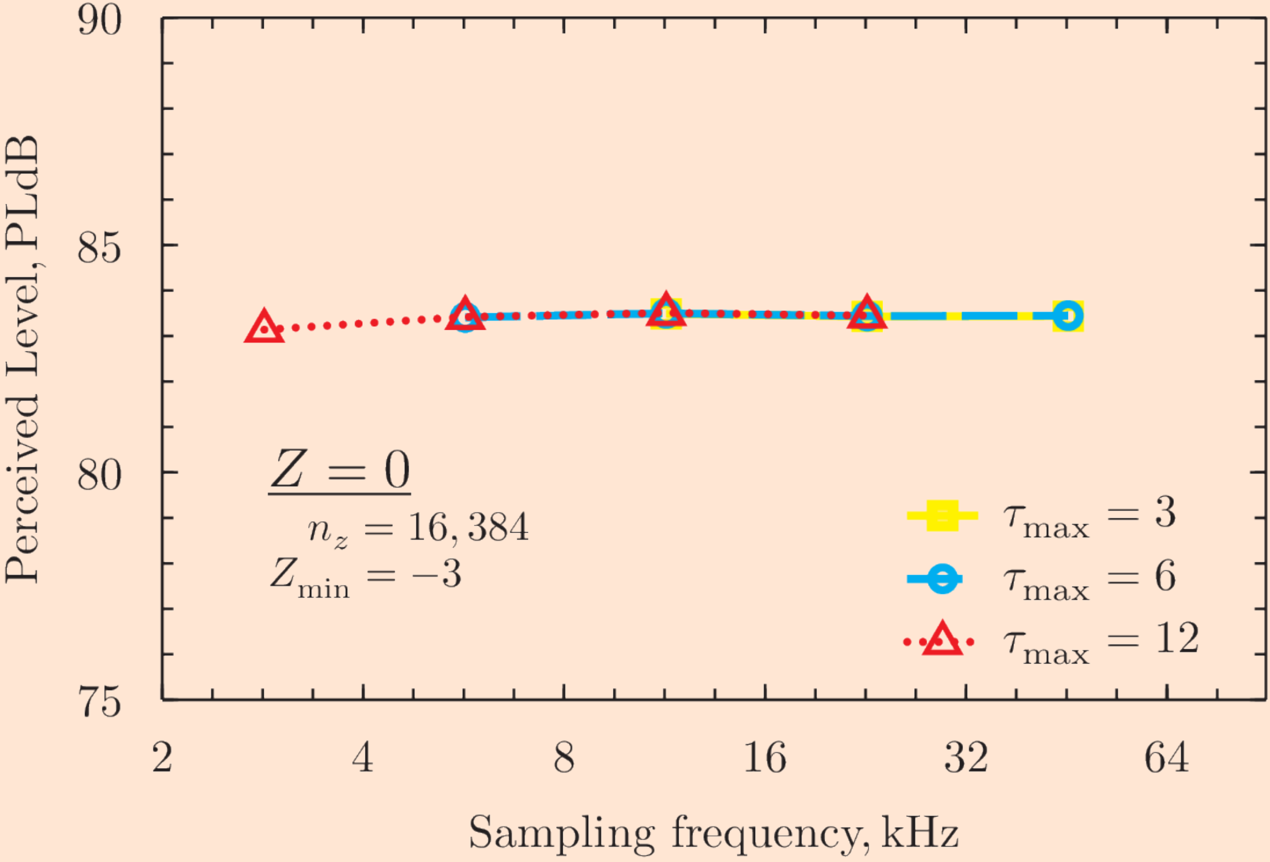
Case1, Optional, $n_\tau = 131,072$



Case1, Optional, Fixed Domain size in *Z*



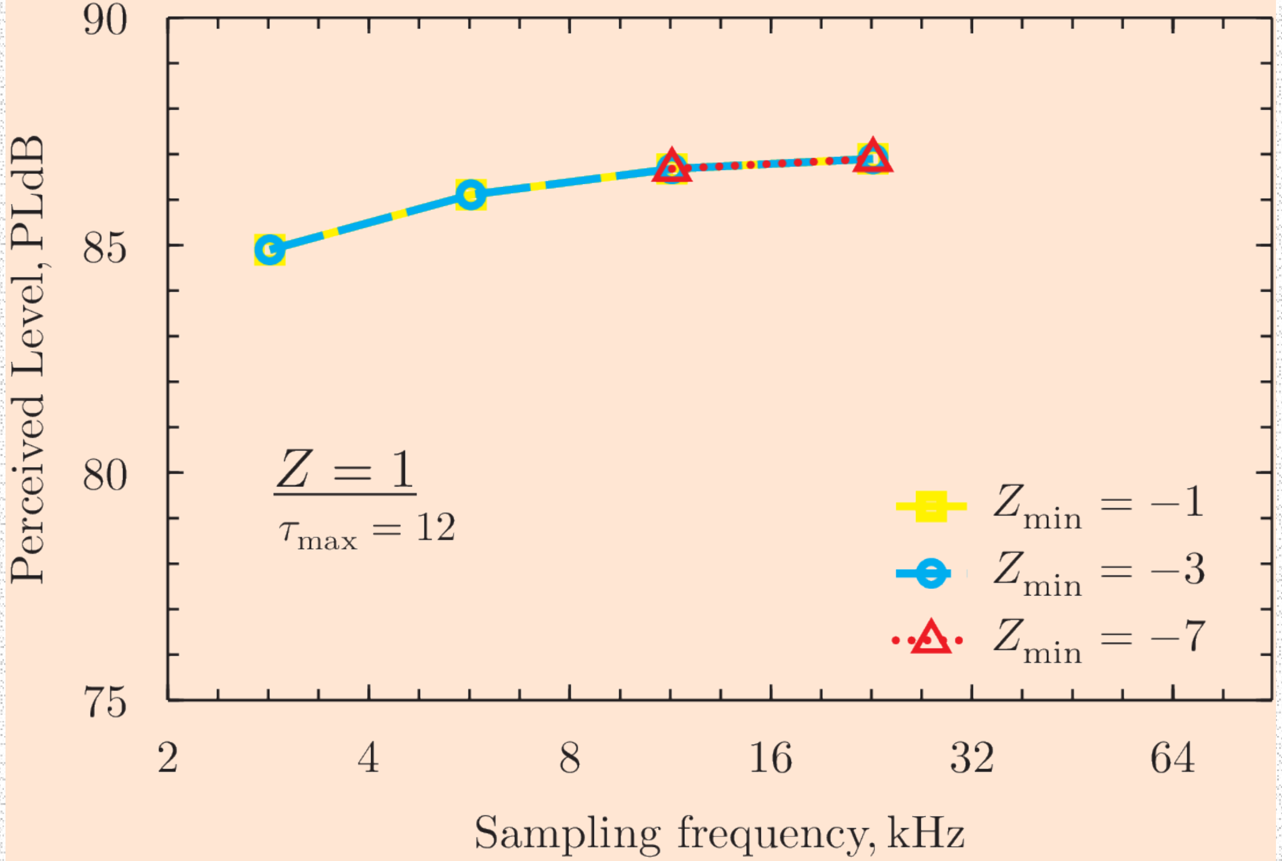
Case1, Optional, Fixed Domain size in *Z*



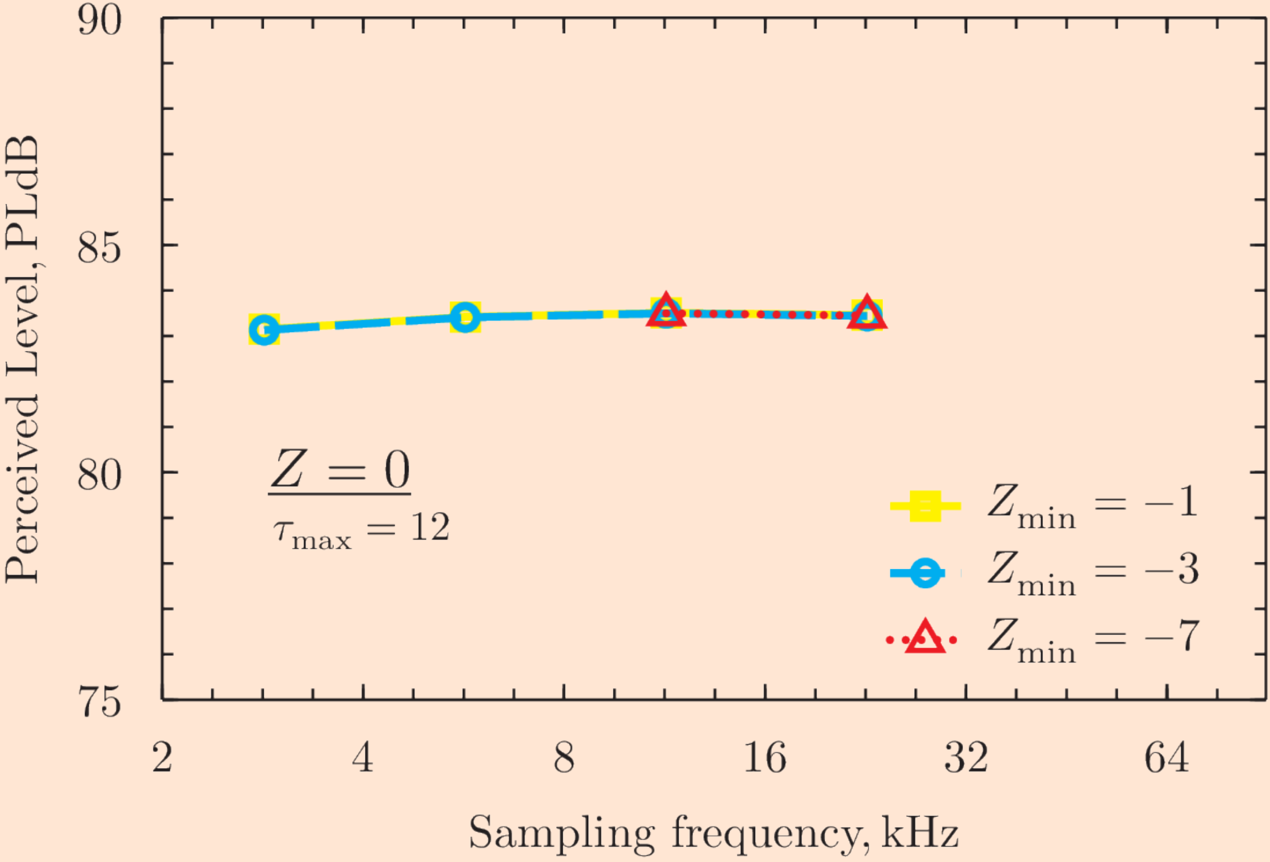
Case1, Optional, Fixed Domain size in Z

$Z = -1$, N/A

Case1, Optional, Fixed Domain size in τ



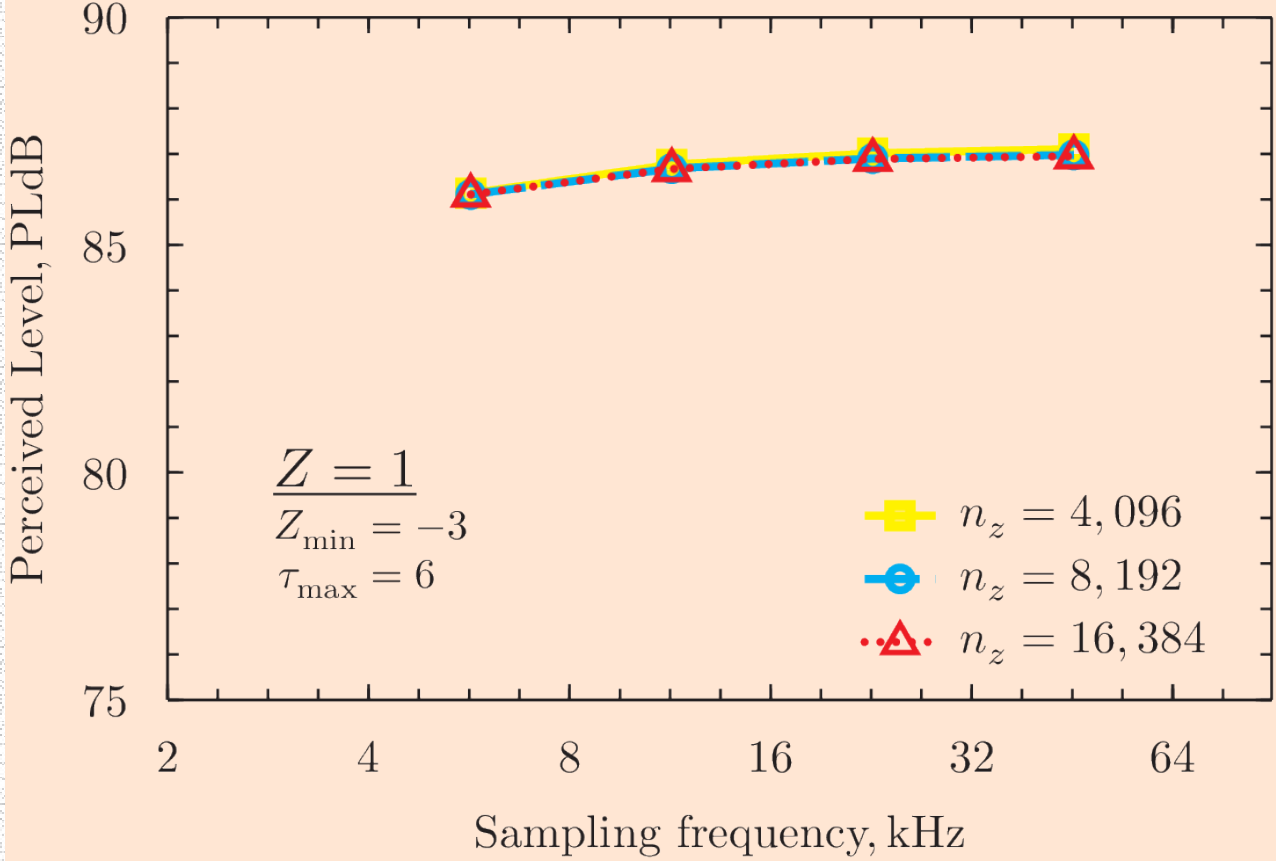
Case1, Optional, Fixed Domain size in τ



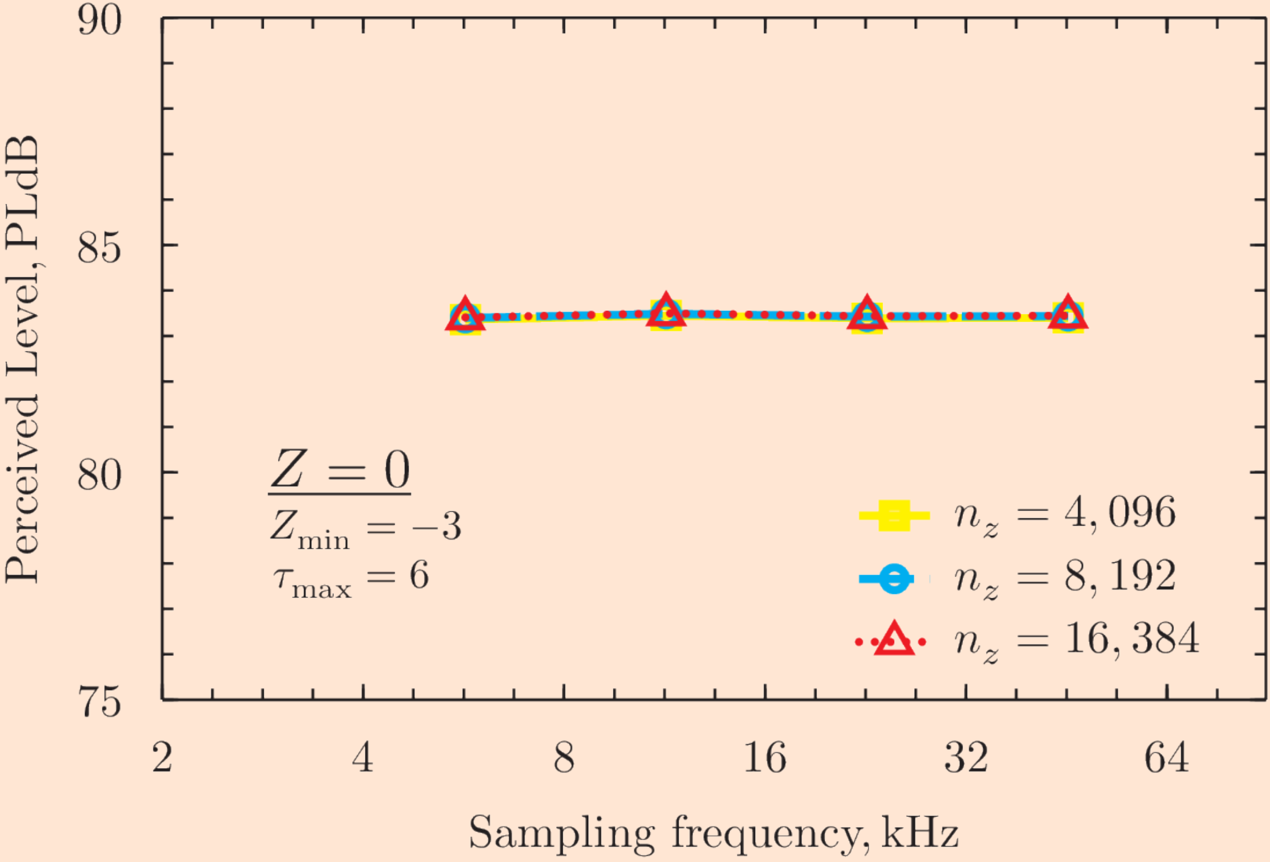
Case1, Optional, Fixed Domain size in τ

$Z = -1$, N/A

Case1, Optional, Fixed Domain size in Z and τ



Case1, Optional, Fixed Domain size in Z and τ



Case1, Optional, Fixed Domain size in Z and τ

$Z = -1$, N/A

Specifying parameters in Lossy NTE

✓2 parameters appeared in Lossy NTE: μ and ε

$$\begin{cases} \mu = 2\beta \dfrac{P_{ac}}{\rho_0 c_0^2}\left(\dfrac{R_{tot} f_{ac}}{2c_0}\right)^{2/3} \\ \varepsilon = \left(\dfrac{2c_0}{R_{tot} f_{ac}}\right)^{2/3} \end{cases}$$

$$\frac{\partial^2 P}{\partial Z^2} - Z\frac{\partial^2 P}{\partial \tau^2} + \frac{\mu}{2}\frac{\partial^2 P^2}{\partial \tau^2} + \left[\frac{\alpha}{\varepsilon^2} + \sum_\nu \frac{\theta_\nu/\varepsilon^2}{1+\tau_\nu \partial/\partial\tau}\right]\frac{\partial^3 P}{\partial \tau^3} = 0$$

P_{ac}, f_{ac} : available from incoming waveform

R_{tot} : assuming $R_{tot} = R_{cau}$

R_{cau} : obtained from the definition of δ

$$\delta = \left(\frac{c_0^2 R_{cau}}{2 f_{ac}^2}\right)^{\frac{1}{3}} \longrightarrow R_{cau} = \frac{2\delta^3 f_{ac}^2}{c_0^2}$$

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