Contrast Source Inversion Using Iterative Multi-Scaling BCS

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2025/04/11

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1 Numerical Analysis: Inhomogeneous Square Object, $\ell = 1.5\lambda$

Test Case Description

Direct solver:

- Side of the investigation domain: $L = 6.0\lambda$
- Cubic domain divided in $\sqrt{D} \times \sqrt{D}$ cells
- Number of cells for the direct solver: $D = 1600$ (discretization $= \lambda/10$)

Investigation domain:

- Cubic domain divided in $\sqrt{N} \times \sqrt{N}$ cells
- Number of cells for the inversion:

  - First Step IMSA: $N^{(1)} = 100$ (discretization $= \lambda/10$)

  - Following Steps IMSA: $N^{(i)}$ not fixed, defined according to the estimated *RoI* $\mathcal{D}^{(i)}$

Measurement domain:

- Total number of measurements: $M = 60$
- Measurement points placed on circles of radius $\rho = 4.5\lambda$

Sources:

- Plane waves
- Number of views: $V = 60$; $\theta_{inc}^{v} = 0 + (v-1) \times (360/V)$
- Amplitude: $A = 1.0$
- Frequency: $F = 300$ MHz ($\lambda = 1$)

Background:

- $\varepsilon_r = 1.0$
- $\sigma = 0$ [S/m]

Scatterer

- Inhomogeneous square object, $\ell = 1.5\lambda$
- $\varepsilon_r^{(1)} \in \{1.20,\ 1.60,\ 2.00\}$ (internal circle)
  $\varepsilon_r^{(2)} = \frac{\varepsilon_r^{(1)}}{2}$ (central circle)
  $\varepsilon_r^{(3)} = \frac{\varepsilon_r^{(1)}}{4}$ (external circle)
- $\sigma = 0$ [S/m]

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1.0.1 Inhomogeneous Square Object, $\ell = 1.5\lambda$, $\tau^{(1)} = 0.20$ - IMSA-BCS reconstructed profiles

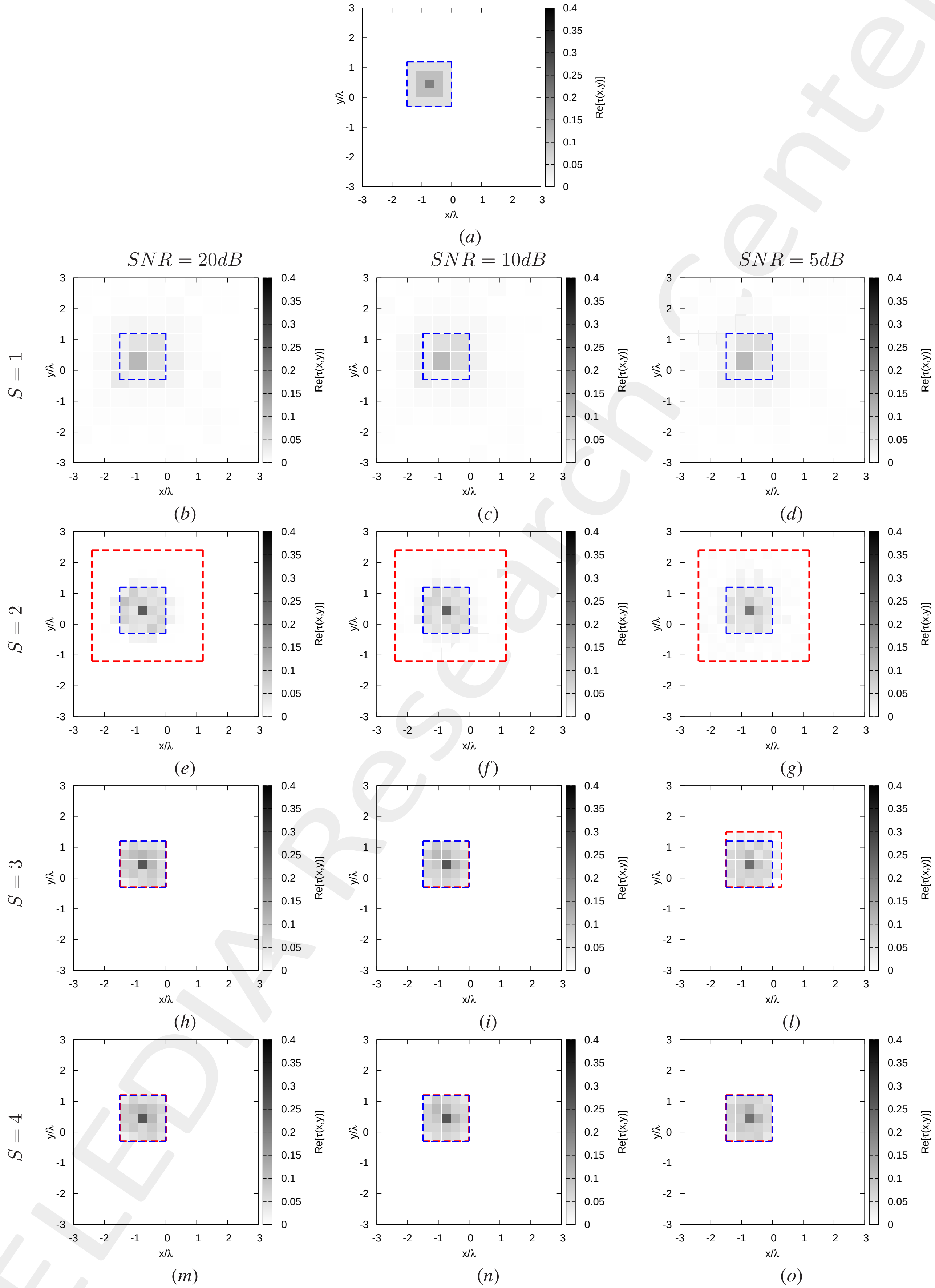

Figure 1: *Inhomogeneous Square Object,* $\ell = 1.5\lambda$, $\tau^{(1)} = 0.20$ - (a) Actual profile and (b)-(o) IMSA-BCS reconstructed profiles for $(b)(e)(h)(m)$ $SNR = 20$ [dB], $(c)(f)(i)(n)$ $SNR = 10$ [dB] and $(d)(g)(l)(o)$ $SNR = 5$ [dB] at the step (b)-(d) $S = 1$, (e)-(g) $S = 2$, (h)-(l) $S = 3$ and (m)-(o) $S = 4$.

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	$SNR = 50dB$			
	$S=1$	$S=2$	$S=3$	$S=4$
ξ_{tot}	5.47×10^{-3}	2.42×10^{-3}	1.25×10^{-3}	1.25×10^{-3}
ξ_{int}	2.14×10^{-2}	2.39×10^{-2}	1.82×10^{-2}	1.82×10^{-2}
ξ_{ext}	4.20×10^{-3}	7.85×10^{-4}	0.00×10^{-1}	0.00×10^{-1}
	$SNR = 20dB$			
	$S=1$	$S=2$	$S=3$	$S=4$
ξ_{tot}	5.59×10^{-3}	2.45×10^{-3}	1.10×10^{-3}	1.10×10^{-3}
ξ_{int}	2.27×10^{-2}	2.51×10^{-2}	1.52×10^{-2}	1.52×10^{-2}
ξ_{ext}	4.21×10^{-3}	7.56×10^{-4}	0.00×10^{-1}	0.00×10^{-1}
	$SNR = 10dB$			
	$S=1$	$S=2$	$S=3$	$S=4$
ξ_{tot}	5.64×10^{-3}	2.30×10^{-3}	1.14×10^{-3}	1.14×10^{-3}
ξ_{int}	2.21×10^{-2}	2.08×10^{-2}	1.68×10^{-2}	1.68×10^{-2}
ξ_{ext}	4.25×10^{-3}	8.86×10^{-4}	0.00×10^{-1}	0.00×10^{-1}
	$SNR = 5dB$			
	$S=1$	$S=2$	$S=3$	$S=4$
ξ_{tot}	6.18×10^{-3}	2.91×10^{-3}	1.59×10^{-3}	1.07×10^{-3}
ξ_{int}	2.37×10^{-2}	2.07×10^{-2}	1.68×10^{-2}	1.59×10^{-2}
ξ_{ext}	4.51×10^{-3}	1.44×10^{-3}	4.60×10^{-4}	0.00×10^{-1}

Table I: *Inhomogeneous Square Object,* $\ell = 1.5\lambda$, $\tau^{(1)} = 0.20$ - Reconstrution errors: total (ξ_{tot}), internal (ξ_{int}) and external (ξ_{ext}) errors.

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	$SNR = 50dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
$L^{(S)}$	6.00	1.50	1.50	1.50
$N^{(S)}$	100	208	208	208
$Q^{(S)}$	100	144	25	25

	$SNR = 20dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
$L^{(S)}$	6.00	1.50	1.50	1.50
$N^{(S)}$	100	208	208	208
$Q^{(S)}$	100	144	25	25

	$SNR = 10dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
$L^{(S)}$	6.00	1.50	1.50	1.50
$N^{(S)}$	100	208	208	208
$Q^{(S)}$	100	144	25	25

	$SNR = 5dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
$L^{(S)}$	6.00	1.50	1.50	1.50
$N^{(S)}$	100	208	208	208
$Q^{(S)}$	100	144	36	25

Table II: *Inhomogeneous Square Object,* $\ell = 1.5\lambda$, $\tau^{(1)} = 0.20$ - Investigation domain parameters: restricted investigation domain size $L^{(S)}$, total number of cells $N^{(S)}$ and number of cells within the restricted domain size $Q^{(S)}$.

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1.0.2 Inhomogeneous Square Object, $\ell = 1.5\lambda$, $\tau^{(1)} = 0.60$ - IMSA-BCS reconstructed profiles

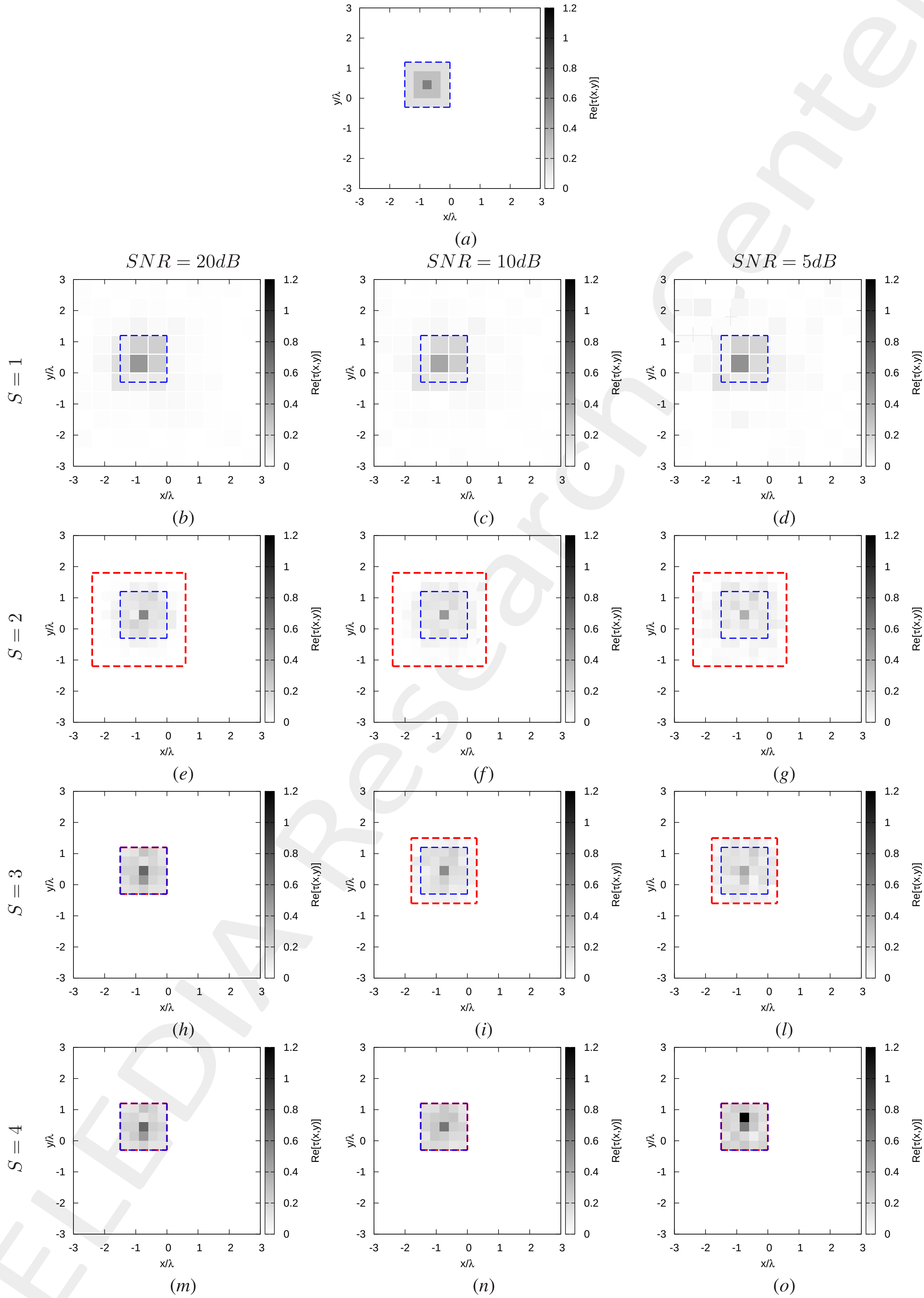

Figure 2: *Inhomogeneous Square Object*, $\ell = 1.5\lambda$, $\tau^{(1)} = 0.60$ - (a) Actual profile and (b)-(o) IMSA-BCS reconstructed profiles for $(b)(e)(h)(m)$ $SNR = 20$ [dB], $(c)(f)(i)(n)$ $SNR = 10$ [dB] and $(d)(g)(l)(o)$ $SNR = 5$ [dB] at the step (b)-(d) $S = 1$, (e)-(g) $S = 2$, (h)-(l) $S = 3$ and (m)-(o) $S = 4$.

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	$SNR = 50dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
ξ_{tot}	1.80×10^{-2}	7.90×10^{-3}	3.32×10^{-3}	3.32×10^{-3}
ξ_{int}	6.63×10^{-2}	5.48×10^{-2}	4.14×10^{-2}	4.14×10^{-2}
ξ_{ext}	1.23×10^{-2}	3.14×10^{-3}	0.00×10^{-1}	0.00×10^{-1}
	$SNR = 20dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
ξ_{tot}	1.81×10^{-2}	8.36×10^{-3}	3.81×10^{-3}	3.81×10^{-3}
ξ_{int}	6.29×10^{-2}	6.00×10^{-2}	5.05×10^{-2}	5.05×10^{-2}
ξ_{ext}	1.28×10^{-2}	3.22×10^{-3}	0.00×10^{-1}	0.00×10^{-1}
	$SNR = 10dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
ξ_{tot}	1.82×10^{-2}	1.00×10^{-2}	7.37×10^{-3}	2.77×10^{-3}
ξ_{int}	5.83×10^{-2}	7.12×10^{-2}	5.45×10^{-2}	3.40×10^{-2}
ξ_{ext}	1.31×10^{-2}	4.69×10^{-3}	2.97×10^{-3}	0.00×10^{-1}
	$SNR = 5dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
ξ_{tot}	2.17×10^{-2}	1.40×10^{-2}	8.96×10^{-3}	1.06×10^{-2}
ξ_{int}	6.70×10^{-2}	8.94×10^{-2}	6.31×10^{-2}	1.38×10^{-1}
ξ_{ext}	1.48×10^{-2}	6.64×10^{-3}	4.04×10^{-3}	0.00×10^{-1}

Table III: *Inhomogeneous Square Object,* $\ell = 1.5\lambda$, $\tau^{(1)} = 0.60$ - Reconstrution errors: total (ξ_{tot}), internal (ξ_{int}) and external (ξ_{ext}) errors.

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	$SNR=50dB$			
	$S=1$	$S=2$	$S=3$	$S=4$
$L^{(S)}$	6.00	1.50	1.50	1.50
$N^{(S)}$	100	175	175	175
$Q^{(S)}$	100	100	25	25
	$SNR=20dB$			
	$S=1$	$S=2$	$S=3$	$S=4$
$L^{(S)}$	6.00	1.50	1.50	1.50
$N^{(S)}$	100	175	175	175
$Q^{(S)}$	100	100	25	25
	$SNR=10dB$			
	$S=1$	$S=2$	$S=3$	$S=4$
$L^{(S)}$	6.00	1.50	1.50	1.50
$N^{(S)}$	100	175	175	175
$Q^{(S)}$	100	100	49	25
	$SNR=5dB$			
	$S=1$	$S=2$	$S=3$	$S=4$
$L^{(S)}$	6.00	1.50	1.20	1.20
$N^{(S)}$	100	175	175	175
$Q^{(S)}$	100	100	49	25

Table IV: *Inhomogeneous Square Object,* $\ell = 1.5\lambda$, $\tau^{(1)} = 0.60$ - Investigation domain parameters: restricted investigation domain size $L^{(S)}$, total number of cells $N^{(S)}$ and number of cells within the restricted domain size $Q^{(S)}$.

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1.0.3 Inhomogeneous Square Object, $\ell = 1.5\lambda$, $\tau^{(1)} = 1.00$ - IMSA-BCS reconstructed profiles

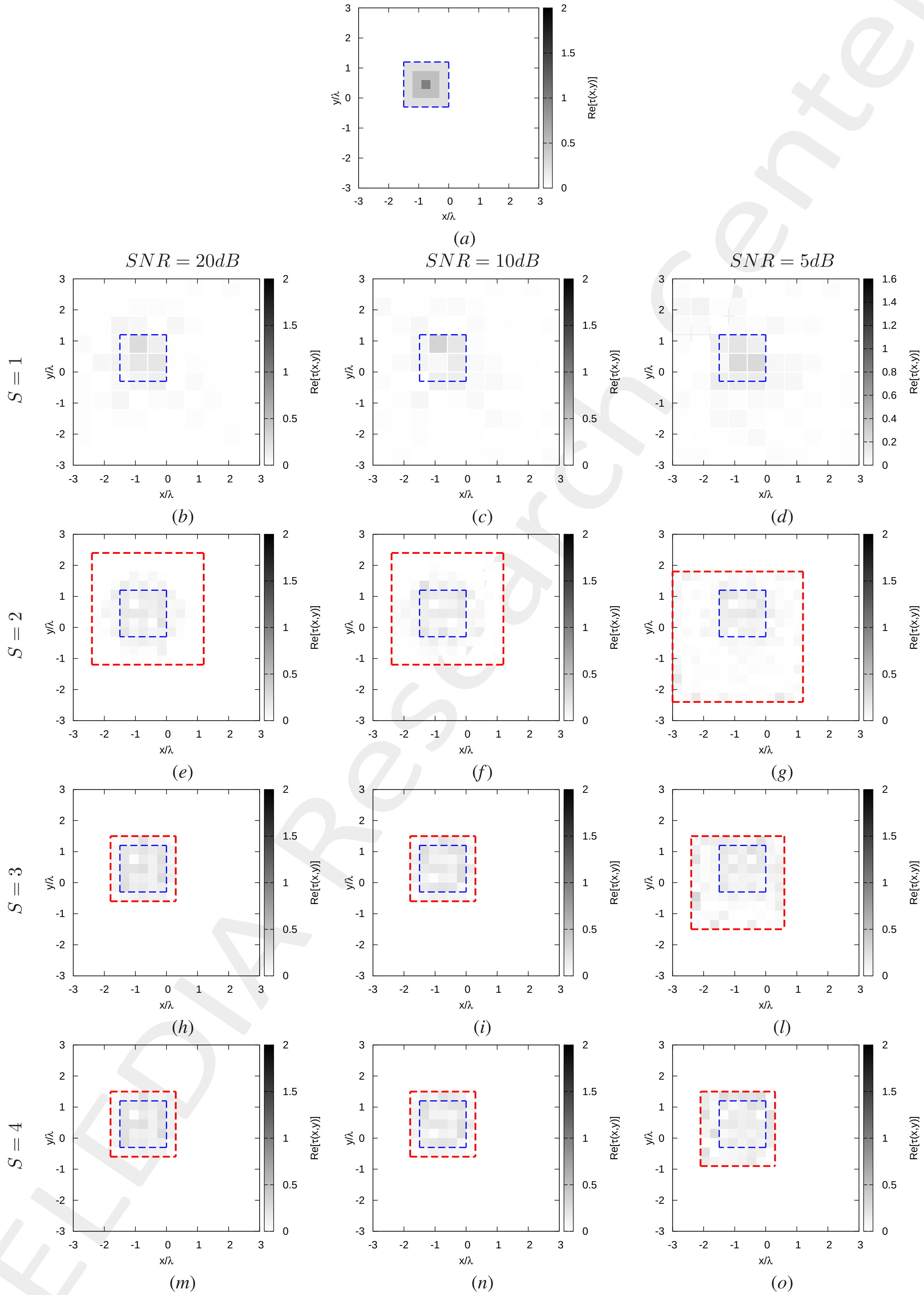

Figure 3: *Inhomogeneous Square Object*, $\ell = 1.5\lambda$, $\tau^{(1)} = 1.00$ - (a) Actual profile and (b)-(o) IMSA-BCS reconstructed profiles for (b)(e)(h)(m) $SNR = 20$ [dB], (c)(f)(i)(n) $SNR = 10$ [dB] and (d)(g)(l)(o) $SNR = 5$ [dB] at the step (b)-(d) $S = 1$, (e)-(g) $S = 2$, (h)-(l) $S = 3$ and (m)-(o) $S = 4$.

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	$SNR = 50dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
ξ_{tot}	3.28×10^{-2}	1.80×10^{-2}	1.47×10^{-2}	1.47×10^{-2}
ξ_{int}	1.43×10^{-1}	1.51×10^{-1}	1.24×10^{-1}	1.24×10^{-1}
ξ_{ext}	1.58×10^{-2}	7.62×10^{-3}	5.63×10^{-3}	5.63×10^{-3}
	$SNR = 20dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
ξ_{tot}	3.09×10^{-2}	1.87×10^{-2}	1.50×10^{-2}	1.50×10^{-2}
ξ_{int}	1.39×10^{-1}	1.53×10^{-1}	1.26×10^{-1}	1.26×10^{-1}
ξ_{ext}	1.54×10^{-2}	7.79×10^{-3}	5.51×10^{-3}	5.51×10^{-3}
	$SNR = 10dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
ξ_{tot}	3.55×10^{-2}	2.05×10^{-2}	1.55×10^{-2}	1.55×10^{-2}
ξ_{int}	1.50×10^{-1}	1.60×10^{-1}	1.33×10^{-1}	1.33×10^{-1}
ξ_{ext}	1.67×10^{-2}	8.51×10^{-3}	5.45×10^{-3}	5.45×10^{-3}
	$SNR = 5dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
ξ_{tot}	4.71×10^{-2}	2.98×10^{-2}	2.81×10^{-2}	2.63×10^{-2}
ξ_{int}	2.09×10^{-1}	1.61×10^{-1}	1.55×10^{-1}	1.63×10^{-1}
ξ_{ext}	2.31×10^{-2}	1.55×10^{-2}	1.47×10^{-2}	1.39×10^{-2}

Table V: *Inhomogeneous Square Object,* $\ell = 1.5\lambda$, $\tau^{(1)} = 1.00$ - Reconstrution errors: total (ξ_{tot}), internal (ξ_{int}) and external (ξ_{ext}) errors.

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	$SNR = 50dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
$L^{(S)}$	6.00	2.10	2.10	2.10
$N^{(S)}$	100	208	208	208
$Q^{(S)}$	100	144	49	49
	$SNR = 20dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
$L^{(S)}$	6.00	2.10	2.10	2.10
$N^{(S)}$	100	208	208	208
$Q^{(S)}$	100	144	49	49
	$SNR = 10dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
$L^{(S)}$	6.00	2.10	2.10	2.10
$N^{(S)}$	100	208	208	208
$Q^{(S)}$	100	144	49	49
	$SNR = 5dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
$L^{(S)}$	6.00	2.40	2.40	2.40
$N^{(S)}$	100	247	247	247
$Q^{(S)}$	100	196	100	64

Table VI: *Inhomogeneous Square Object,* $\ell = 1.5\lambda$, $\tau^{(1)} = 1.00$ - Investigation domain parameters: restricted investigation domain size $L^{(S)}$, total number of cells $N^{(S)}$ and number of cells within the restricted domain size $Q^{(S)}$.

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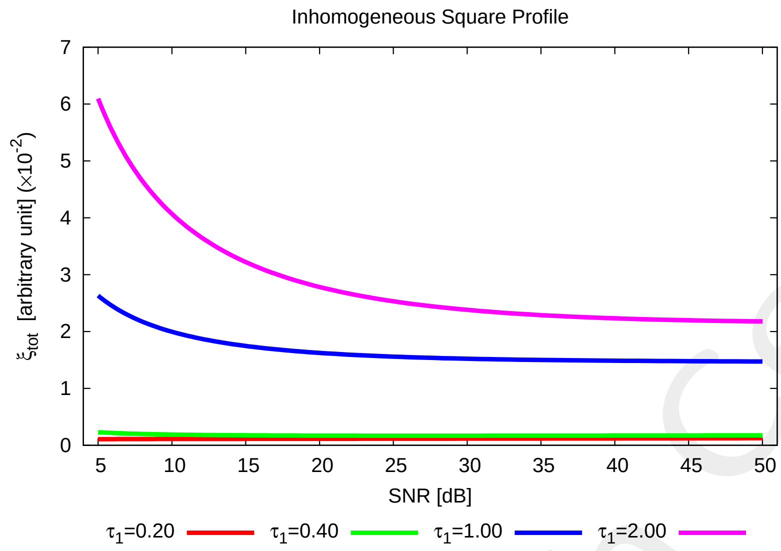
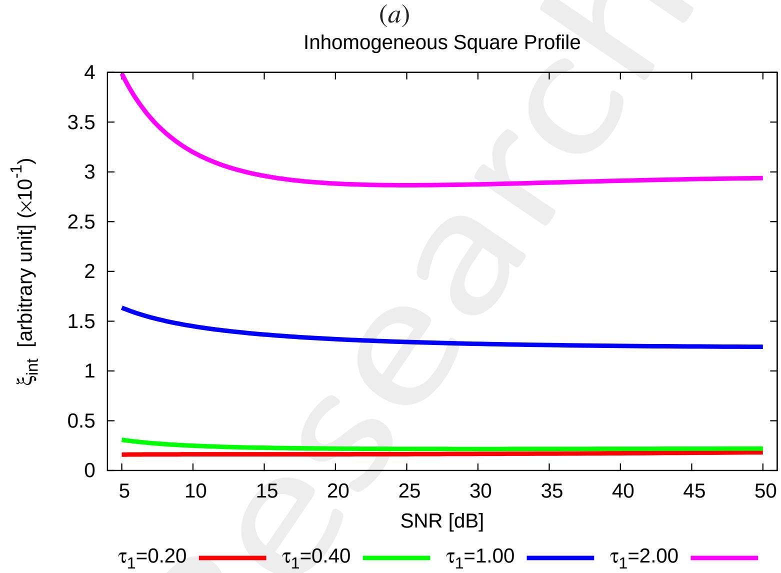
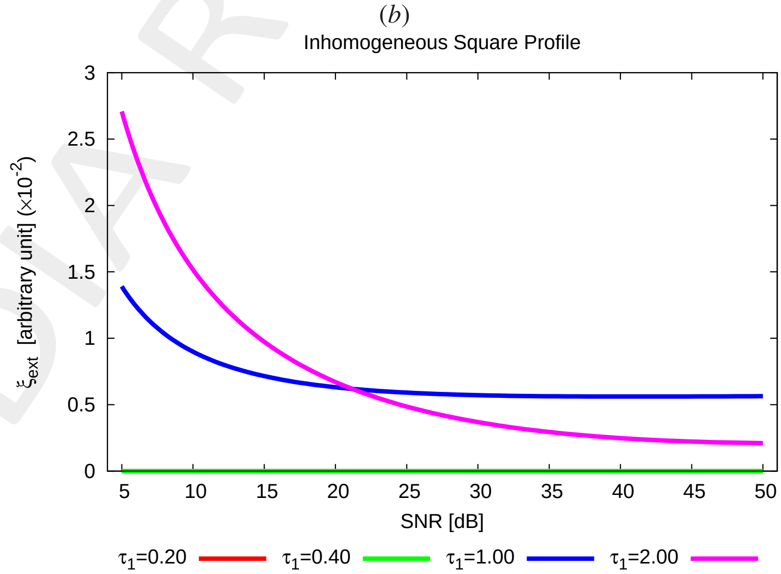
1.0.4 Inhomogeneous Square Object, $\ell = 1.5\lambda$ - Resume: Errors vs. SNR



(a)



(b)



(c)

Figure 4: *Inhomogeneous Square Object,* $\ell = 1.5\lambda$ - Reconstruction errors vs. SNR: (a) total error, (b) internal error and (c) external error.

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1.1 Numerical Analysis: Punctured Rectangle

Test Case Description

Direct solver:

- Side of the investigation domain: $L = 6.0\lambda$
- Cubic domain divided in $\sqrt{D} \times \sqrt{D}$ cells
- Number of cells for the direct solver: $D = 1600$ (discretization $= \lambda/10$)

Investigation domain:

- Cubic domain divided in $\sqrt{N} \times \sqrt{N}$ cells
- Number of cells for the inversion:

  - First Step IMSA: $N^{(1)} = 100$ (discretization $= \lambda/10$)

  - Following Steps IMSA: $N^{(i)}$ not fixed, defined according to the estimated $RoI\ \mathcal{D}^{(i)}$

Measurement domain:

- Total number of measurements: $M = 60$
- Measurement points placed on circles of radius $\rho = 4.5\lambda$

Sources:

- Plane waves
- Number of views: $V = 60$; $\theta_{inc}^{v} = 0 + (v-1) \times (360/V)$
- Amplitude: $A = 1.0$
- Frequency: $F = 300$ MHz ($\lambda = 1$)

Background:

- $\varepsilon_r = 1.0$
- $\sigma = 0$ [S/m]

Scatterer

- Punctured rectangle
- $\varepsilon_r \in \{1.10,\ 1.20\}$
- $\sigma = 0$ [S/m]

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1.1.1 Punctured Rectangle, $\tau = 0.10$ - IMSA-BCS reconstructed profiles

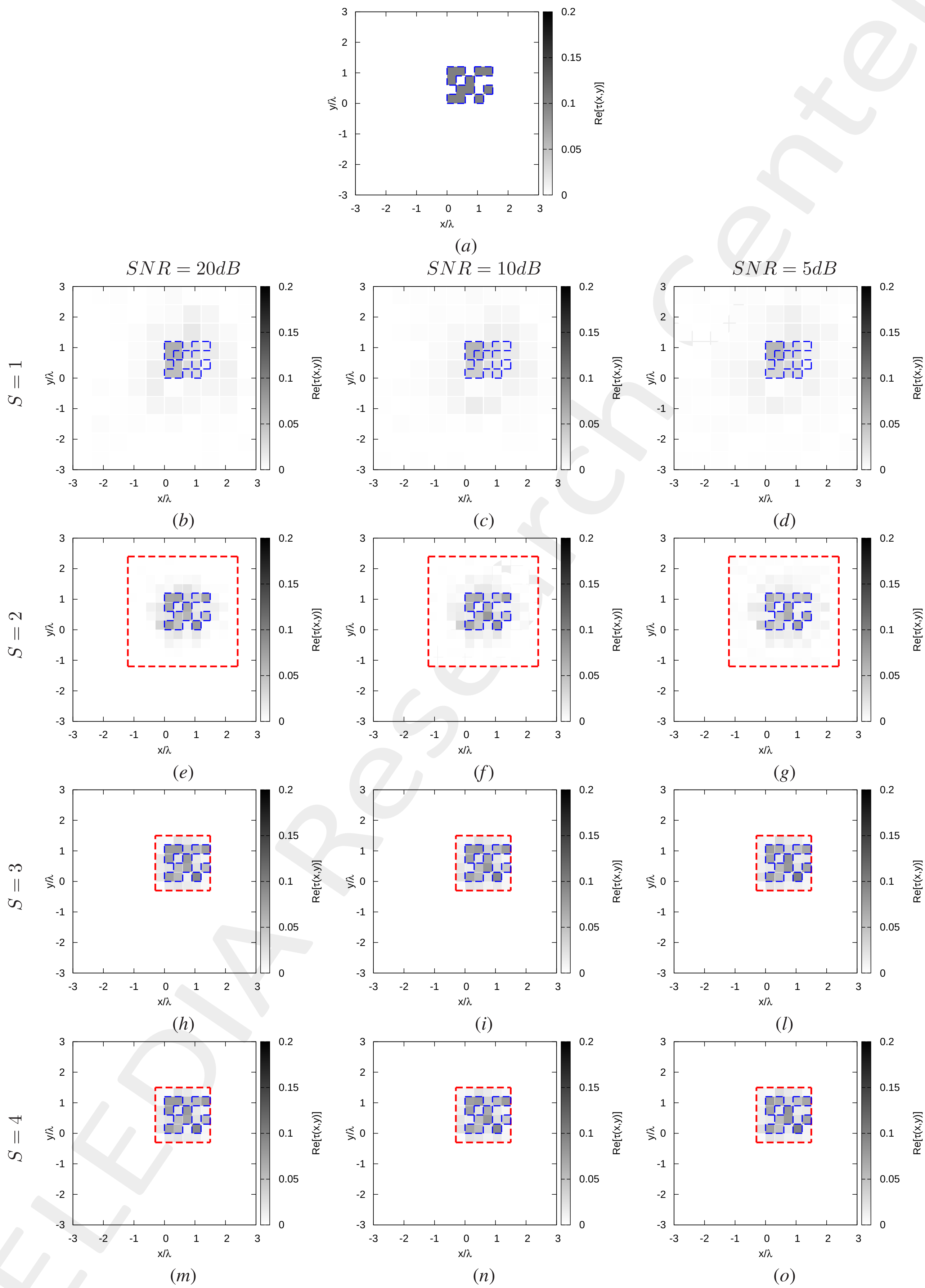

Figure 5: *Punctured Rectangle*, $\tau = 0.10$ - (*a*) Actual profile and (*b*)-(*o*) IMSA-BCS reconstructed profiles for (*b*)(*e*)(*h*)(*m*) $SNR = 20$ [dB], (*c*)(*f*)(*i*)(*n*) $SNR = 10$ [dB] and (*d*)(*g*)(*l*)(*o*) $SNR = 5$ [dB] at the step (*b*)-(*d*) $S = 1$, (*e*)-(*g*) $S = 2$, (*h*)-(*l*) $S = 3$ and (*m*)-(*o*) $S = 4$.

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	$SNR = 50dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
ξ_{tot}	4.94×10^{-3}	2.19×10^{-3}	1.77×10^{-3}	1.56×10^{-3}
ξ_{int}	5.48×10^{-2}	3.45×10^{-2}	2.79×10^{-2}	2.44×10^{-2}
ξ_{ext}	3.31×10^{-3}	1.16×10^{-3}	9.43×10^{-4}	8.09×10^{-4}
	$SNR = 20dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
ξ_{tot}	4.95×10^{-3}	2.24×10^{-3}	1.73×10^{-3}	1.73×10^{-3}
ξ_{int}	5.46×10^{-2}	3.52×10^{-2}	2.72×10^{-2}	2.72×10^{-2}
ξ_{ext}	3.28×10^{-3}	1.18×10^{-3}	9.17×10^{-4}	9.17×10^{-4}
	$SNR = 10dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
ξ_{tot}	5.20×10^{-3}	2.39×10^{-3}	1.84×10^{-3}	1.84×10^{-3}
ξ_{int}	5.78×10^{-2}	3.74×10^{-2}	2.88×10^{-2}	2.88×10^{-2}
ξ_{ext}	3.38×10^{-3}	1.25×10^{-3}	9.77×10^{-4}	9.77×10^{-4}
	$SNR = 5dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
ξ_{tot}	5.55×10^{-3}	2.85×10^{-3}	1.80×10^{-3}	1.80×10^{-3}
ξ_{int}	5.92×10^{-2}	4.28×10^{-2}	2.70×10^{-2}	2.70×10^{-2}
ξ_{ext}	3.62×10^{-3}	1.48×10^{-3}	9.71×10^{-4}	9.71×10^{-4}

Table VII: *Punctured Rectangle,* $\tau = 0.10$ - Reconstrution errors: total (ξ_{tot}), internal (ξ_{int}) and external (ξ_{ext}) errors.

	$SNR = 50dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
$L^{(S)}$	6.00	1.50	1.50	1.50
$N^{(S)}$	100	208	208	208
$Q^{(S)}$	100	144	36	25
	$SNR = 20dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
$L^{(S)}$	6.00	1.80	1.80	1.80
$N^{(S)}$	100	208	208	208
$Q^{(S)}$	100	144	36	36
	$SNR = 10dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
$L^{(S)}$	6.00	1.80	1.80	1.80
$N^{(S)}$	100	208	208	208
$Q^{(S)}$	100	144	36	36
	$SNR = 5dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
$L^{(S)}$	6.00	1.80	1.80	1.80
$N^{(S)}$	100	208	208	208
$Q^{(S)}$	100	144	36	36

Table VIII: *Punctured Rectangle,* $\tau = 0.10$ - Investigation domain parameters: restricted investigation domain size $L^{(S)}$, total number of cells $N^{(S)}$ and number of cells within the restricted domain size $Q^{(S)}$.

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1.1.2 Punctured Rectangle, $\tau = 0.20$ - IMSA-BCS reconstructed profiles

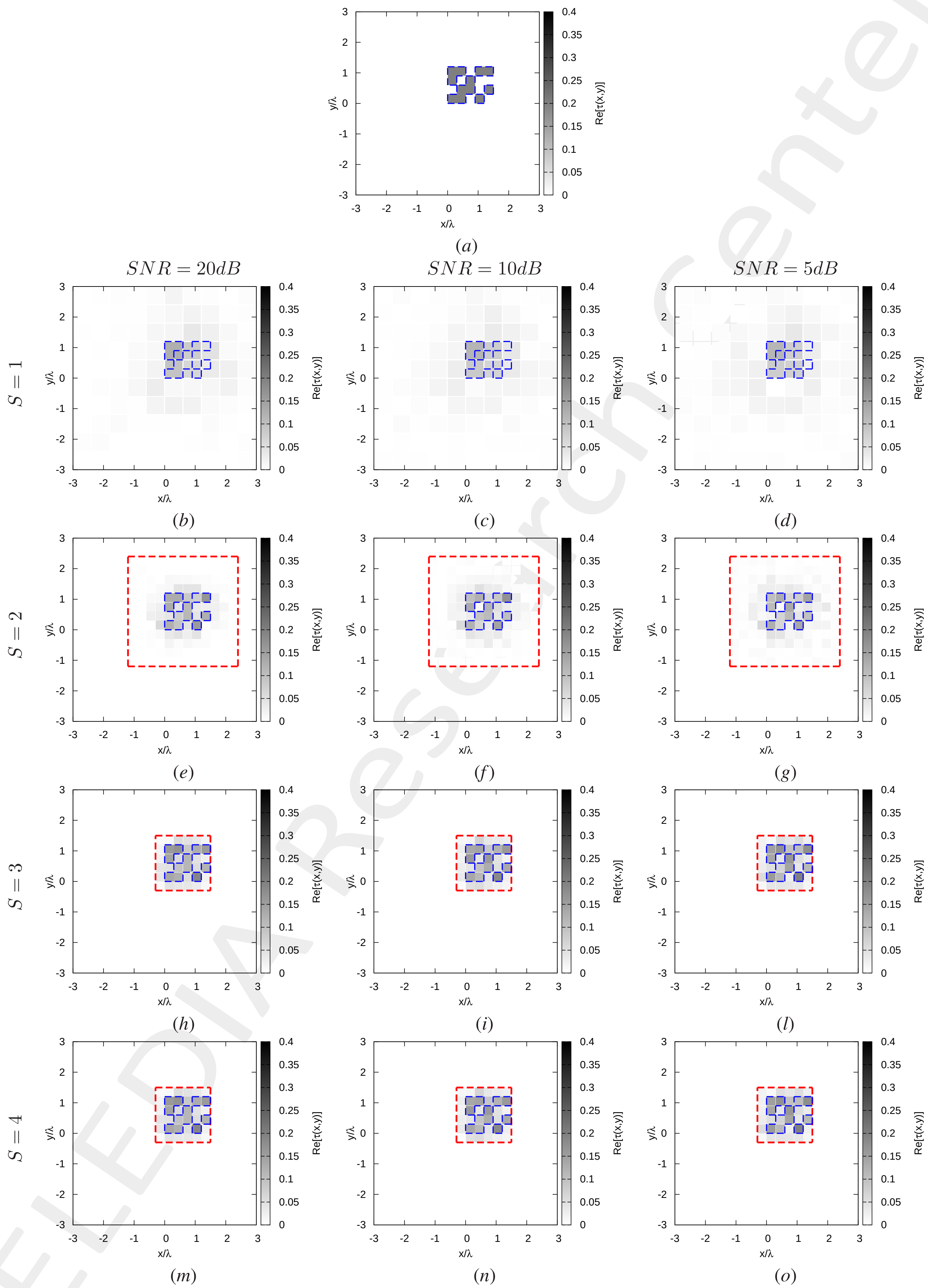

Figure 6: *Punctured Rectangle*, $\tau = 0.20$ - (a) Actual profile and (b)-(o) IMSA-BCS reconstructed profiles for $(b)(e)(h)(m)$ $SNR = 20$ [dB], $(c)(f)(i)(n)$ $SNR = 10$ [dB] and $(d)(g)(l)(o)$ $SNR = 5$ [dB] at the step (b)-(d) $S = 1$, (e)-(g) $S = 2$, (h)-(l) $S = 3$ and (m)-(o) $S = 4$.

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	$SNR = 50dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
ξ_{tot}	1.05×10^{-2}	4.64×10^{-3}	3.81×10^{-3}	3.81×10^{-3}
ξ_{int}	9.02×10^{-2}	6.40×10^{-2}	5.15×10^{-2}	5.15×10^{-2}
ξ_{ext}	7.60×10^{-3}	2.64×10^{-3}	2.25×10^{-3}	2.25×10^{-3}
	$SNR = 20dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
ξ_{tot}	1.10×10^{-2}	4.86×10^{-3}	3.83×10^{-3}	3.83×10^{-3}
ξ_{int}	9.54×10^{-2}	6.72×10^{-2}	5.19×10^{-2}	5.19×10^{-2}
ξ_{ext}	7.79×10^{-3}	2.76×10^{-3}	2.21×10^{-3}	2.21×10^{-3}
	$SNR = 10dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
ξ_{tot}	1.12×10^{-2}	5.34×10^{-3}	3.73×10^{-3}	3.73×10^{-3}
ξ_{int}	9.97×10^{-2}	7.23×10^{-2}	5.08×10^{-2}	5.08×10^{-2}
ξ_{ext}	7.84×10^{-3}	2.99×10^{-3}	2.18×10^{-3}	2.18×10^{-3}
	$SNR = 5dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
ξ_{tot}	1.16×10^{-2}	5.95×10^{-3}	3.81×10^{-3}	3.81×10^{-3}
ξ_{int}	1.01×10^{-1}	7.71×10^{-2}	4.94×10^{-2}	4.94×10^{-2}
ξ_{ext}	8.03×10^{-3}	3.33×10^{-3}	2.25×10^{-3}	2.25×10^{-3}

Table IX: *Punctured Rectangle,* $\tau = 0.20$ - Reconstrution errors: total (ξ_{tot}), internal (ξ_{int}) and external (ξ_{ext}) errors.

	$SNR = 50dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
$L^{(S)}$	6.00	1.80	1.80	1.80
$N^{(S)}$	100	208	208	208
$Q^{(S)}$	100	144	36	36
	$SNR = 20dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
$L^{(S)}$	6.00	1.80	1.80	1.80
$N^{(S)}$	100	208	208	208
$Q^{(S)}$	100	144	36	36
	$SNR = 10dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
$L^{(S)}$	6.00	1.80	1.80	1.80
$N^{(S)}$	100	208	208	208
$Q^{(S)}$	100	144	36	36
	$SNR = 5dB$			
	$S = 1$	$S = 2$	$S = 3$	$S = 4$
$L^{(S)}$	6.00	1.80	1.80	1.80
$N^{(S)}$	100	208	208	208
$Q^{(S)}$	100	144	36	36

Table X: *Punctured Rectangle,* $\tau = 0.20$ - Investigation domain parameters: restricted investigation domain size $L^{(S)}$, total number of cells $N^{(S)}$ and number of cells within the restricted domain size $Q^{(S)}$.

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More information on the topics of this document can be found in the following list of references.

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