Robust ABF for Large, Passive Broadband Sonar Arrays

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Introduction: Themes

ABF for large arrays ($100 < N < 10000$ elements) require particular attention to computing efficiency

- Element space DMR > $O(ND^2)$

"Ideal" reduced complexity adaptive beamformer:

- Adaptation space dimension, N_a, close to required adaptive degrees of freedom D
- Consistent with spatial sampling theory
- Steering direction invariant
- "Robust robustness"

Broadband beamforming:

- computing efficiency inherent at low frequency
- can trade high SNR signal suppression for spatial resolution

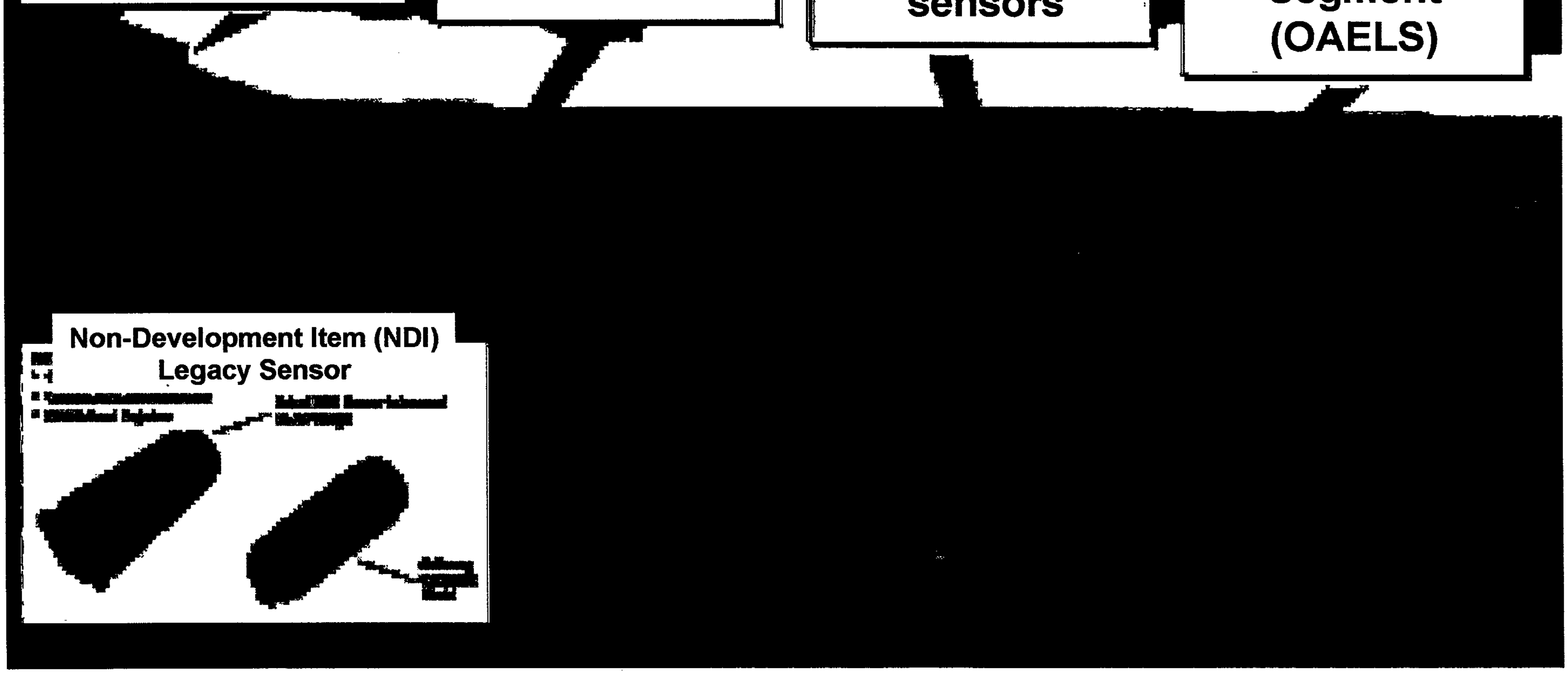
LOPS AO Array Wet Subsystem(AWS)

Trunk Terminus Segment (TTS) NSWC PEV

Observatory Trunk Segment (OTS)

Horizontal Array Segment (HAS) 1664 sensors

Off-board Array Element Location Segment (OAELS)



Complexity (C) in Dominant Mode Rejection (DMR) Adaptive Beamforming (ABF)

- N = number of sensors
- S = number of steering directions
- N_a = number of adaptively filtered channels
- D = number of adaptive degrees of freedom

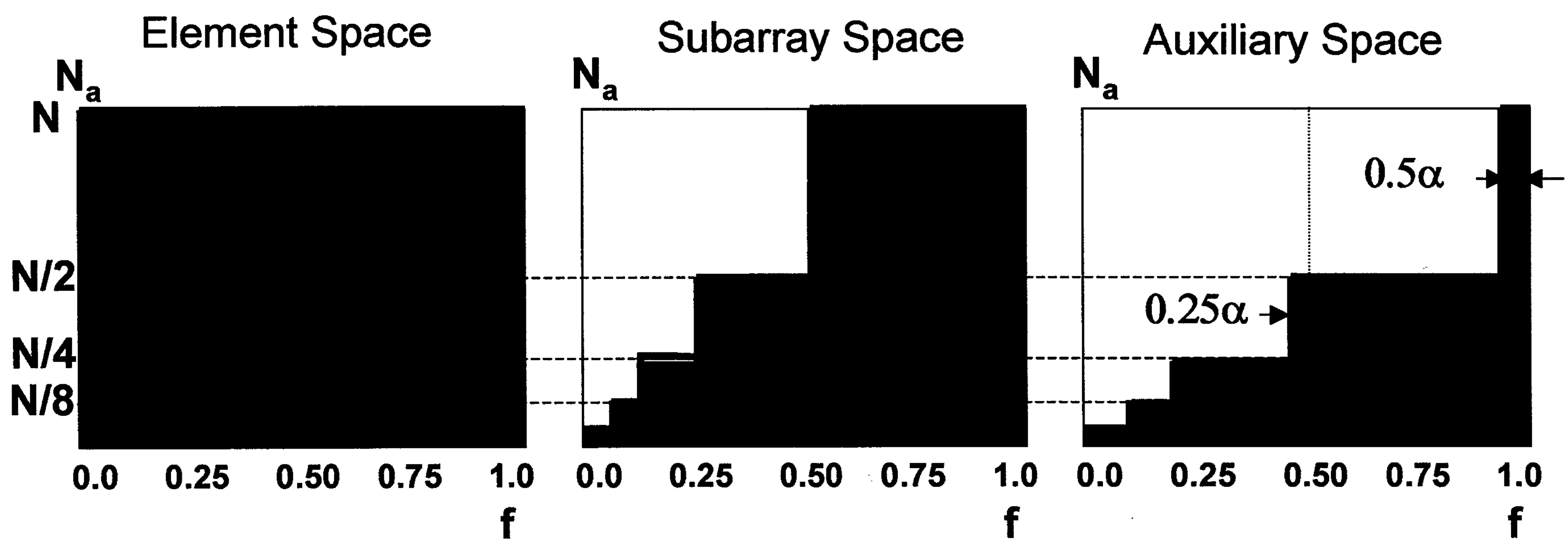
[redacted]

Candidate ASAP Methods for Large BB Arrays

[redacted]

Adaptive Degrees of Freedom: Frequency Dependence

N = number of sensors $\lambda/2$ spaced sensors in linear array
N_a = number of adaptive channels
f = frequency normalized by the $\lambda/2$ spacing design frequency
$f=1$ is array design frequency



Area = N

Area = 2N/3

Area = (α+1)N/3

$N_a = N_a$(Number of Sources, Number of $\lambda/2$-s in Aperture) (???)

Measures of Performance

- **Qualitative: Bearing-Time-Recording (BTR) side-by-side beauty contest**
- **Quantitative: Array Gain (AG)**

[redacted]

$\mathbf{w}(\theta_{targ})$ = beamforming filter vector for beam steered at θ_{targ}

$\mathbf{P}_{true}(\theta_{targ})$ = Cross-Channel Spectral Density Matrix (CSDM)

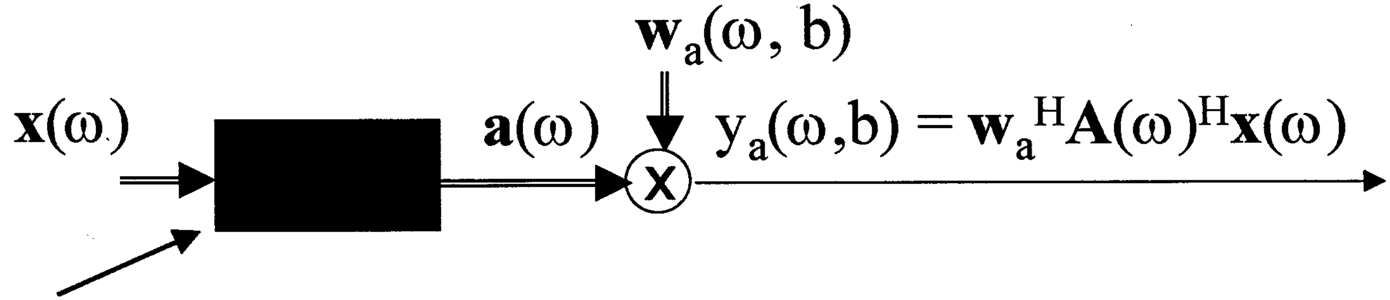
$$= \mathbf{d}(\theta_{targ})\mathbf{d}(\theta_{targ})^H, \qquad \mathrm{Trace}(\mathbf{P}_{true}(\theta_{targ})) = N$$

$$\mathbf{Q}_{true}(\mathrm{all}\,\theta \neq \theta_{targ}) = \sum_m \alpha_m \mathbf{d}(\theta_m)\mathbf{d}(\theta_m)^H + \alpha_0 \mathbf{I}_N, \qquad \mathrm{Trace}(\mathbf{Q}_{true}(\theta_{targ})) = N$$

AG MOP Usage

- AG is given as a function of θ_{targ} for static source examples
- AG is given along the bearing track of a clairvoyant designated target tracker for dynamic source examples

ABF with Subarray Preprocessing



Steering invariant subarray grouping:

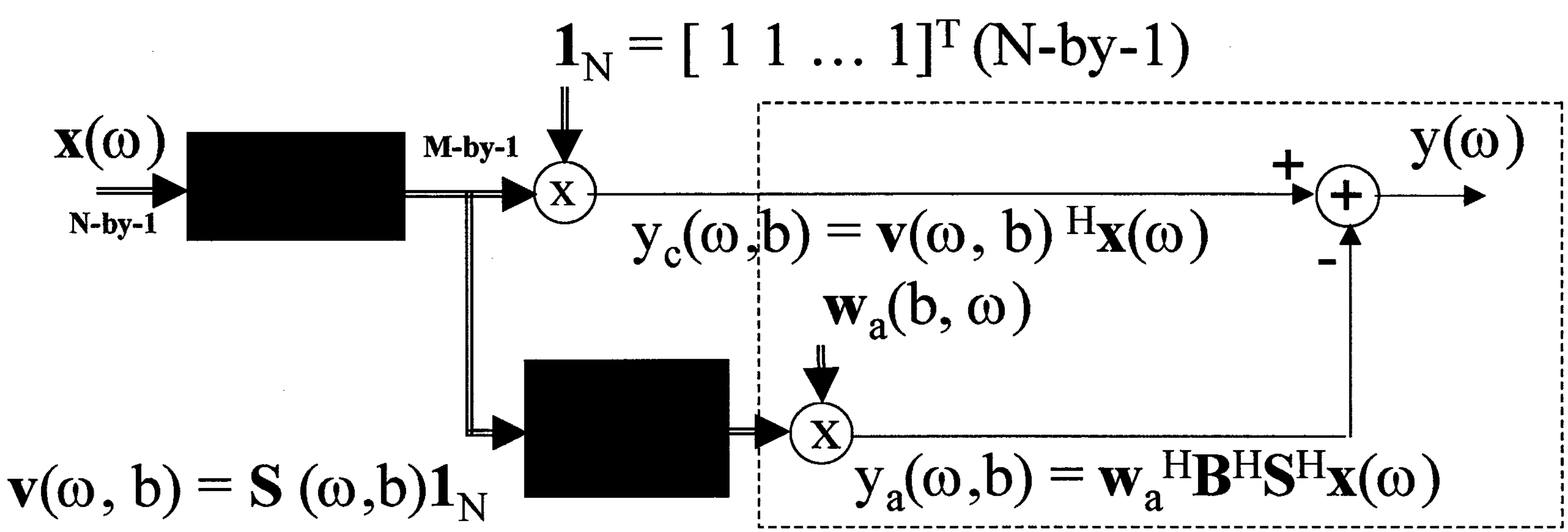
$$\mathbf{v}_a(\omega, b) = \mathbf{A}(\omega)^H \mathbf{v}(\omega, b)$$

Suppress ω and b notation:

$$\mathbf{w}_a = \frac{1}{\mathbf{v}_a^H \mathbf{R}_{aa}^{-1} \mathbf{v}_a} \mathbf{R}_{aa}^{-1} \mathbf{v}_a$$

[redacted]

GSC with Presteering and Signal Blocking Distortionless Response (DR)



Unconstrained "Weiner Filter"

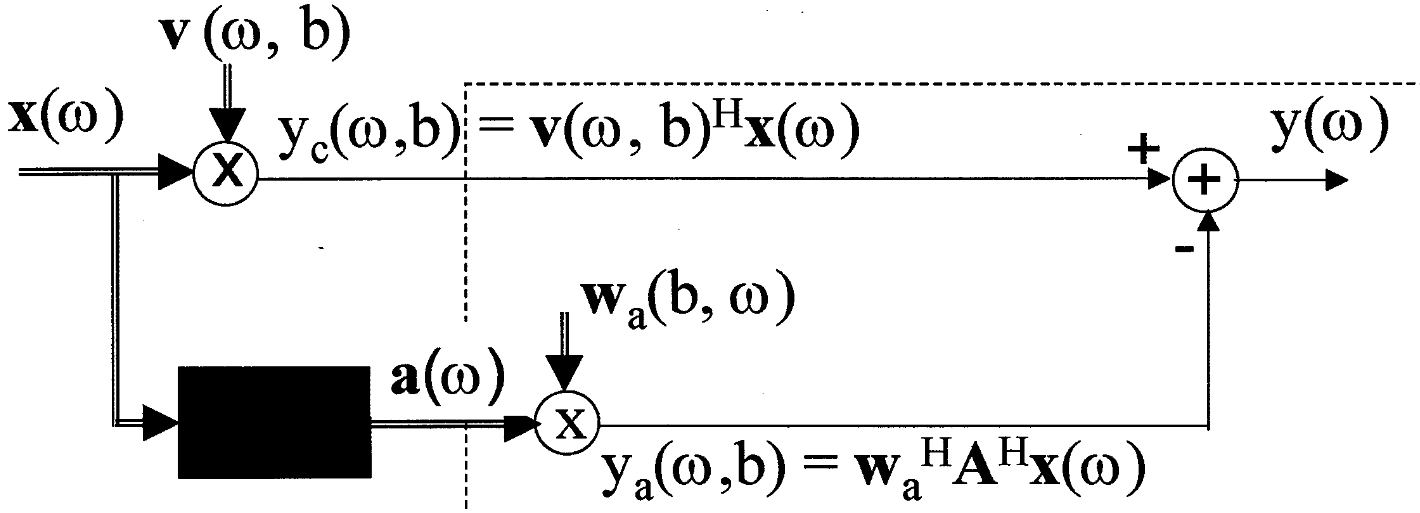
Suppress ω **and** b **notation:**

$$\mathbf{B}^H \mathbf{1}_N = \mathbf{0}_M = [0\ 0\ \ldots\ 0]^T \text{ (M-by-1)}$$

$$\mathbf{w}_a = [\mathbf{B}^H \mathbf{S}^H \mathbf{R}_{xx} \mathbf{S} \mathbf{B}]^{-1} \mathbf{B}^H \mathbf{S}^H \mathbf{R}_{xx} \mathbf{v}$$

[redacted]

Steering Invariant DR Sidelobe Cancellation (SISC) Process



$\mathbf{v_a}(\omega, b) = \mathbf{A}(\omega)\mathbf{v}(\omega, b)$

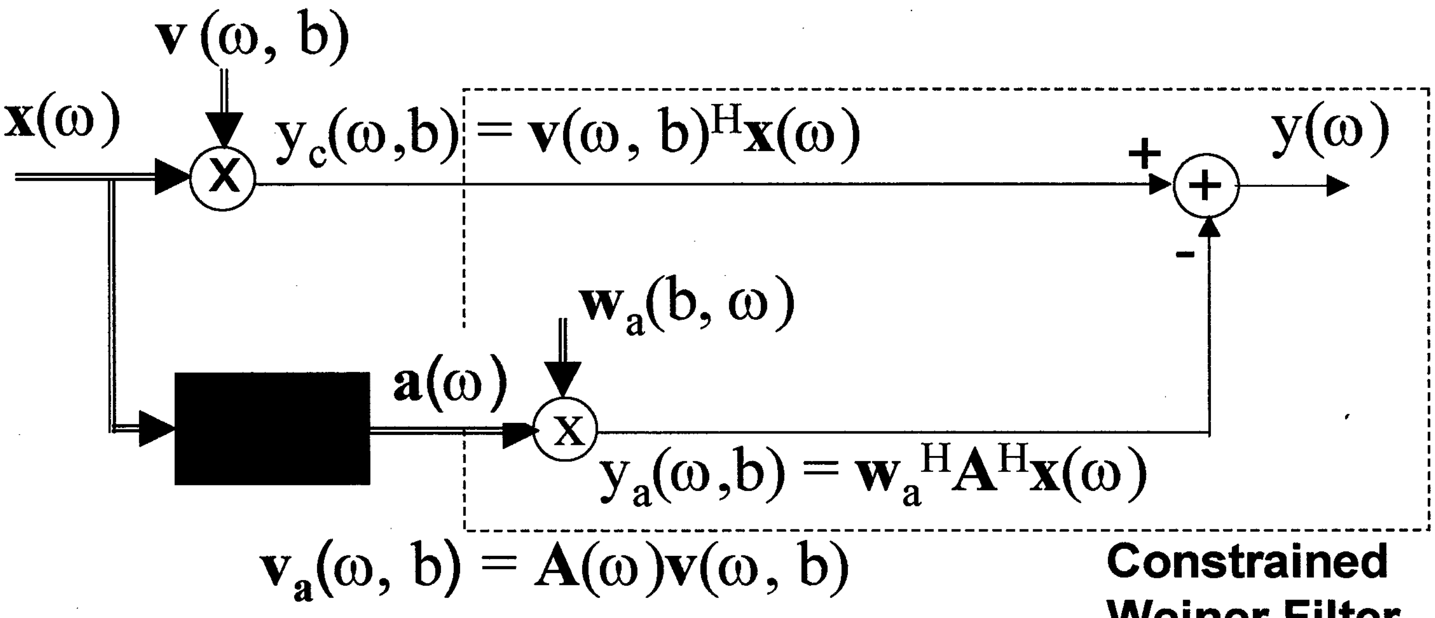
Constrained Weiner Filter

Suppress ω **and** b:

$$\mathbf{w}_a = \mathbf{R}_{aa}^{-1}\left(\mathbf{r}_{ac} - \left(\frac{\mathbf{r}_{ac}^H \mathbf{R}_{aa}^{-1}\mathbf{v}_a}{\mathbf{v}_a^H \mathbf{R}_{aa}^{-1}\mathbf{v}_a}\right)\mathbf{v}_a\right)$$

[redacted]

Steering Invariant DR Sidelobe Cancellation (SISC) Process



Suppress ω **and** b:

$$\mathbf{w} = \frac{\mathbf{v} - \mathbf{A}\mathbf{w}_a}{1 - \mathbf{w}_a^H \mathbf{A}^H \mathbf{v}} \quad \textbf{with} \quad \mathbf{w}_a = \mathbf{R}_{aa}^{-1}\left(\mathbf{r}_{ac} - \alpha \mathbf{v}_a\right)$$

[redacted]

Robust Robustness (RR): Robustness Management

CBF ($\mathbf{v}$) and unconstrained ABF ($\mathbf{w}_0$) linear blend

$$\mathbf{w} = (1-\beta)\,\mathbf{v} + \beta\,\mathbf{w}_0,$$

where on a beam-by-beam as-needed basis (RR),

$$\beta = \begin{cases} 1, \text{ for } |\mathbf{w}_0 - \mathbf{v}|^2 \le G \\ \dfrac{G^{1/2}}{|\mathbf{w}_0 - \mathbf{v}|}, \text{ for } |\mathbf{w}_0 - \mathbf{v}|^2 > G \end{cases}$$

$$G = \mathrm{WNGC} - 1.$$

For a Sidelobe Cancellation ABF

$$\mathbf{w}_0 = \mathbf{v} - \mathbf{A}\mathbf{w}_a$$

and the

$$\mathbf{w} = \mathbf{v} - \beta\mathbf{A}\mathbf{w}_a$$ (really simple!).

ESMVDR (l) and SI(G)SC w/o RR (r): NumHydPerGroup = 6 (M = 8, N = 48, pert=0.)

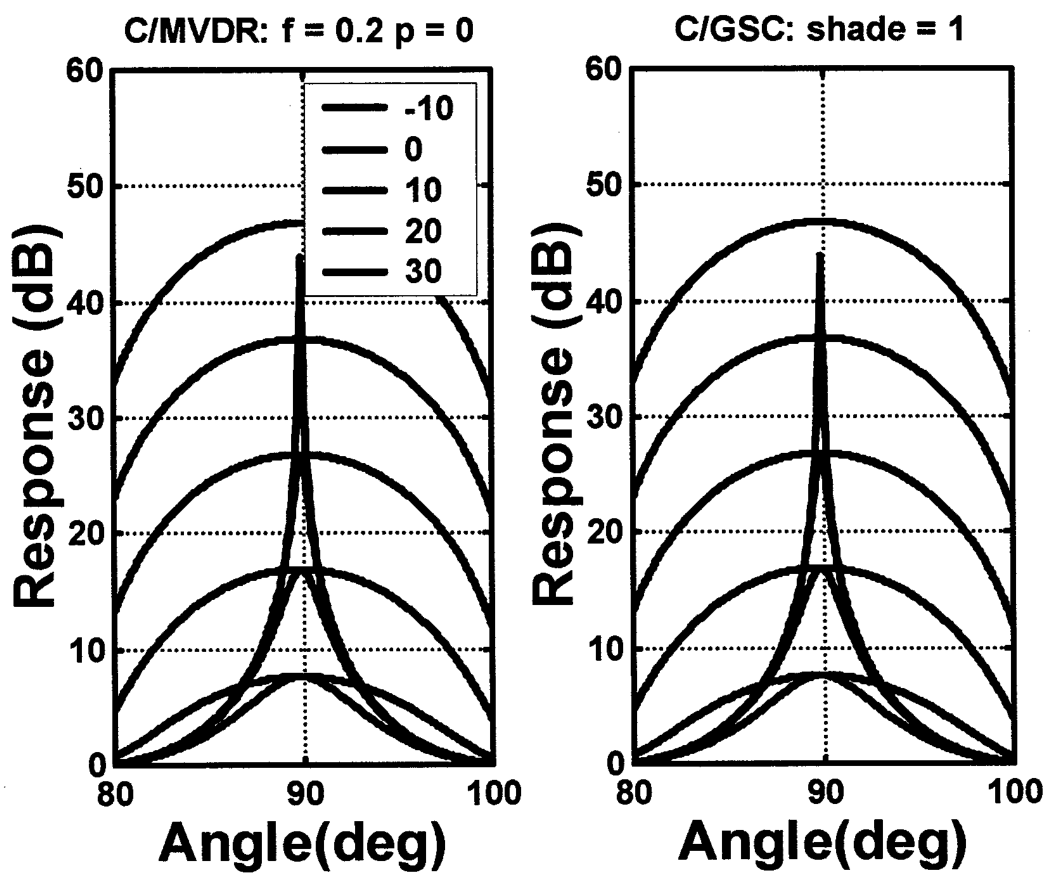


Figure 3.

ESMVDR (l) and SI(G)SC w/o RR (r): NumHydPerGroup = 6 (M = 8, N = 48, pert=0.07)

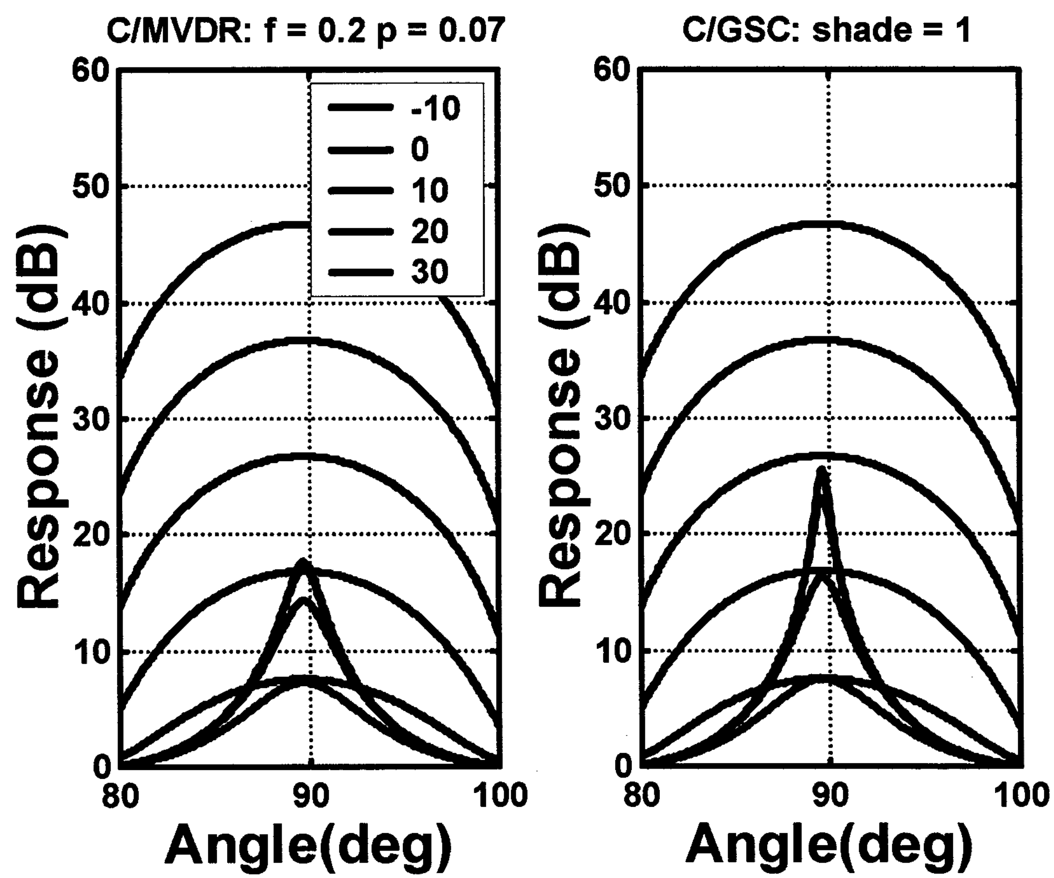


Figure 3.1

ESMVDR (l) and SI(G)SC with RR (r): NumHydPerGroup = 6 (M = 8, N = 48, pert=0.07)

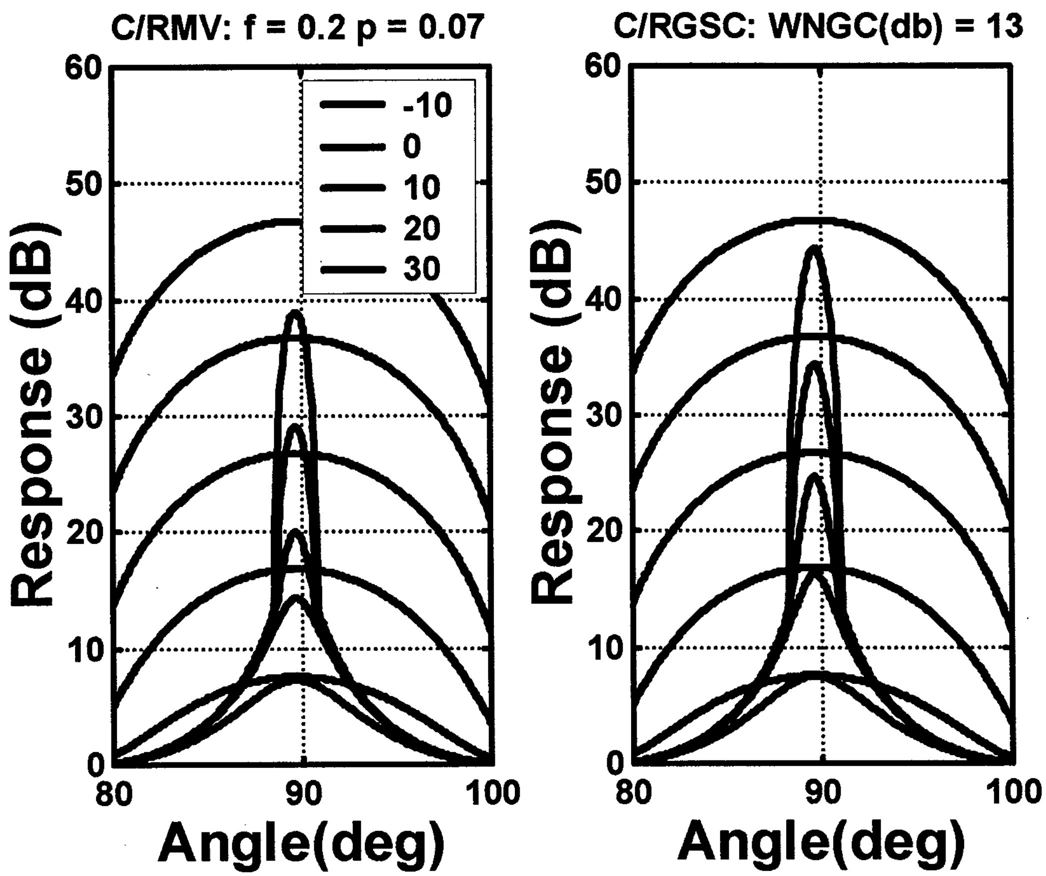
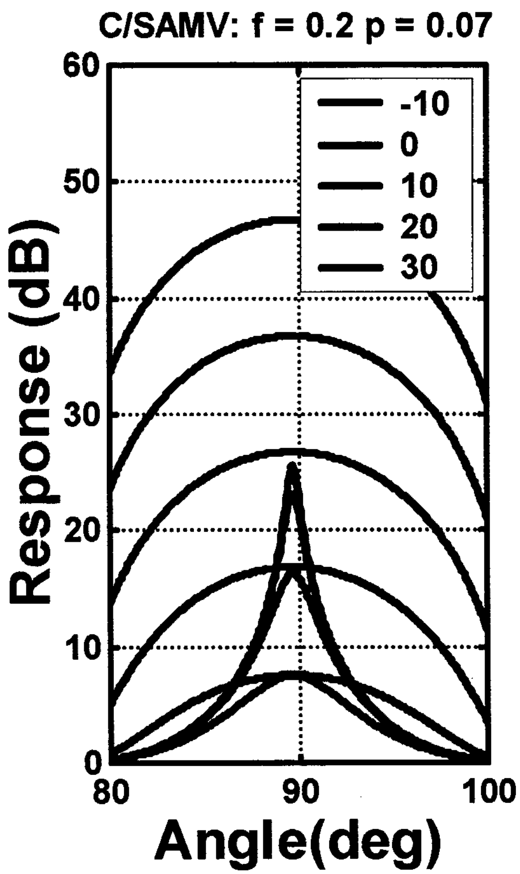
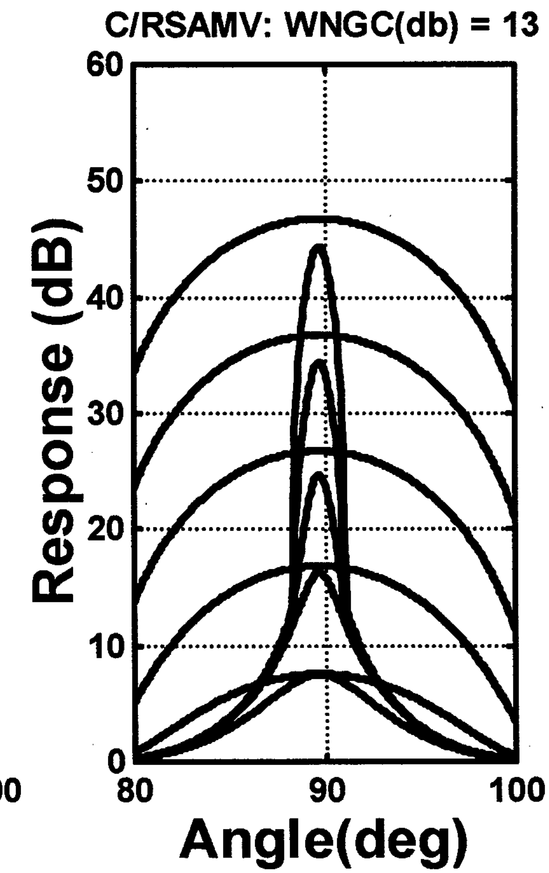


Figure 3.2

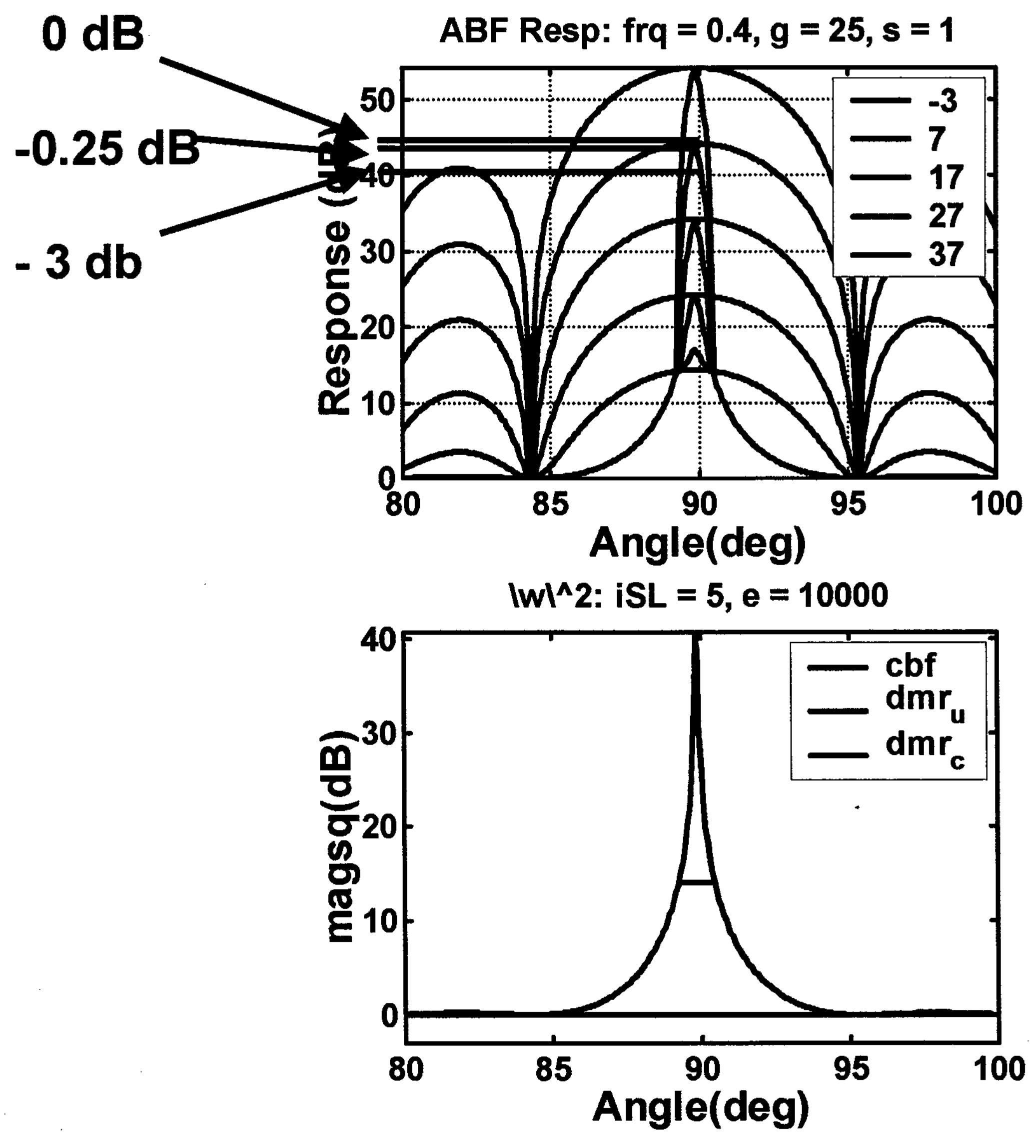
Subarray Preprocessing w/o (l) and with (r) RR: NumHydPerSA = 6 (M = 8, N = 48, pert=0.07)





Blended CBF-DMR Point Design

(Owsley, SAM 02)



Design Procedure: One step pre-solution for G in terms of specified allowable signal suppression v. SNR .

Six Stationary Sources: ES

(pert = 0.0, N = 48, D = 7, f =0.2, sa group size = 4)

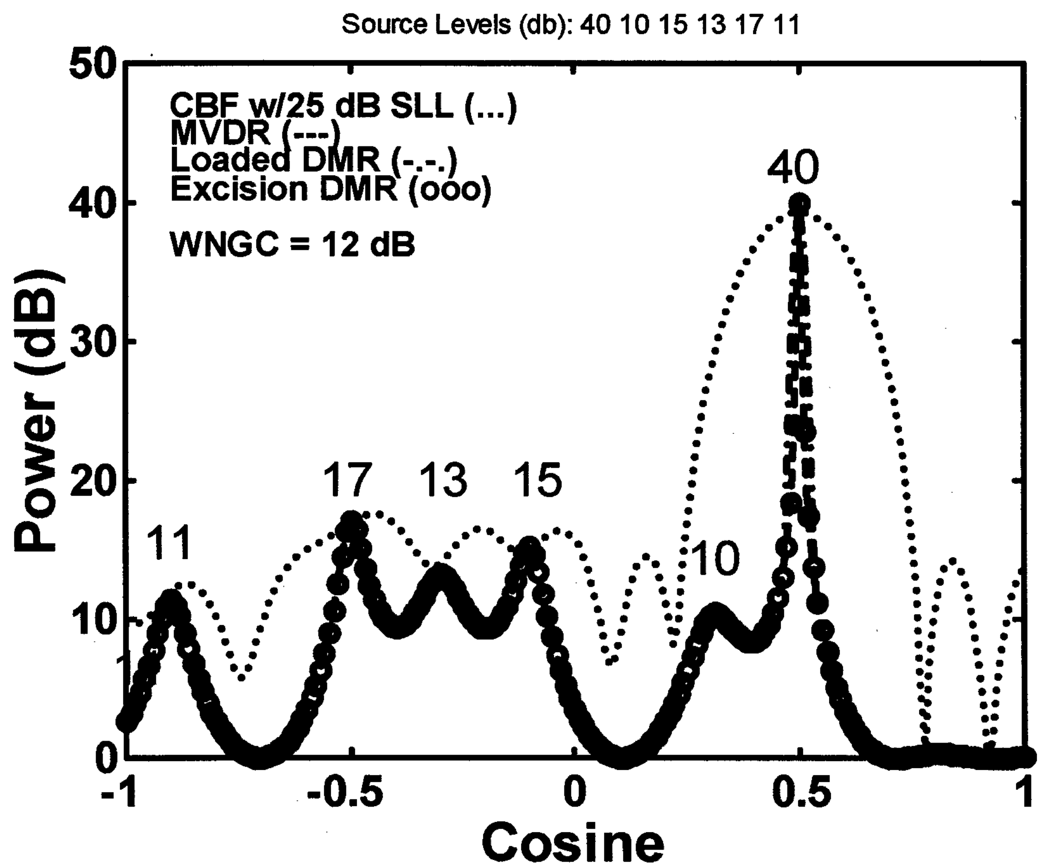


Figure 4.1

Six Stationary Sources

(pert = 0.0, N = 48, D = 7, f =0.2, sa group size = 4)

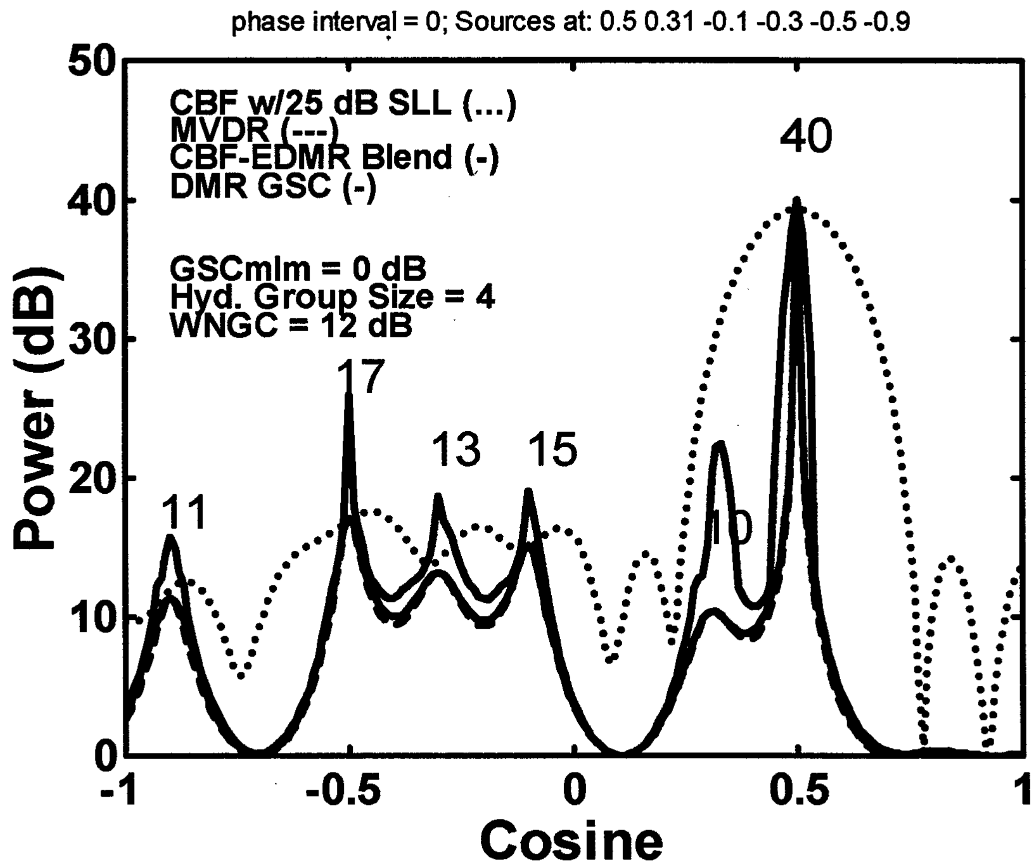


Figure 4.2

Six Stationary Sources

(pert = 0.0, N = 48, D = 7, f =0.2, sa group size = 4)

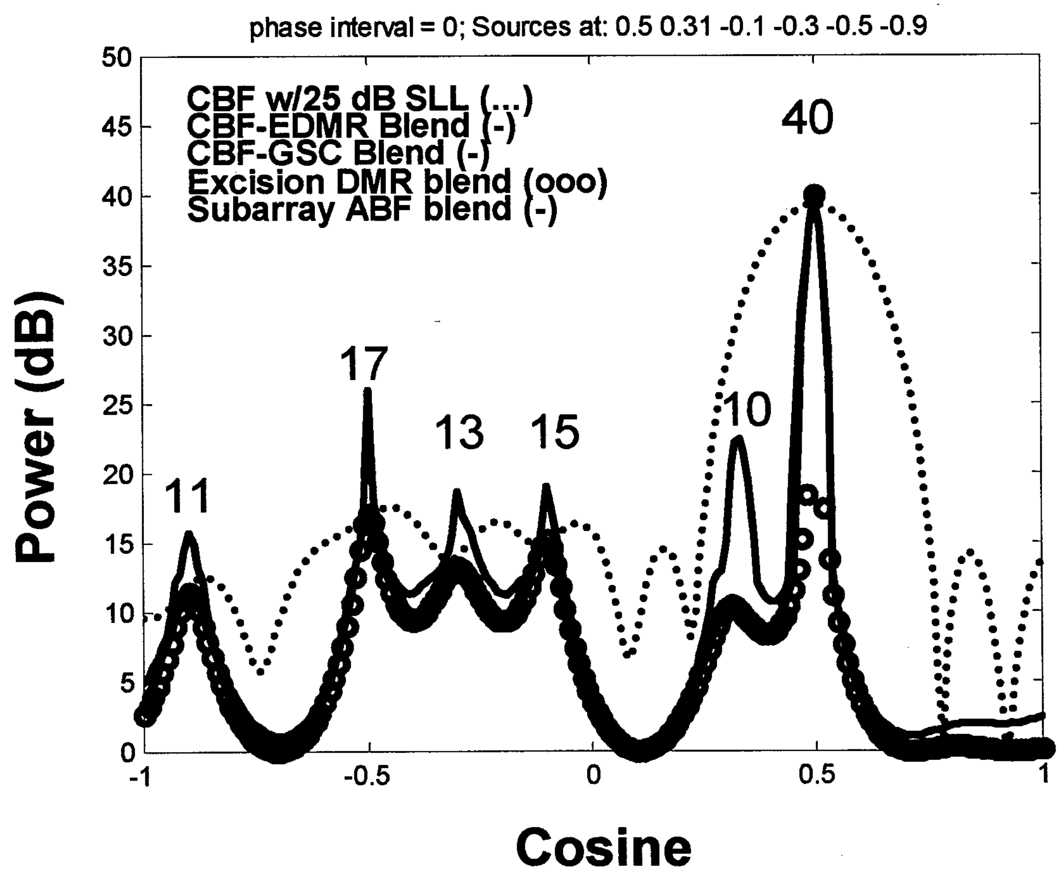


Figure 4.3

Six Stationary Sources

(pert = 0.0, N = 48, D = 7, f =0.2, sa group size = 4)

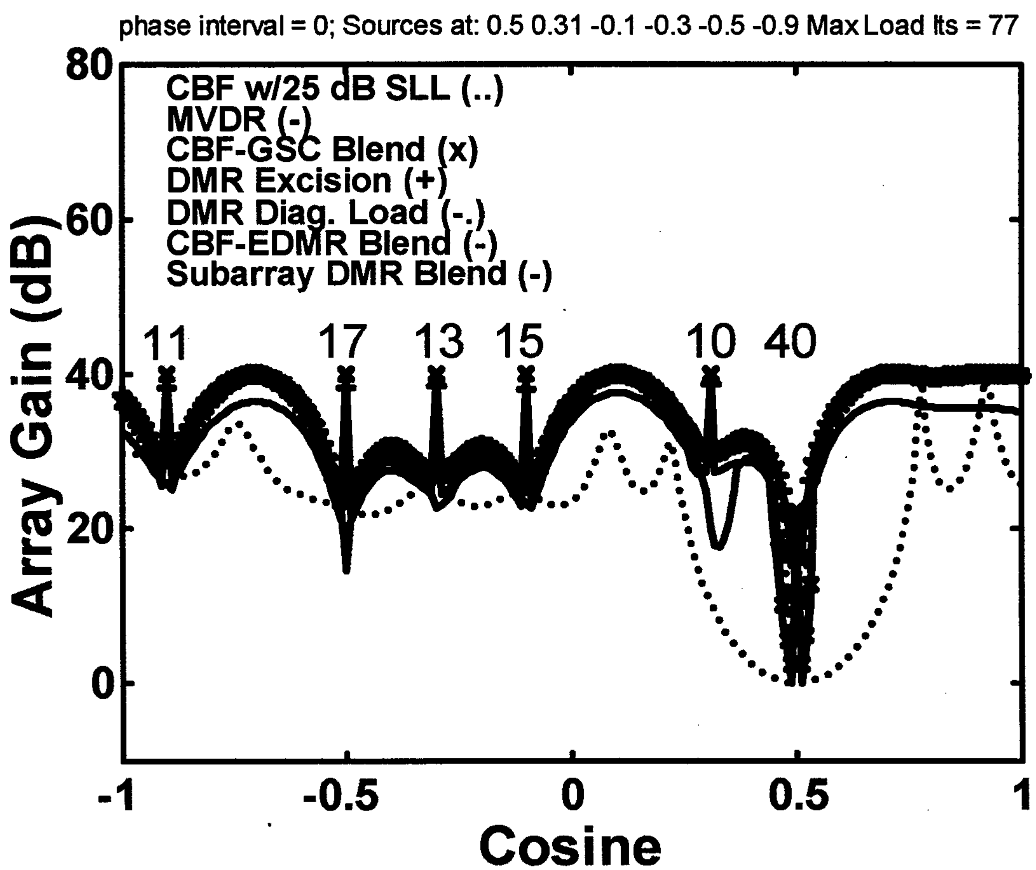


Figure 4.4

Six Stationary Sources

(pert=0.07, D = 7, N=48, M=12, f =0.2, sa group size = 4)

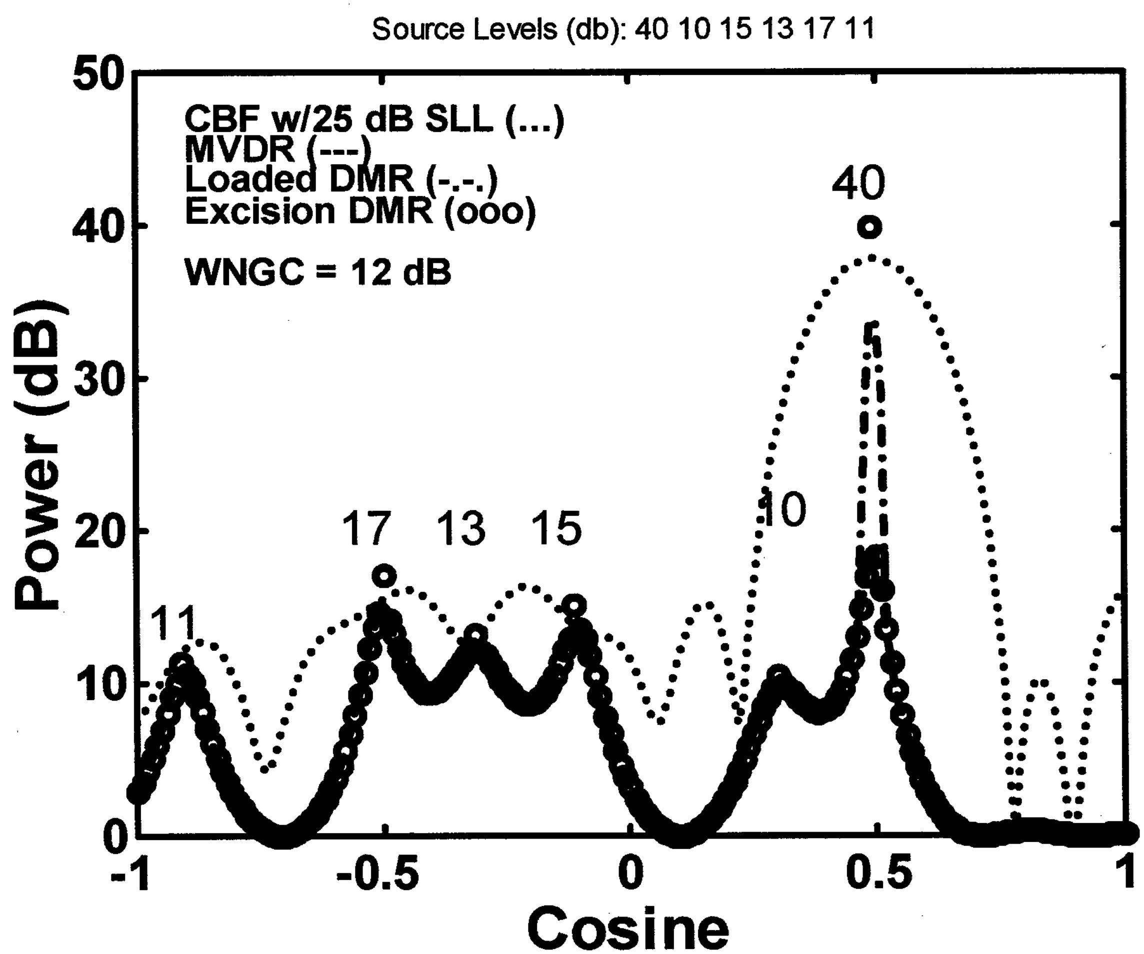


Figure 5.1

Six Stationary Sources

(pert=0.07, D = 7, N=48, M=12, f =0.2, sa group size = 4)

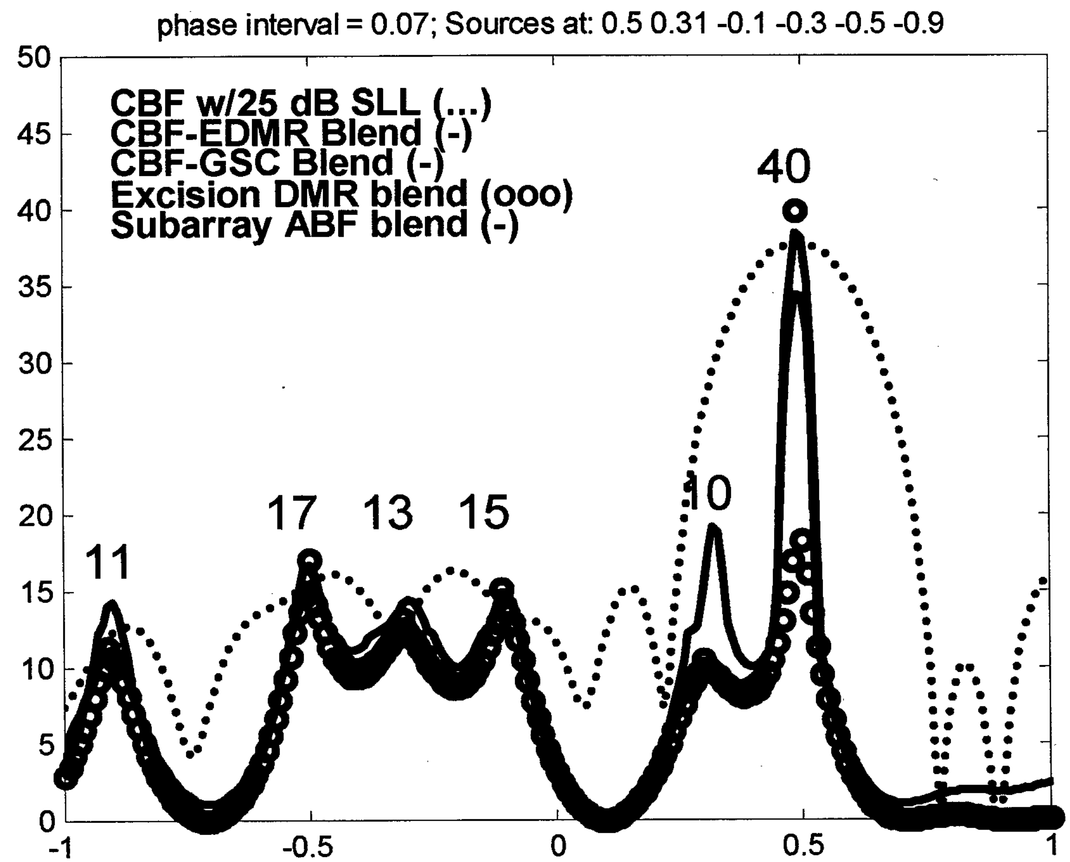


Figure 5.3

Six Stationary Sources

(pert=0.07, D = 7, N=48, M=12, f =0.2, sa group size = 4)

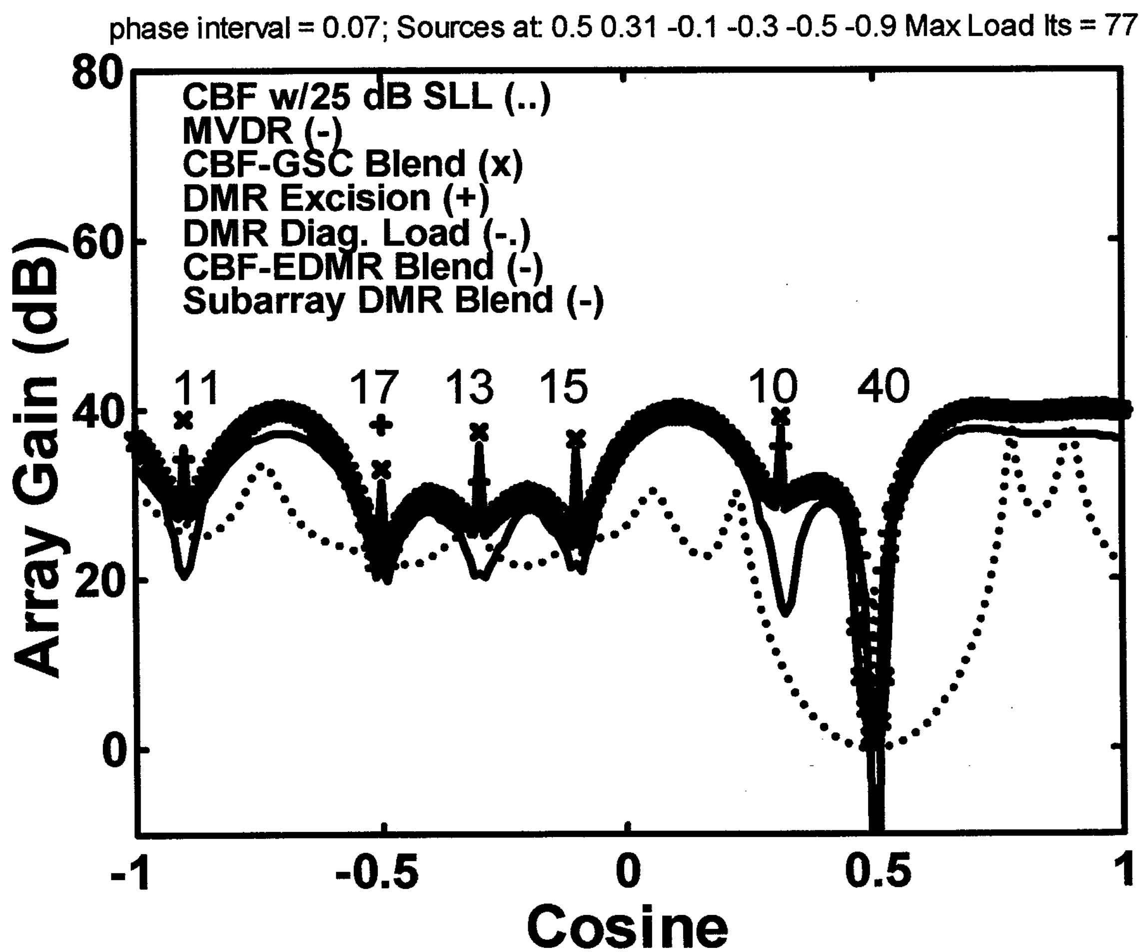


Figure 5.4

Six Stationary Sources

(pert =0.07, N =48, M = 8, D = 7, f =0.2, number of sensors per sa = 6)

phase interval = 0.07; Sources at: 0.5 0.31 -0.1 -0.3 -0.5 -0.9

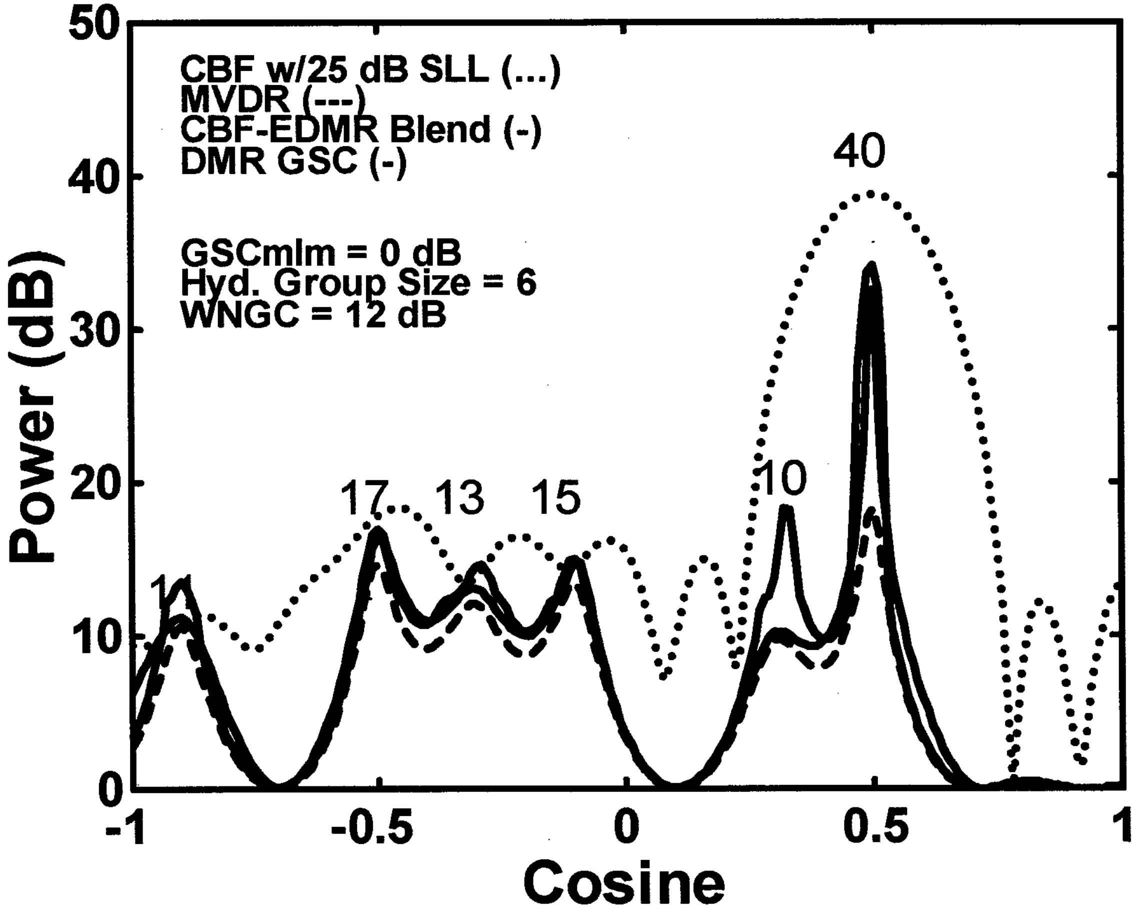


Figure 6.2

Six Stationary Sources

(pert =0.07, N =48, M = 8, D = 7, f =0.2, number of sensors per sa = 6)

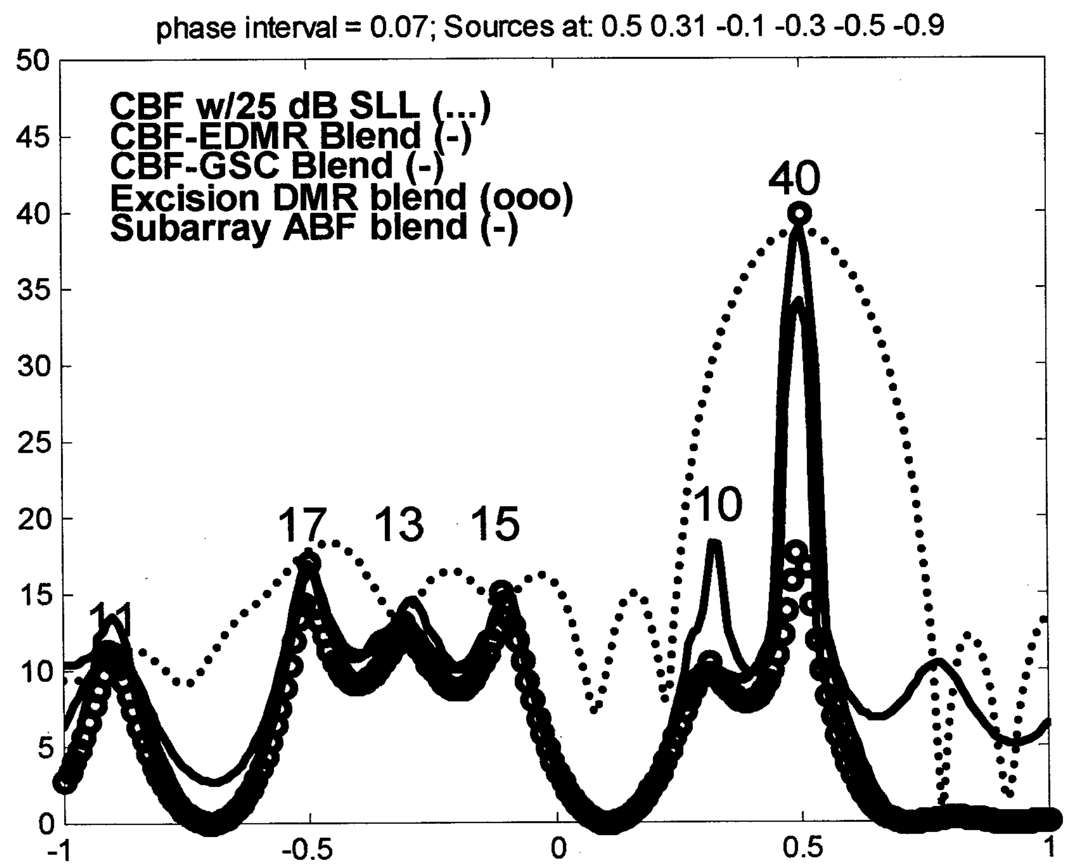


Figure 6.3

Six Stationary Sources

(pert =0.07, N =48, M = 8 , D = 7, f =0.2, number of sensors per sa = 6)

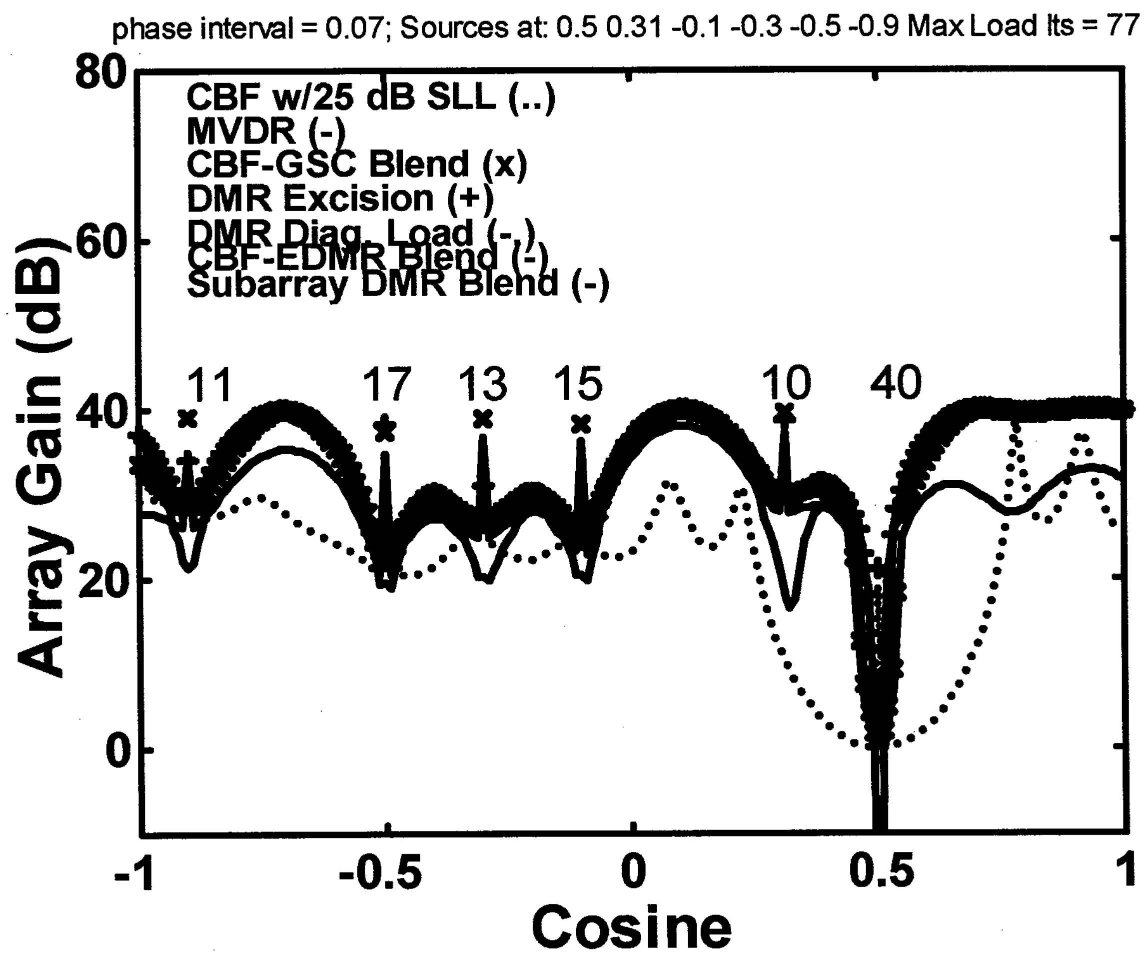
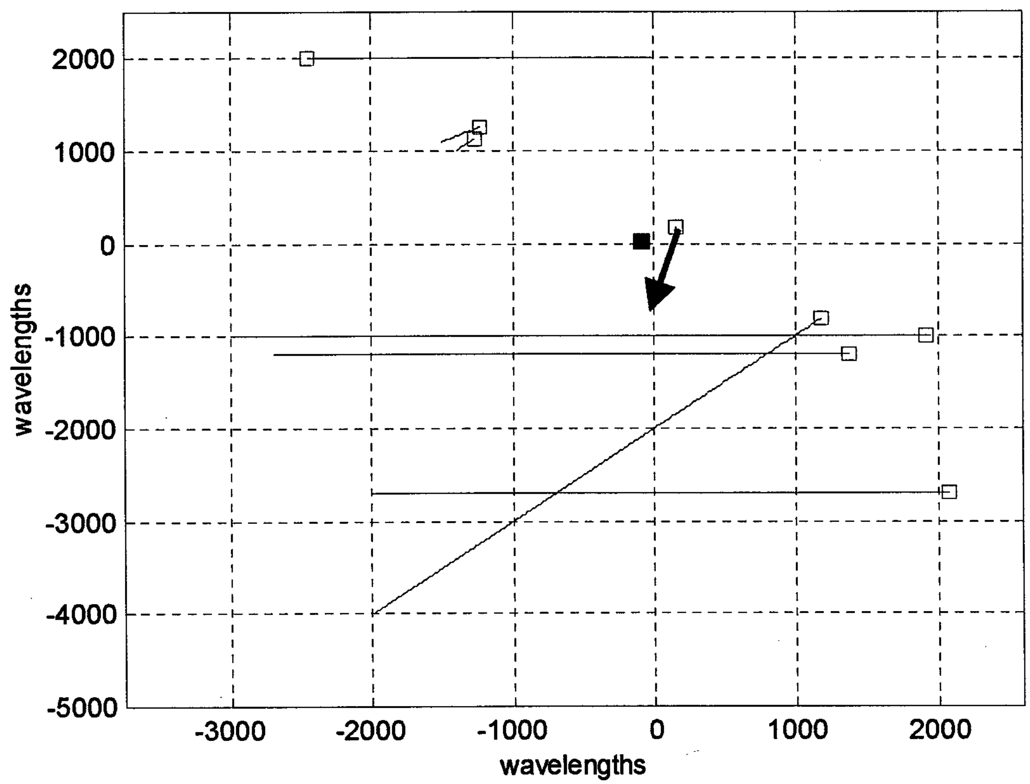


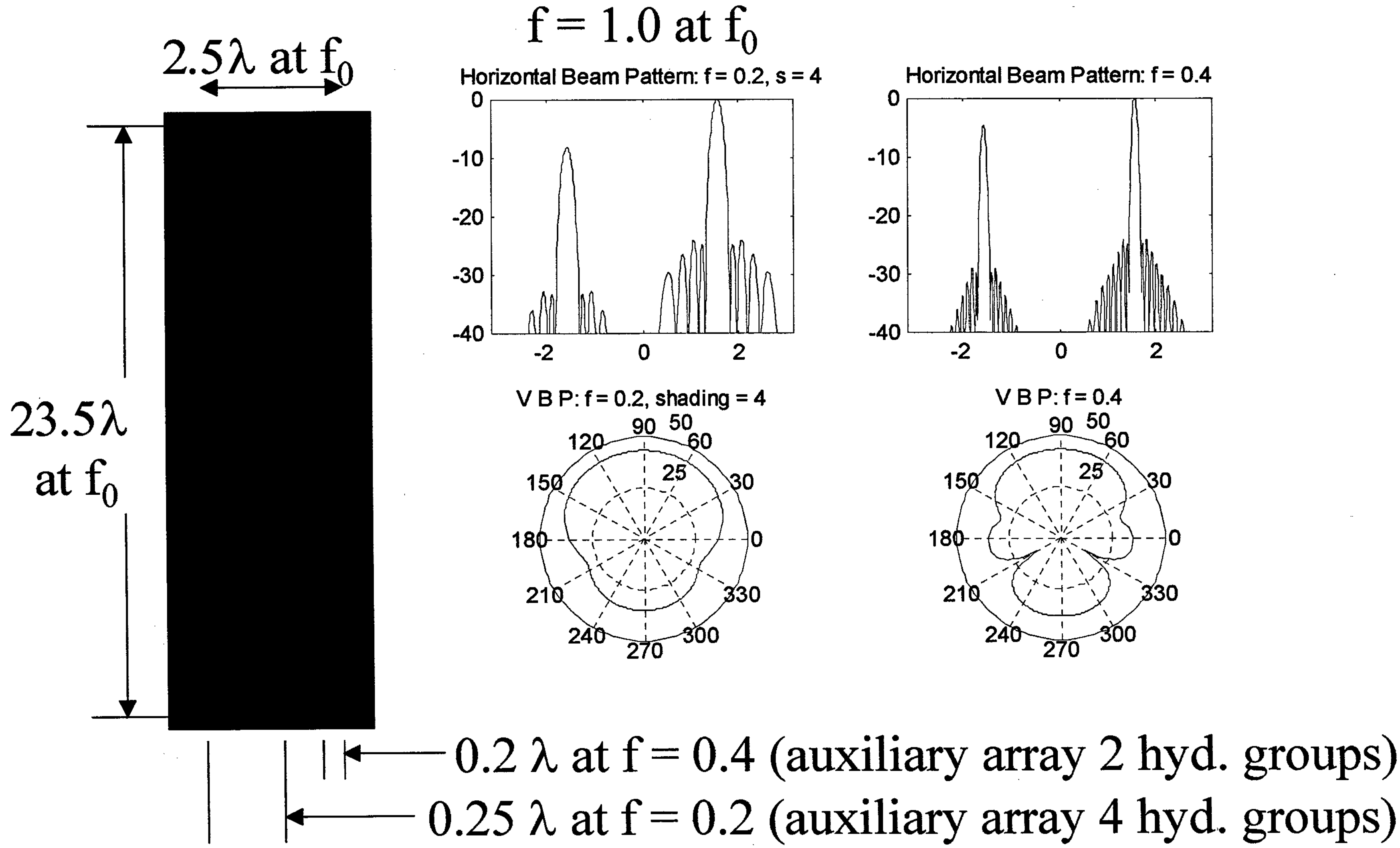
Figure 6.4

Ship Tracks: 30 Minute Event

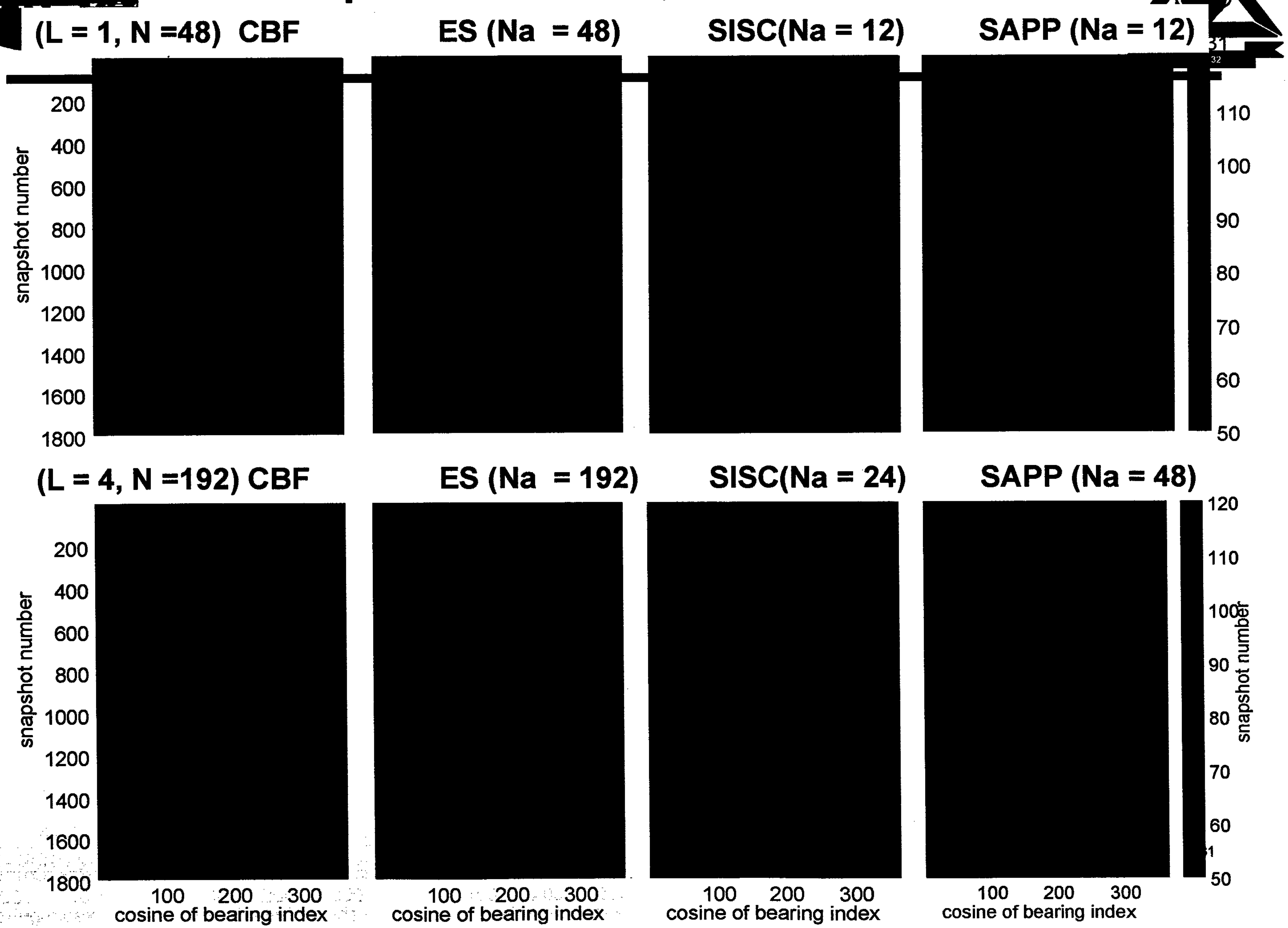
Multiple Source Tracks Re: Own Ship at Origin



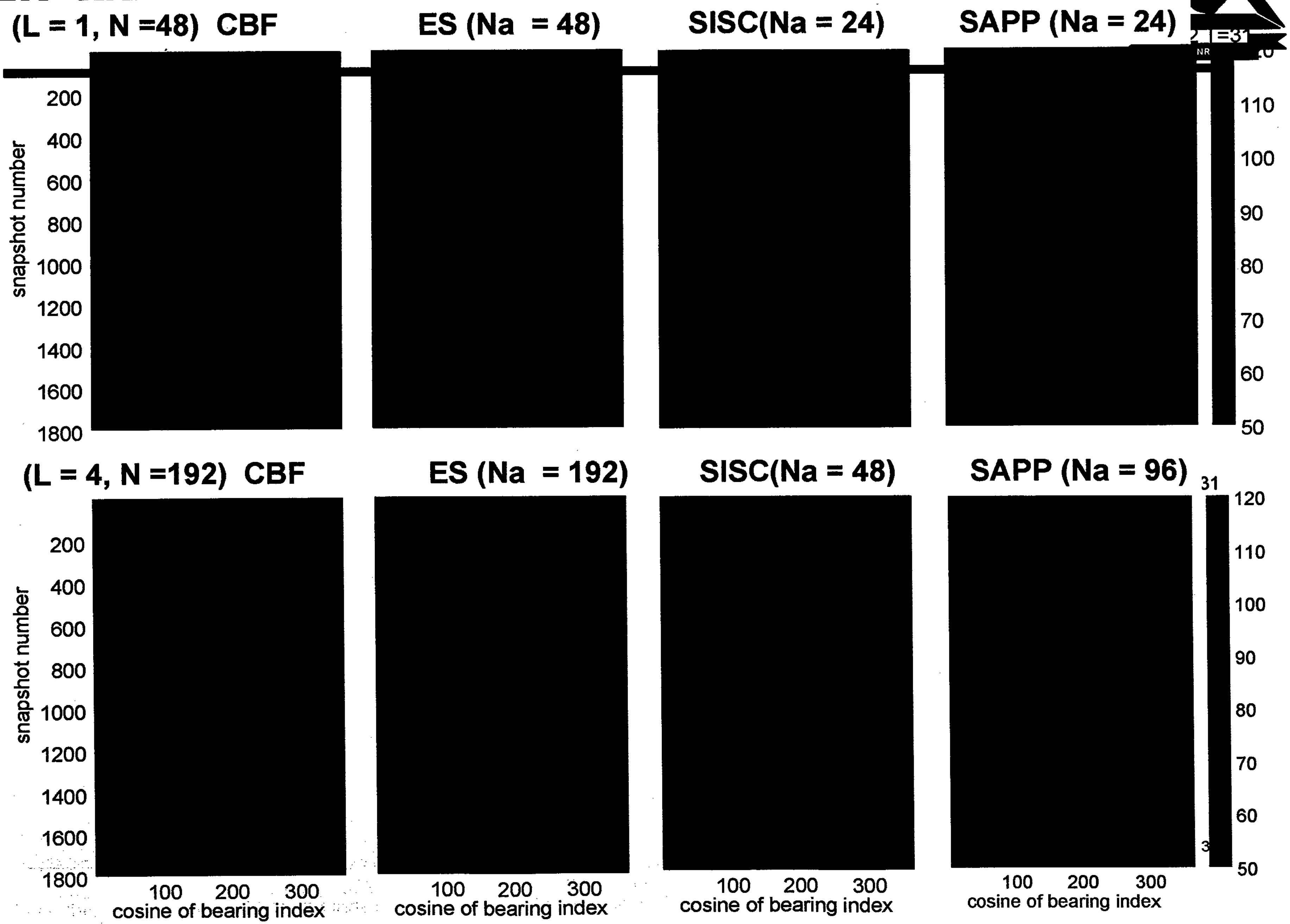
ONR Acoustic Observatory Segment
(L = 1, N = 48) or (L = 4, N = 192)



BTR Comparison: f = 0.2, D = 10 (PKE = Phase Known Exactly)



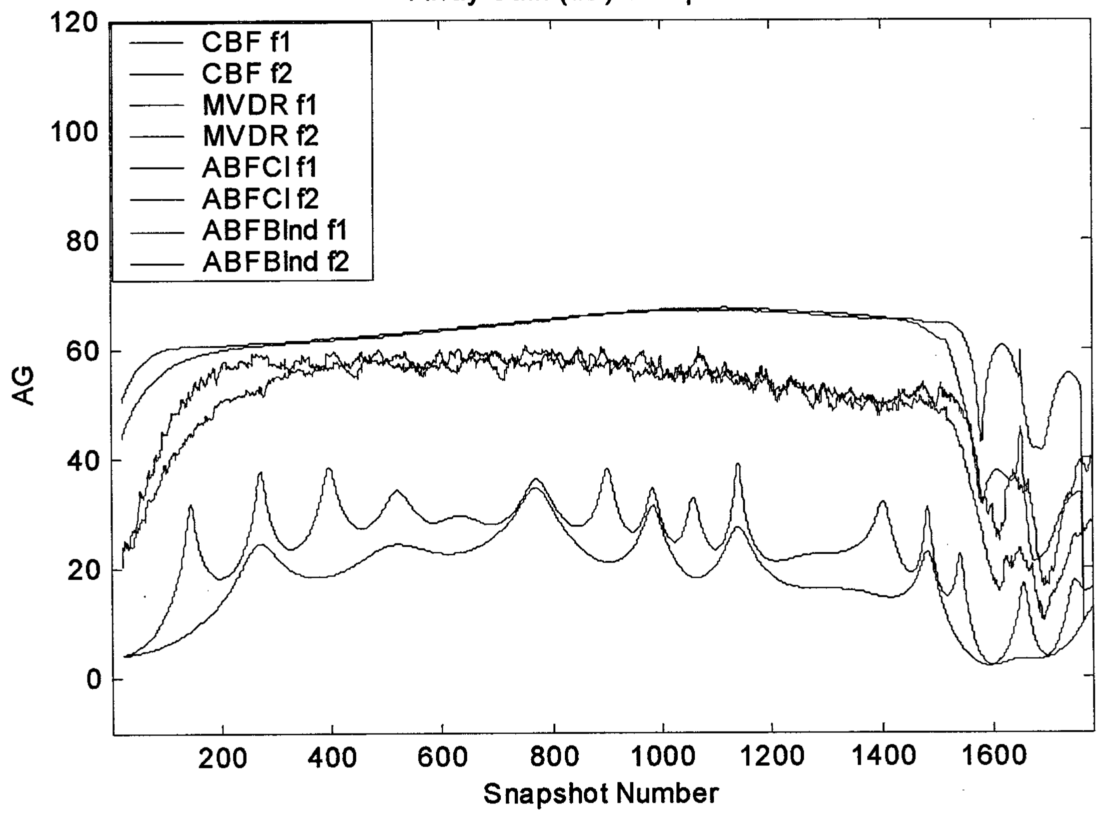
BTR Comparison: f = 0.4, D = 12 (PKE = Phase Known Exactly)



AG ES DMR: N = 48, D = 10/12

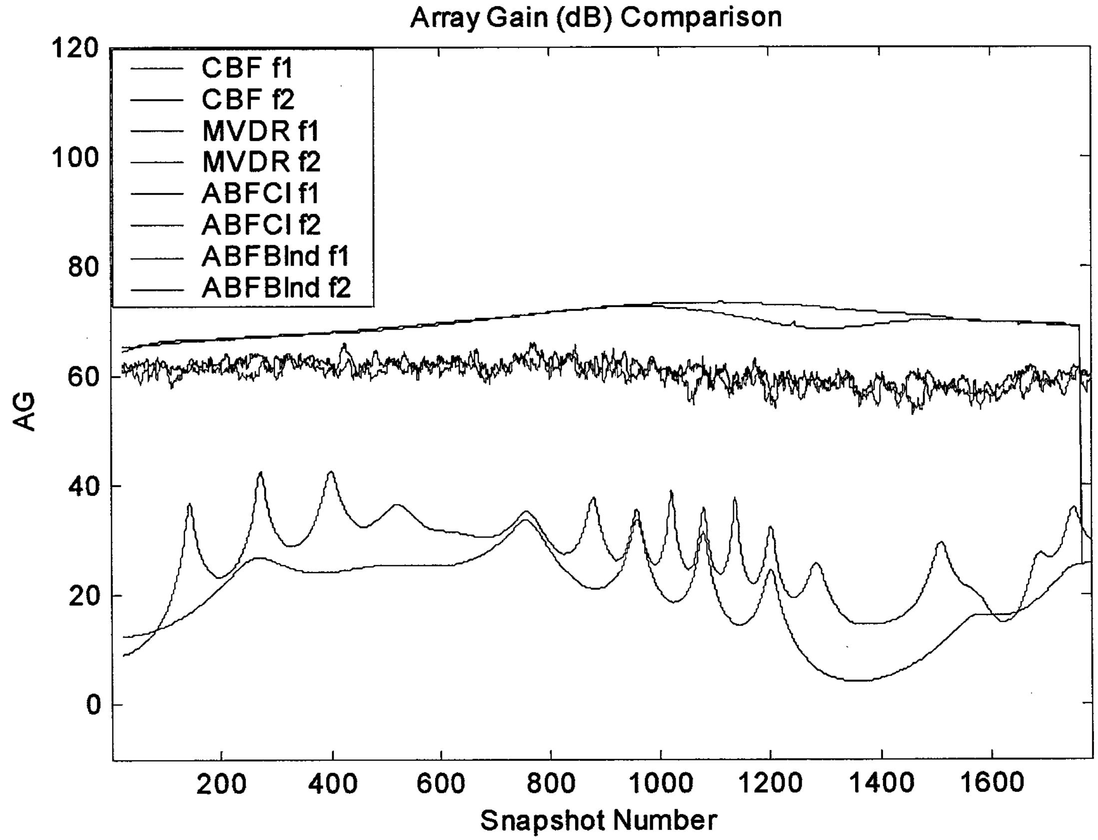
(PKE WNGC = 12 db)

Array Gain (dB) Comparison



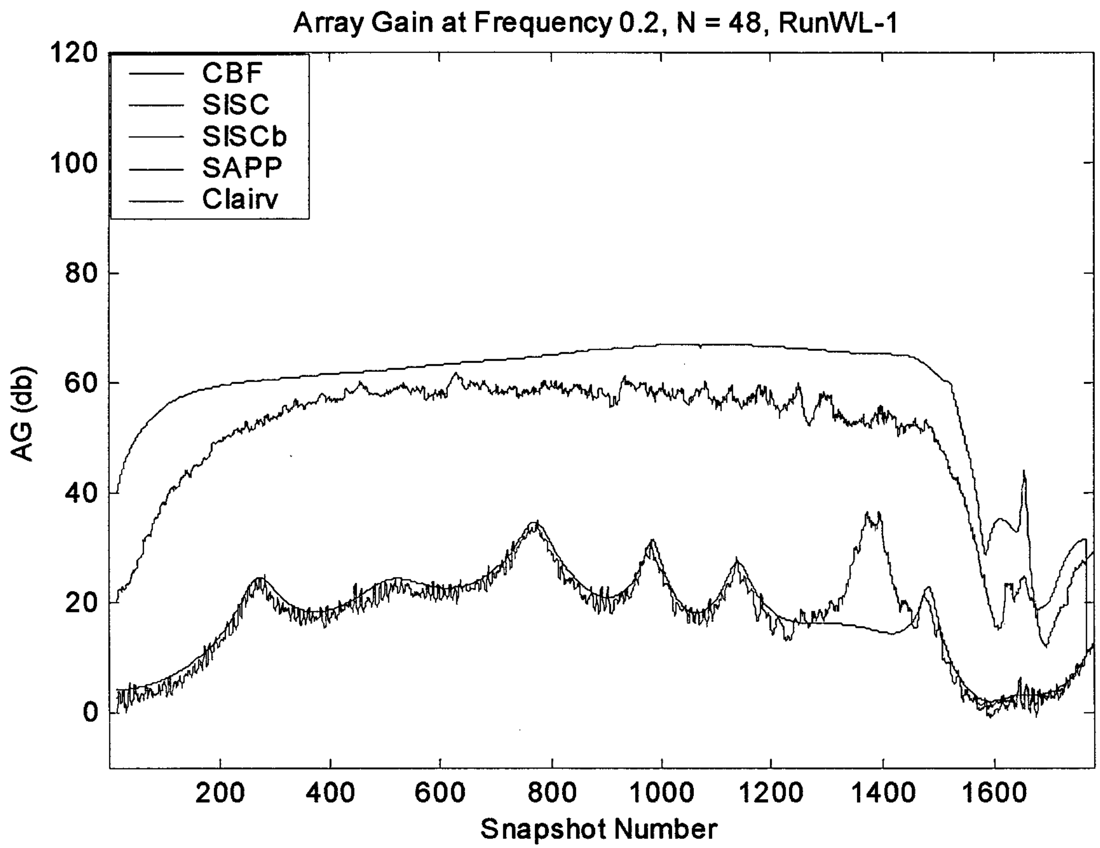
AG ES DMR: N = 192, D = 10/12

(PKE WNGC = 12 db)



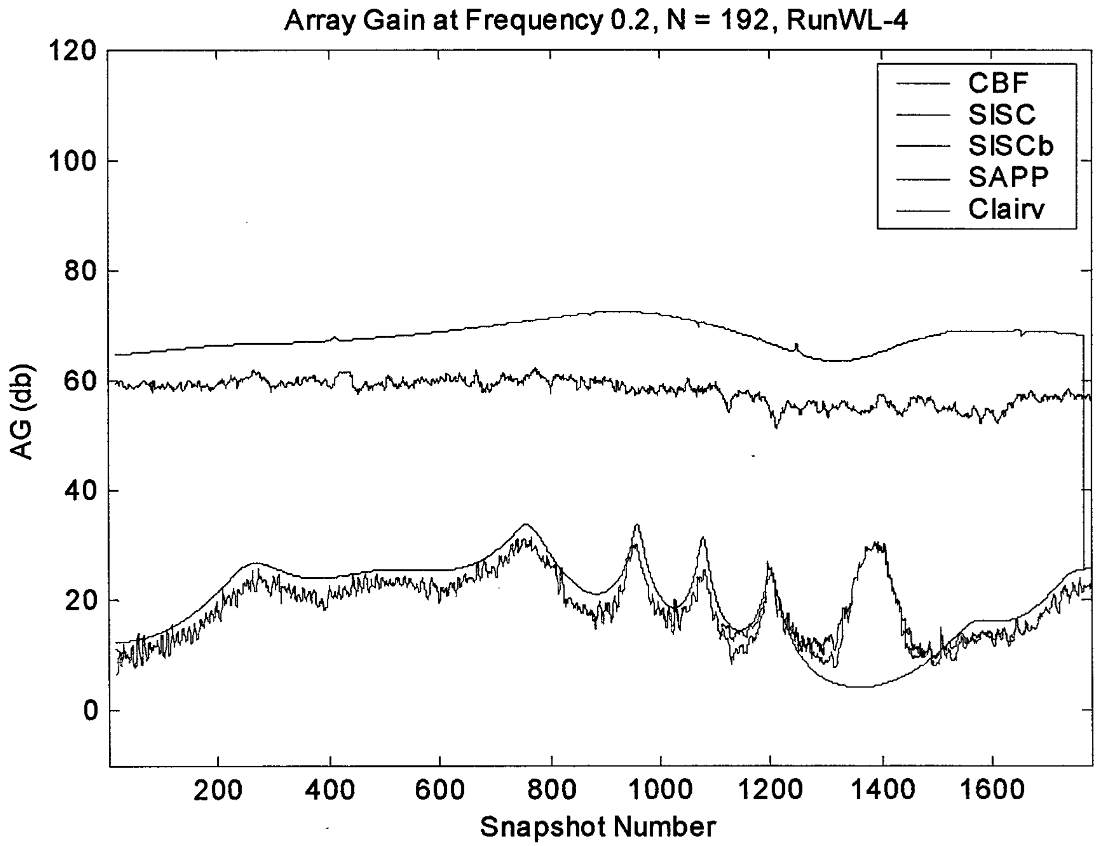
AG DMR: f = 0.2, N_a = 12, D = 10

(PKE)



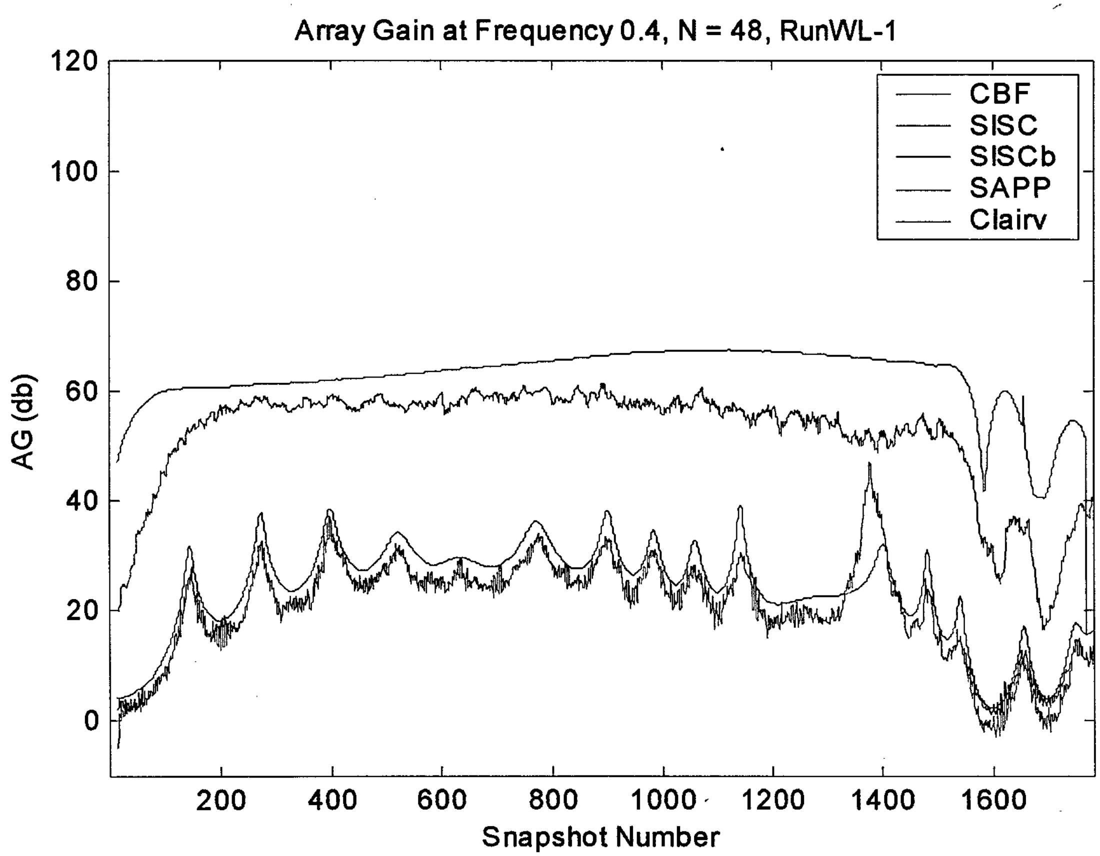
AG SA/SC DMR: f = 0.2, N = 192, D = 10/12

(PKE)



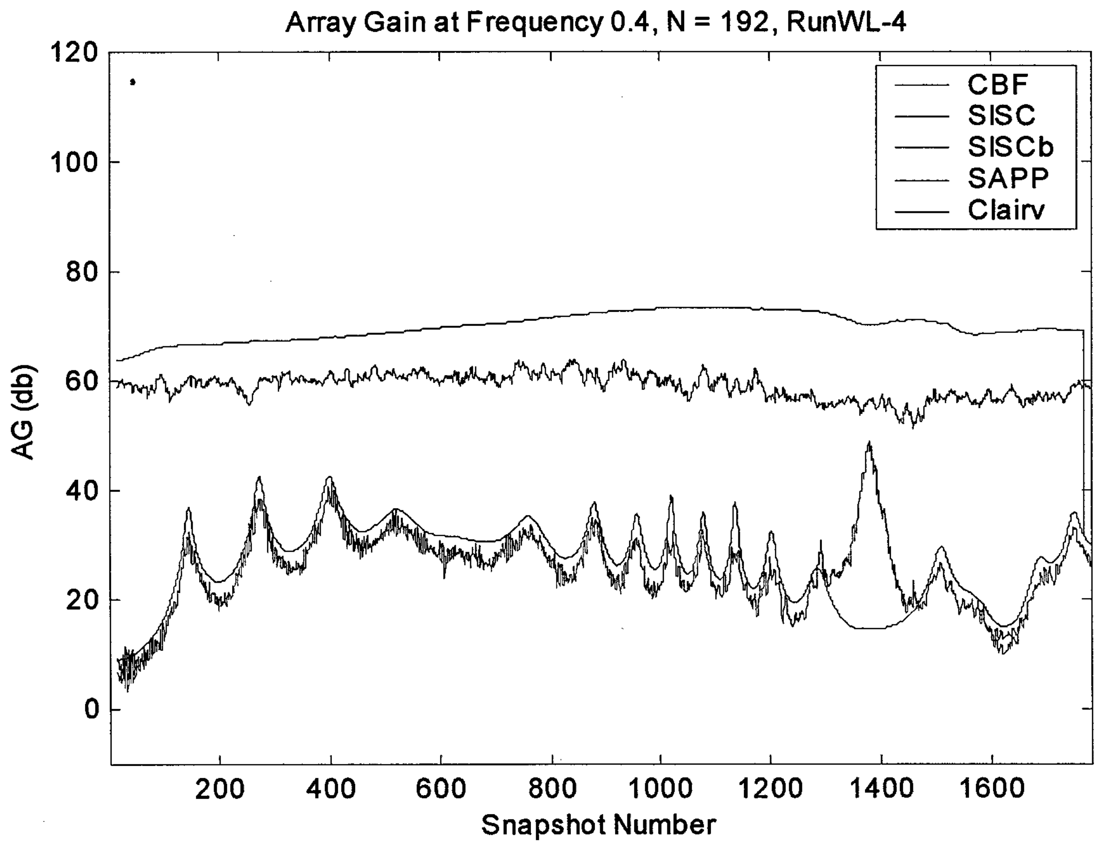
AG DMR: $f = 0.4, N_a = 24, D = 12$

(PKE)

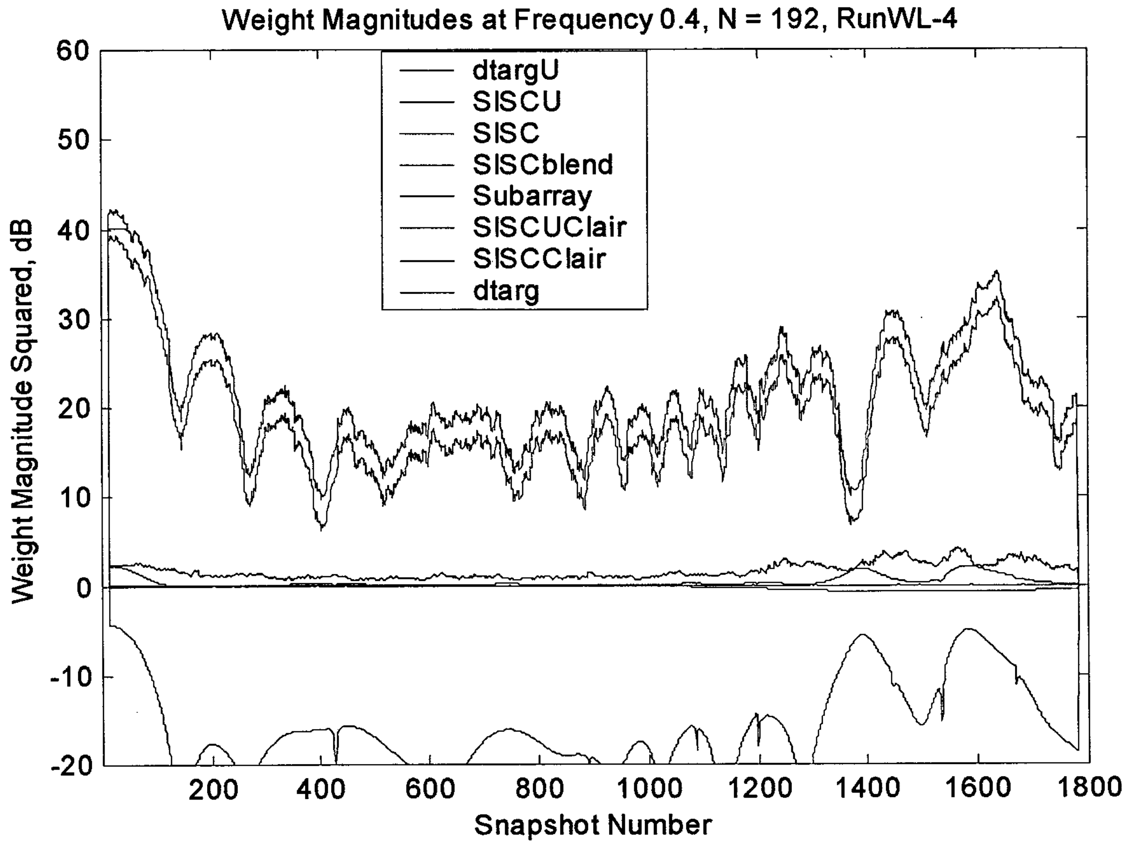


AG SA/SC DMR: f = 0.4, N = 192, D = 10/12

(PKE)



Clue to SISC AG Degradation: Stochastic v. Clairvoyant Weight Vector MS



Final Comments

Candidate ABF spaces for efficient DMR ABF:
Beam, subarray, auxiliary (sparseness is key)

Adaptation space sample vector should/can be independent of beam steering direction and have N_a order O(D + safety factor).

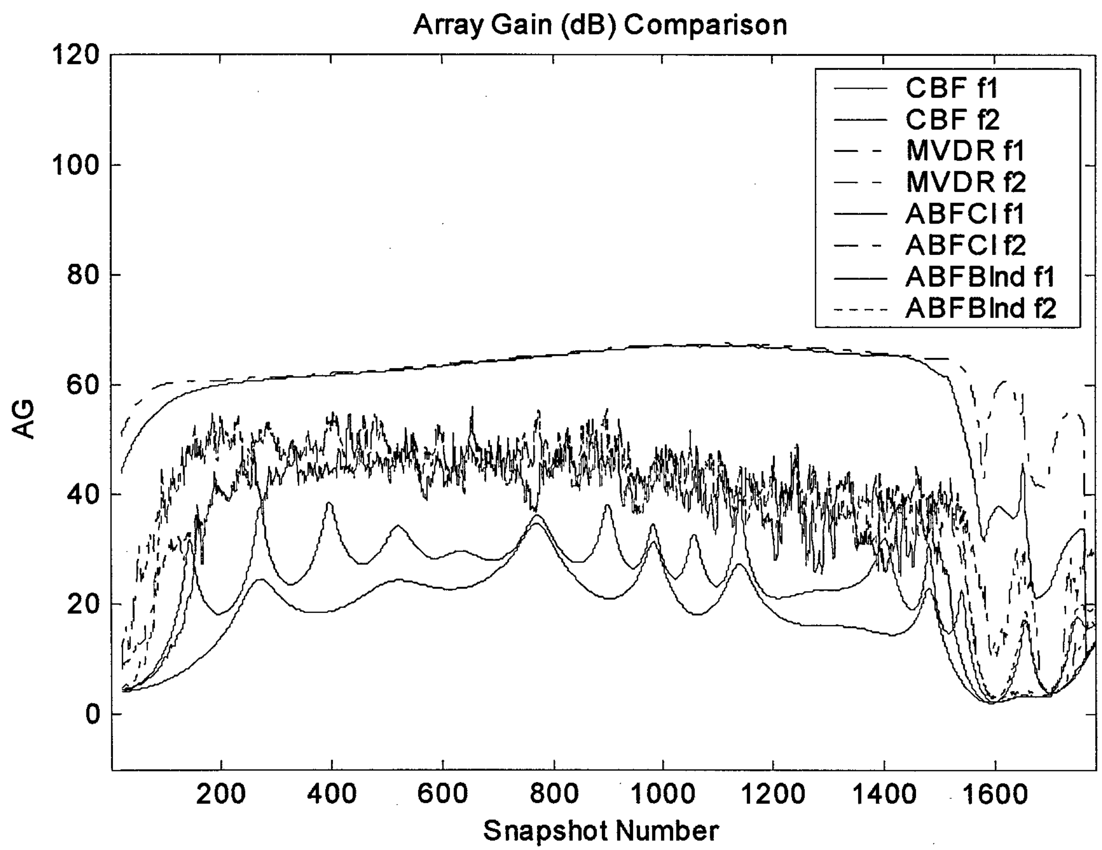
The Steering Invariant Sidelobe Canceller (SISC) is an auxiliary space method that can "hedge" on the spatial sampling theorem and increase efficiency. AG is an open issue.

"Measure" the need for ABF at higher frequencies.

Signal Suppression v. Spatial Resolution: Clairvoyant ABF without an infinite number of beams suppresses loud sources but, by definition, produces "the best" spatial resolution.

BACKUP

AG ES DMR: N = 48, D = 10/12 (2 degree phase pert)



Session V: Sonar I (Classified)

Adaptive Beamforming with the T-16 Array for Broadband Detection

H. Cox/ Orincon Corporation
S. Kogon/ MIT Lincoln Laboratory
H. Lai/ Orincon Corporation
T. Phipps/ UT ARL

Adaptive Array Processing for the MK-48 Torpedo in a Shallow Water Countermeasure Scenario

A. Mirkin/ NUWC
N. Pulsone/ MIT Lincoln Laboratory

An Adaptive Beamformer for Spectrum Analysis in Passive Sonar Systems

S. Kogon/ MIT Lincoln Laboratory
K. Arsenault/ MIT Lincoln Laboratory

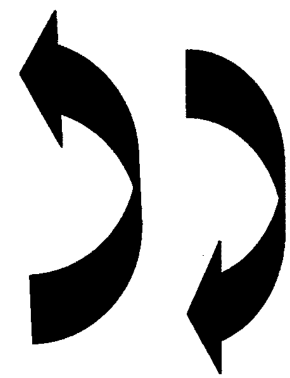
Sub-Aperture Beamspace Adaptive Array Processing

H. Freese/ SAIC
B. Sperry / SAIC
K. Votaw/ / SAIC

Session V: Sonar I - Themes

<u>Detection v. Classification in Clutter</u>

ABF for Detection in Clutter
- Spatial resolution is key
- Aggressive/minimally constrained BB ABF
- High SNR signal suppression is acceptable



ABF for Classification in Clutter
- Minimum spectral distortion is key
- Highly constrained mainlobe ABF
- Must balance rejection of undesired interference in the beam with suppression of desired signal in the same beam

<u>Rapid Adaptivity</u>
- Reverberation, shipping dynamics, array motion and high data dimensionality

Shipping Parameters

Number of sources = 8

Source SoA = 1.5 knts.

Source SoA = 4.1 knts.

Source SoA = 8.2 knts.

Source SoA = 6.8 knts.

Source SoA = 7.5 knts.

Source SoA = 6.8 knts.

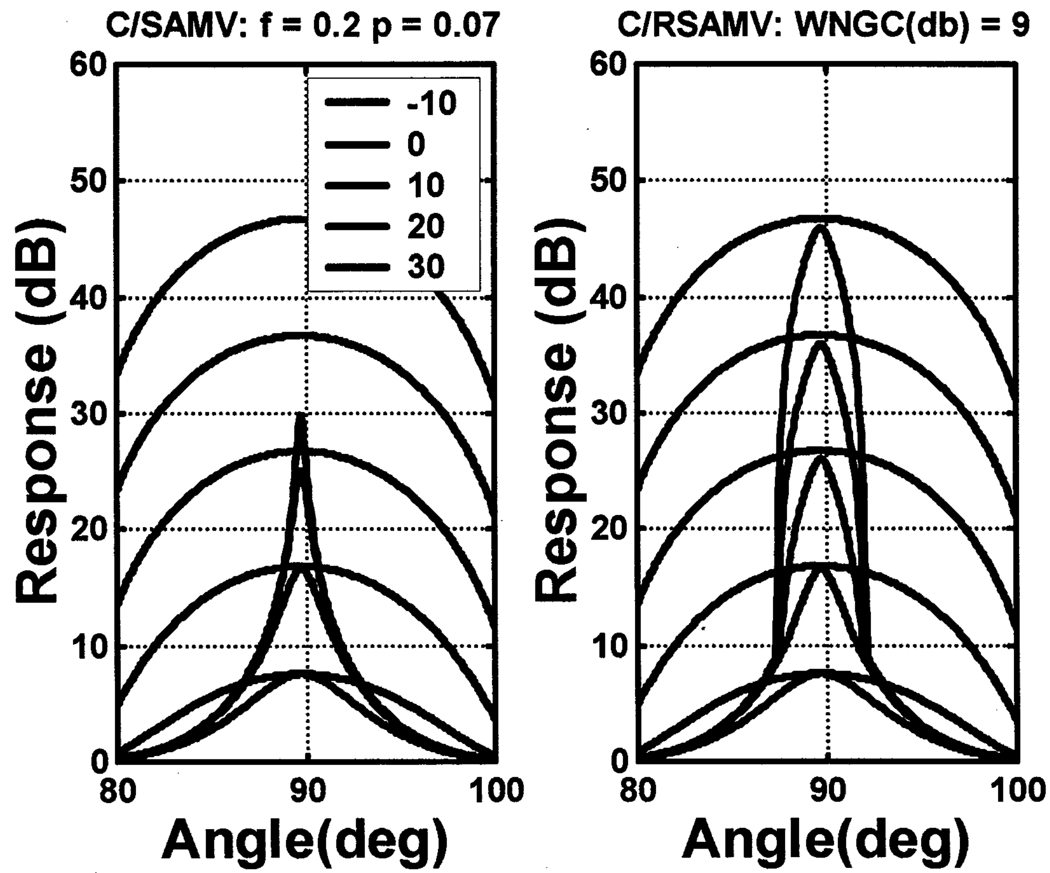
Source SoA = 0.5 knts.

Source SoA = 0.3 knts.

Source Level Range(wl) Prop Loss Amb Level SNR SoA(wl/s) Heading (SourceInfo = 1.0e+003 *)

Source Level	Range(wl)	Prop Loss	Amb Level	SNR	SoA(wl/s)	Heading
0.1000	0.7018	0.0569	0.0600	-0.0169	0.0015	0.0800
0.1650	2.0000	0.0660	0.0600	0.0390	0.0041	0.1800
0.1700	3.1623	0.0700	0.0600	0.0400	0.0082	0
0.1500	3.3601	0.0705	0.0600	0.0195	0.0068	0
0.1650	4.4721	0.0730	0.0600	0.0320	0.0075	0.0450
0.1600	2.9547	0.0694	0.0600	0.0306	0.0068	0
0.1200	1.8601	0.0654	0.0600	-0.0054	0.0005	0.0300
0.1250	1.7205	0.0647	0.0600	0.0003	0.0003	0.0450

Figure 3.4


C/SAMV: f = 0.2 p = 0.07
Response (dB)
Angle(deg)
-10
0
10
20
30
60
50
40
30
20
10
0
80
90
100
C/RSAMV: WNGC(db) = 9
Response (dB)
Angle(deg)

Six Stationary Sources

(pert=0.07, D = 7, N=48, M=12, f =0.2, sa group size = 4)

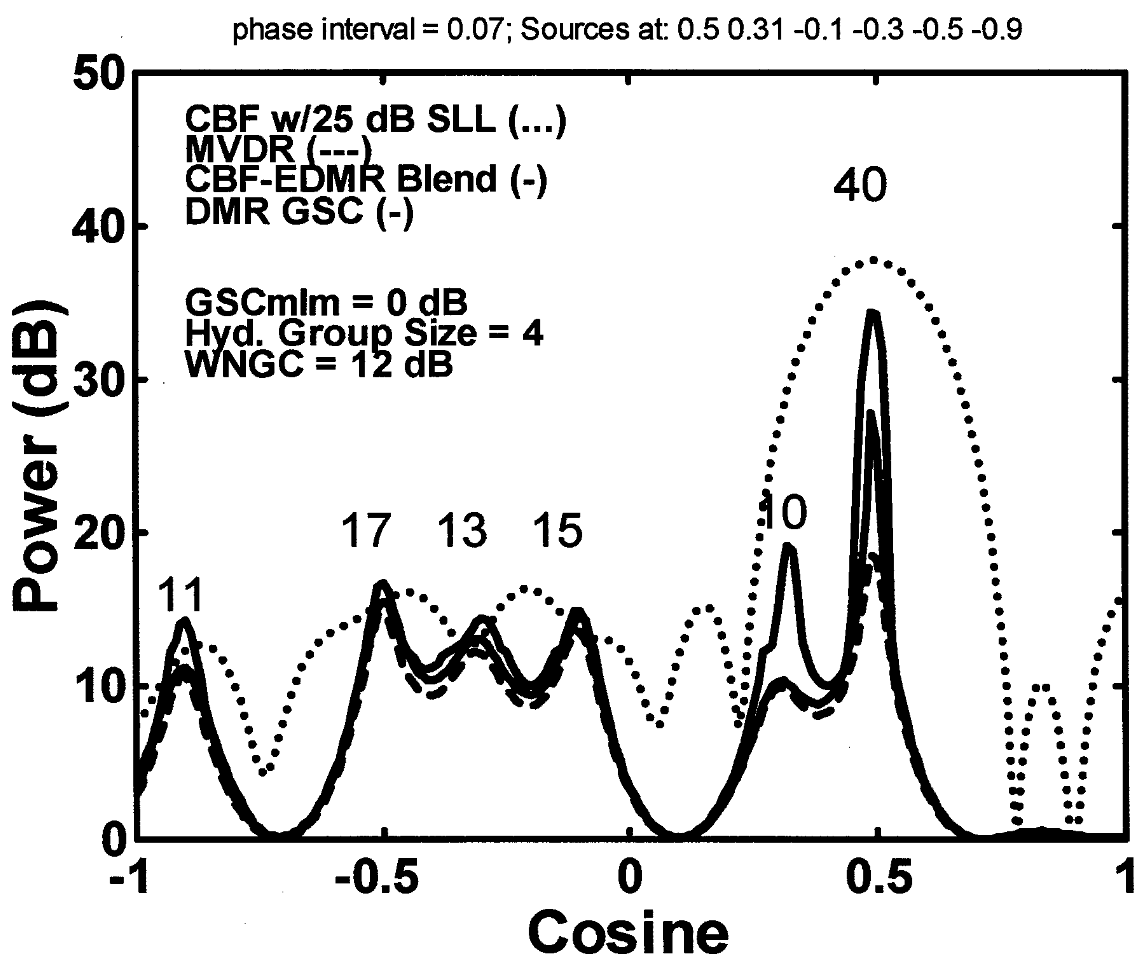


Figure 5.2