AFRL-SN-RS-TR-2001-146 Vol III (of VI)
Final Technical Report
July 2001

KNOWLEDGE BASE APPLICATIONS TO ADAPTIVE SPACE-TIME PROCESSING, VOLUME III: RADAR FILTERING RULE BOOK

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AFRL-SN-RS-TR-2001-146 Vol III (of VI) has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	JULY 2001	Final Aug 95 - Jul 99

4. TITLE AND SUBTITLE
KNOWLEDGE BASE APPLICATIONS TO ADAPTIVE SPACE-TIME PROCESSING, VOLUME III: RADAR FILTERING RULE BOOK

5. FUNDING NUMBERS
C - F30602-95-C-0041
PE - 62702F
PR - 4506
TA - 11
WU - 2B

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8. PERFORMING ORGANIZATION REPORT NUMBER
SRC TD 97-1466

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory/SNRT
26 Electronic Pky
Rome New York 13441-4514

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFRL-SN-RS-TR-2001-146
Vol III (of VI)

11. SUPPLEMENTARY NOTES
Air Force Research Laboratory Project Engineer: Michael C. Wicks/SNRT/(315) 330-2556

12a. DISTRIBUTION AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report describes potential radar filtering for a knowledge-based space-time adaptive processor. The description for each rule includes a brief discussion, a list of data sources required for decision making, a list of the filter parameters that must be specified by the knowledge base controller, and the decision process.

14. SUBJECT TERMS
Radar, Algorithms, Signal Processing, Space-Time Adaptive Processing, STAP

15. NUMBER OF PAGES
40

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Standard Form 298 (Rev. 2-89) (EG)
Prescribed by ANSI Std. 239.18
Designed using Perform Pro, WHS/DIOR, Oct 94

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1.0 Introduction

Six knowledge base control (KBC) radar filtering rules are presented here. The description for each rule includes a brief discussion, a list of data sources required for decision making ("KBC input"), a list of the filter parameters that must be specified by the knowledge base controller ("KBC output"), and the decision process ("KBC algorithms"). The associated filter processors are described in a companion document [1]. Examples contained in that report were used, in part, in determining the rules described here.

Rule 1, "Subarray/Sub-CPI Nulling," refers to a nonadaptive method whereby optimized space/time subarrays are formed that "prefilter" interference prior to adaptive filtering (e.g., space/time adaptive processing (STAP)). Rule 2, "Space/Time Sidelobe Levels," refers to determining the optimum receive array weighting and Doppler filter weighting to apply in deterministic filtering and in the steering vector for STAP filtering. Rule 3, "STAP Selection," refers to selection of the optimum STAP method to apply, or whether to apply STAP at all. Rule 4, "Array Notching Plus Spatial Only Adaptivity (Antijam)," refers to the deterministic notching of the receive antenna array factor for purpose of suppressing moving discretes type clutter (aircraft, highway traffic, etc.) from the test and reference range cells applied in STAP (STAP is particularly vulnerable to moving discretes type clutter). Rule 5, "Sample Selection/Shadowing," refers to the optimum means of choosing reference range cells for STAP. Finally, Rule 6, "Diagonal Loading," refers to determination of the minimum amount of diagonal loading required for STAP.

This rulebook, of course, is neither optimized nor complete. It encapsulates the best decisions (including "educated guesses") made within the time and funding constraints of the current effort. With time, it is hoped that additional data and experiences would be applied to modifying the current rules to bring them to a more "optimum" state and to including additional rules that would apply to airborne radar system variants not addressed here. For example, some rules, such as Sample Selection/Shadowing (Rule 5), are based on particularly limited data.

Also, the rules to date apply only to monostatic radar, to STAP channels spatially arrayed in one dimension, to "notching" in space only (although subarray nulling in time as well as in space is addressed), to sidelobe barrage noise jamming only, and to the use of diagonal loading rather than mainlobe constraints for limiting target signal suppression in STAP. Other subjects such as bistatic radar, coherent repeater jamming, and mainlobe constraints are addressed in [1].

It was assumed, also, that processing limitations would not be a principal issue in rule selection. Consequently, rules were selected with little regard to the processing resource load of the radar. For example, it usually was assumed that pulse compression and Doppler filtering would precede STAP since limited degree of freedom adaptivity was shown to be most effective if all deterministic filtering occurs first. (Otherwise the degrees of freedom would be "spread thin" suppressing clutter that would subsequently be suppressed by the deterministic filters. A caution here is that with post compression/post Doppler STAP the pulse compression sidelobes must be low enough to keep the target return well below noise in the reference range cells or excessive diagonal loading (Rule 6) or mainlobe constraints may be required.) Processing load is far greater for post compression/post Doppler STAP.

2.0 Rules

2.1 Subarray/Sub-CPI Nulling (Rule 1)

Subarrays in space and in time (sub-CPIs) are formed such that the subarrays (in space) null Doppler filter mainlobe clutter and the sub-CPIs null antenna mainlobe clutter. The subarray/sub-CPI weights are determined nonadaptively as optimal factored binomial distributions in space and in time. The purpose of this filter processor is to reduce the clutter dynamic range prior to STAP. The knowledge base controller (KBC) determines the sizes of the subarrays and sub-CPIs and passes this information to the filter. The subarrays will be overlapping and the sub-CPIs will be overlapping so that the respective separations will be one column spacing in space and one PRI in time. Overlapping is important to avoid space/time grating lobes.

2.1.1 Data Sources

Data required by the KBC, to determine the subarray/sub-CPI parameters required by the filter, are obtained from the following sources:

1. Radar parameter data base [transmit power (P_t), antenna gains (G_t, G_r), Doppler filter gain (G_d), frequency, noise figure (F), loss (L)]
2. Radar scheduler/controller [test range cell (R_t), test range rate cell (v_t), beam position (θ_o)]
3. Mission data base [minimum target cross section (σ_t)]
4. Platform control data [drift ("crab") angle (θ_c) and platform velocity (v_o)]
5. Radar detection processor [minimum signal to noise ratio (SNR_{min})]
6. Result of Rule 2 (space/time sidelobe levels)

Here, SNR_{min} is determined in the detection processor as the signal to noise ratio that will yield a desired false alarm rate and detection probability.

2.1.2 Filter Parameters

The following parameters are determined by the KBC and transmitted to the filter:

1. Decision whether to digital subarray
2. Number of subarray elements (n_{rs})
3. Number of sub-CPI pulses (n_{ds})

2.1.3 Decision Process

If the antenna feed architecture contains analog combining in azimuth, as would be the case with fewer receivers than array columns, the decision is not to digitally form subarrays/sub-CPIs. Also, if the test range cell or test range rate cell (Doppler bin) are clutter free, subarrays/sub-CPIs are not to be formed. A clutter free range rate cell occurs when the target radial velocity relative to ground (v_t) satisfies

$$\begin{aligned} v_t &> v_0 \ \text{ or } \ v_t < v_0\left(\cos\theta_c + \sin(\theta_0+\theta_c)\right) \quad \text{for } \theta_c > 0 \\ v_t &< -v_0 \ \text{ or } \ v_t > v_0\left(\cos\theta_c - \sin(\theta_0+\theta_c)\right) \quad \text{for } \theta_c < 0 \end{aligned} \tag{2-1}$$

where

θ_o = beam position azimuth angle (see Figure 2-1)

θ_c = drift (crab) angle (see Figure 2-1)

v_o = platform velocity

Otherwise, subarray/sub-CPIs are to be formed and the KBC determines n_{rs} and n_{ds} an iterative procedure described below.

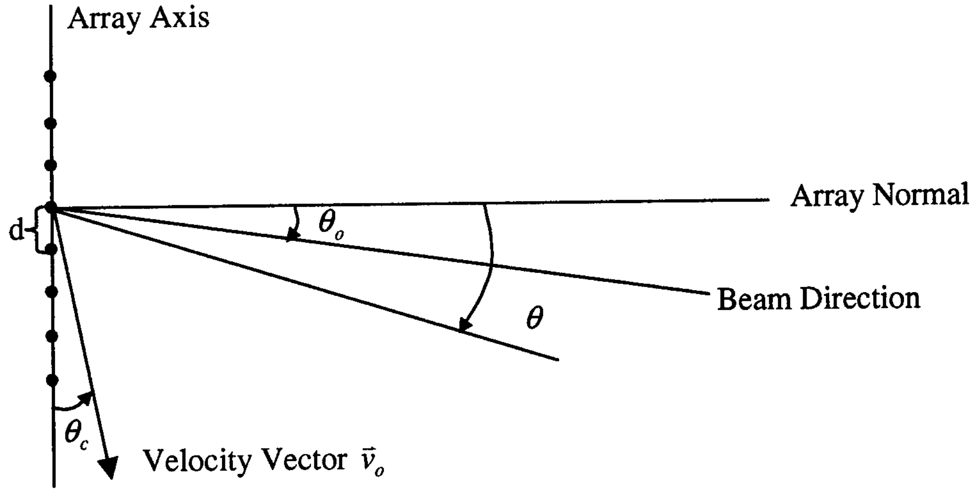

Figure 2-1: Antenna Geometry in Horizontal Plane

First, some secondary parameters are defined. The maximum estimated signal to noise ratio (SNR_{max}) is determined from the radar parameters, test range cell (R_t), and minimum target cross section (σ_t) in accordance with the radar range equation. Here, the absence of all external interference (jamming, clutter, etc.) is assumed so that maximum signal to noise occurs with uniform transmit and receive aperture weightings and uniform Doppler filter weighting. The appropriate equation is

$$SNR_{\max} = \frac{P_t\, G_t\, G_r\, G_d\, \sigma_t\, \lambda^2}{(4\pi)^3\, R_t^4\, k_b\, T_o\, B\, F\, L} \qquad (1\text{-}2)$$

where,

P_t = transmitter radiated power (W)

G_t = transmit antenna directive gain

G_r = receive antenna directive gain

G_d = Doppler filter gain

λ = wavelength (m)

k_b = Boltzmann's Constant ($W/Hz/K$)

T_0 = 290 K ($kT_0 = 4 \cdot 10^{-21}$ W/Hz)

F = receiver noise figure

B = bandwidth (Hz)

L = receive antenna loss

Also, the processing margin (r) is defined as

$$r = SNR_{max} / SNR_{min}$$

The objective of the iterative procedure, then, is to apply as much interference suppression processing as possible without allowing the signal to noise loss due to processing (f_ℓ) to exceed r. The contributions to this loss are weighting losses and subarray/sub-CPI scan losses. In particular,

$$f_\ell = \left(\eta_{eff}\; G_{rs}\,(0)\, G_{ds}\,(v_t)\right)^{-1} \qquad (2\text{-}3)$$

where,

η_{eff} = total transmit/receive antenna aperture/Doppler filter efficiency

$G_{rs}(\psi)$ = subarray gain normalized to unity in peak direction

$G_{ds}(v_r)$ = sub-CPI gain normalized to unity at peak Doppler velocity (radial, velocity)

ψ = *sine* space azimuth angle relative to that of the beam position

v_r = radial velocity relative to beam direction ground radial velocity

Here,

$$\psi = sin(\theta) - sin(\theta_0) \tag{2-4}$$

where, θ = azimuth angle (see Figure 2-1) and

$$v_r = v - v_0\, sin(\theta_0 + \theta_c) \tag{2-5}$$

where, v = radial velocity of the scatterer or scattering center. Also

$$\eta_{eff} = \eta_t\eta_r\eta_d\eta_{rs}\eta_{ds} \tag{2-6}$$

where, η_t, η_r, and η_d are, respectively, the transmit aperture azimuth plane efficiency, receive array factor efficiency, and CPI factor (Doppler) efficiency. These quantities are directly determined from the weights corresponding to the respective sidelobe levels s_t (transmit antenna), s_r (receive antenna), and s_d (Doppler Filter). The losses corresponding to these efficiencies usually can be neglected in the decision process here. If desired, they can be computed from the corresponding N weights, w_i, $i = 1\ldots N$, according to

$$\eta = \frac{\left(\sum_{i=1}^{N} w_i\right)^2}{N\sum_{i=1}^{N} w_i^2} \tag{2-7}$$

Linear Taylor distribution weights are recommended.

The remaining efficiencies, η_{rs} and η_{ds}, refer to the subarray efficiency and sub-CPI efficiency, respectively. Let $w_{a\ell}, \ell = 1,\ldots n_{rs}$, and $w_{di}, i = 1,\ldots n_{ds}$, correspond to the respective weights (complex numbers because the subarray/sub-CPIs are steered). The efficiencies then are related to n_{rs} and n_{ds} by

$$\eta_{rs} = \frac{\left(\sum_{\ell=1}^{n_{rs}} |w_{a\ell}|\right)^2}{n_{rs} \sum_{\ell=1}^{n_{rs}} |w_{a\ell}|^2} \tag{2-8}$$

and

$$\eta_{ds} = \frac{\left(\sum_{i=1}^{n_{ds}} |w_{di}|\right)^2}{n_{ds} \sum_{i=1}^{n_{ds}} |w_{di}|^2} \tag{2-9}$$

where the binomial weights for an *n* element subarray (or *n* pulse sub-CPI) are given by

$$|w_i| = \binom{n-1}{i-1}(-i)^{i-1} \qquad i = 1,2,\ldots,n \tag{2-10}$$

Also, the subarray/sub-CPI gains ($G_{rs}(\psi)$ and $G_{ds}(v_r)$) are given by

$$G_{rs}(\psi) = \frac{\left|\sum_{\ell=1}^{n_{rs}} w_{a\ell} e^{jk\psi\ell d}\right|^2}{{\sum_{\ell=1}^{n_{rs}} |w_{a\ell}|}^{2}} \tag{2-11}$$

and

$$G_{ds}(v_r) = \frac{\left|\sum_{i=1}^{n_{ds}} w_{di} e^{jk2(v_r - v_t)iT}\right|^2}{{\sum_{i=1}^{n_{ds}} |w_{di}|}^{2}} \tag{2-12}$$

where

k = wavenumber

d = antenna column spacing

T = pulse repetition interval (PRI)

The iterative procedure, then, for determining the subarray/sub-CPIs is an attempt to maximize clutter suppression within the constraint

$$f_\ell < r \tag{2-13}$$

In this procedure, beam broadening factors β_a, β_d are determined from Figure 2-2 [2] in accordance with the receive antenna sidelobe level (for determining β_a) and the Doppler filter sidelobe level (for determining β_d). Also, the normalized antenna beamwidth in velocity space (v_w'), as mapped by the clutter ridge, and the normalized Doppler filter beamwidth in angle space (ψ_w'), as mapped by the clutter ridge, are determined according to

$$v_w' = v_0 \frac{\cos(\theta_0 + \theta_c)}{\cos\theta_0} \beta_a \frac{2T}{D} \tag{2-14}$$

and

$$\psi_w' = \frac{1}{v_0\left(\cos\theta_c - \sin\theta_c\,(\psi_t + \sin\theta_0)\left(1 - (\psi_t + \sin\theta_0)^2\right)^{-1/2}\right)} \beta_d \frac{d}{2T_{CPI}} \tag{2-15}$$

where, ψ_t, the sine space value along the clutter ridge corresponding to the test cell radial velocity ($v_r = v_t$), is given by

$$\psi_t = \sin\left(-\theta_c + \sin^{-1}\left(\frac{v_t}{v_0} + \sin(\theta_0 + \theta_c)\right)\right) - \sin\theta_0 \tag{2-16}$$

Also,

D = receive antenna aperture width (azimuth dimension)

T_{CPI} = time for one coherent processing interval

Equations 2-11 and 2-12, in combination with 2-10, 2-14, and 2-15, are plotted in Figure 2-3.

The iterative procedure for determining the number of elements in a subarray (n_{rs}) and pulses in a sub-CPI (n_{ds}), thus, is as follows: initial values of n_{rs} and n_{ds} are determined from the normalized binomial distribution patterns graphed in Figure 2-3 by requiring that the respective null widths of ψ_w' and v_w' (abscissas of the graph) correspond to maximum pattern levels within the nulls equal to the Doppler sidelobe level (s_d) and two-way antenna sidelobe level ($s_t\ s_r$), respectively. (The maximum subarray/sub-CPI pattern level within a "null" of specified width is given by the graph of Figure 2-3.)

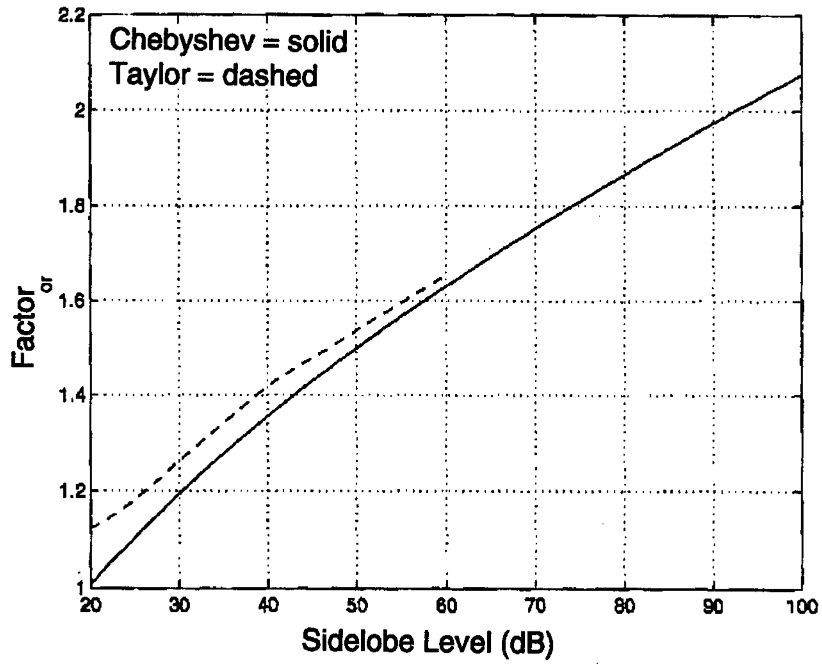

Figure 2-2: Beam Broadening Factor (= 1 for Uniform Ill.)

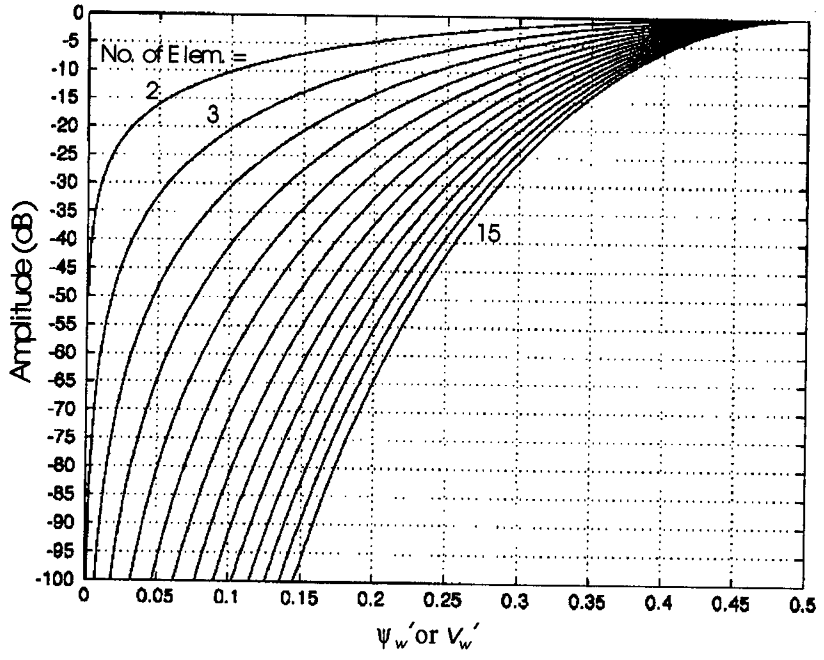

Figure 2-3: Binomial Weighted Gain Patterns vs. Normalized Sine Angle or Normalized Velocity

The corresponding value of f_l is determined and compared with r. If f_l is less than r, the subarrays/sub-CPIs are fully defined. If greater, some amount of space/time mainlobe clutter in excess of respective sidelobe clutter must be allowed to pass through the subarray/sub-CPI nulls. The procedure, here, is to compute the subarray/sub-CPI gain losses, $G_{rs}(0)$ and $G_{ds}(v_t)$, corresponding to n_{rs} and n_{ds}. If $G_{rs}(0) < G_{ds}(v_t)$, reduce n_{rs} by 1 and repeat the procedure of this paragraph. If $G_{rs}(0) > G_{ds}(v_t)$, reduce n_{ds} by 1 and repeat the procedure of this paragraph. In this manner, the domain that contributes most to gain loss is adjusted first.

If

$$v_o < \lambda/2T \tag{2-17}$$

mainlobe Doppler foldover clutter is present. In this case, the above procedure can be modified to apply to several levels of subarrays. The first set of subarrays ("first level subarrays") are themselves combined into subarrays forming the second level subarrays, etc. The combiner weights of one level of subarrays are determined by the above procedure to "null" one Doppler ambiguity lobe. In principle, there would be as many subarray levels as ambiguity lobes. Ambiguity lobes corresponding to clutter directions $|\theta| > \sim 70^\circ$ could probably be ignored because the antenna element pattern would suppress this clutter. The relationship between θ and corresponding ground radial velocity v_c is given by

$$v_c = v_0 \sin(\theta + \theta_c) - v_0 \sin(\theta_0 + \theta_c) \tag{2-18}$$

which can be easily be solved for θ corresponding to

$$v_c = v_t \pm \lambda/2T \tag{2-19}$$

2.2 Space/Time Sidelobe Levels (Rule 2)

Sidelobe levels in space (transmit and receive antennas) and in time (Doppler filter) are determined according to the following rules.

2.2.1 Data Sources

Data required by the KBC, to determine the sidelobe levels required by the filter, are obtained from the following sources:

1. Radar parameter data base (including transmit sidelobe level, receive sidelobe level floor and Doppler filter sidelobe level floor)
2. Radar scheduler/controller (test range cell (R_t), test range rate cell (v_t), beam position (θ_0))
3. Platform control data (drift (crab) angle (θ_c) and platform velocity (v_0))

2.2.2 Filter Parameters

The following parameters are determined by the KBC and transmitted to the filter:

1. Transmit sidelobe level (s_t)
2. Receive sidelobe level (s_r)
3. Doppler filter sidelobe level (s_d)

2.2.3 Decision Process

The transmit sidelobe level usually would be fixed and known in the radar data base.

If the test range rate cell is clutter free (see Rule 1 for criteria), low Doppler sidelobes are required, preferably at the level dictated by the RMS phase stability of the receivers ("sidelobe floor" as contained in the radar data base). The receive antenna sidelobes can be at the level associated with uniform weighting (greatest gain and resolution).

If the test range cell is clutter free, both receive antenna and Doppler sidelobe levels can be high (associated with uniform weighting).

Otherwise, the receive antenna sidelobe level should be as low as that dictated by antenna RMS amplitude and phase errors and receiver mismatch (radar data base contains this sidelobe level floor), and the Doppler sidelobe level should be as low as that dictated by receiver stability. In some instances, such as in a target rich environment, it may be essential to retain the maximum possible resolution in space (antenna beamwidth) and in time (Doppler filter width). This requirement could be requested by the tracker, for example, as it tries to distinguish targets within tight clusters or tries to associate targets in crossing trajectories. Figure 2-2 can be used by the KBC to estimate the resolution cost associated with a sidelobe level.

2.3 STAP Selection (Rule 3)

Many space/time adaptive algorithms (STAP) were compared primarily by application to MCARM measured data. As a result, some rules were identified about the use of STAP in general as well as about specific algorithm selection.

2.3.1 Data Sources

Data required by the KBC, to determine the STAP method and parameters required by the filter, are obtained from the following sources:

1. Radar scheduler/controller (test range rate cell (v_t), beam position (θ_0))
2. Platform control data (drift ("crab") angle (θ_c) and platform velocity (v_0))
3. Result of Rule 2 (Doppler sidelobe level)

4. Result of Rule 4 (decision whether to notch)
5. Result of Rule 5 (adequacy of secondary data samples)

2.3.2 Filter Parameters

The following parameters are determined by the KBC and transmitted to the filter:

1. Decision whether to apply STAP
2. STAP method

2.3.3 Decision Process

The decision whether to apply STAP and the specific algorithm to apply is made in accordance with the conditions set forth in Table 2-1. If the secondary data set is deemed insufficient to support STAP, nonadaptive filtering must be applied. If the crab angle (θ_c) is small (< few degrees) and the PRF can be selected to satisfy the displaced phase center (DPCA) condition $v_0T = md$ where m = small integer, T = PRI, v_0 = platform velocity, and d = spacing between array columns or subarrays (subarrays must be equally spaced) then element space DPCA is selected. If the DPCA condition is not satisfied, or if the subarrays are unequally spaced, the approximate implementation of DPCA based upon combining sum and difference beams (Σ,Δ DPCA) is selected. Here, the monopulse slope must be estimated, and of course, the sum and difference beams must be formed prior to DPCA processing. Alternatively, 2 or 3 pulse MTI can be applied.

Table 2-1: STAP Algorithm Selection

Condition				Algorithm
Secondary Data Set	Notching	Doppler Weighting	Target Doppler	
Insufficient	--	--	--	DPCA, MTI (Nonadaptive)
Limited	--	--	--	Σ, Δ ADPCA (Small N_{DOF} STAP)
Ample	--	Light	--	Σ, Δ & Subarrays ADPCA (Large N_{DOF} STAP)
Ample	Spatial	Heavy	--	Σ, Δ ADPCA (Small N_{DOF} STAP)
Ample	None	Heavy	Mainlobe	Σ, Δ & Subarrays Factored STAP (Large N_{DOF} STAP)
Ample	None	Heavy	Sidelobe	Σ, Δ & Subarrays ADPCA (Large N_{DOF} STAP)

The structures of the STAP methods chosen for Table 2-1 are defined by the flow diagrams in Figures 2-4 through 2-6. The number of degrees of freedom (N_{DOF}) is defined, here, as the product of the spatial channels (or beams) and Doppler bins applied in the STAP. (The number of rows or columns in the relevant covariance matrix is equal to N_{DOF}.) All the STAP methods chosen are "post Doppler" and "beam space," with beam space implying either Σ,Δ beams or Σ,Δ beams combined with elements (or subarrays). These methods were found to be the most effective especially for small N_{DOF}. Preceding adaptivity with all deterministic filtering (spatial by beamforming and temporal by Doppler filtering) allows the available degrees of freedom to be applied only against clutter passing through the deterministic filters. If deterministic filtering follows adaptivity, the degrees of freedom would be "spread thin" in an attempt to optimize suppression of all clutter, including that which would have been filtered deterministically subsequent to STAP.

An important underlying assumption to the rule that Doppler filtering and beamforming precede STAP is that pulse compression with heavy time sidelobe suppression weighting (in excess of ~ 40 dB) also precede STAP. Otherwise, if pulse compression follows STAP, the target SNR is likely to be substantial in the range cells used for weight determination (reference data cells) because of the gain associated with Doppler filtering and beamforming. Substantial target SNR in the reference cells would require that heavy diagonal loading or "hard" mainlobe constraints be applied in weight computation to prevent target gain loss in the adaptive process. Thus, it has been found that when STAP precedes pulse compression, STAP performance is best if STAP also precedes Doppler filtering. If the only beams formed in the STAP algorithm are Σ,Δ beams, the very small target SNR in the Δ channel serves the purpose of a "hard" constraint (referred to as preadaptive filtering in [Applebaum and Chapman's paper]. So, perhaps it is not surprising that the Σ,Δ ADPCA and Σ,Δ & Subarrays ADPCA algorithms in Table 2-1 have been found not to degrade too badly with precompression STAP as long as the Doppler filtering is relocated to follow the STAP in each case. (The Joint Domain Localized (JDL) algorithm, for example, has been found to perform poorly with precompression STAP.) The Σ,Δ & Subarrays Factored STAP algorithm in Table 2-1 should be replaced with the Σ,Δ & Subarrays ADPCA (pre-Doppler version) algorithm if STAP precedes pulse compression.

Even with pre-Doppler STAP algorithms, a modest amount of diagonal loading may still be required if the STAP precedes pulse compression. The appropriate lower bound on diagonal loading for all cases is addressed in Rule 6.

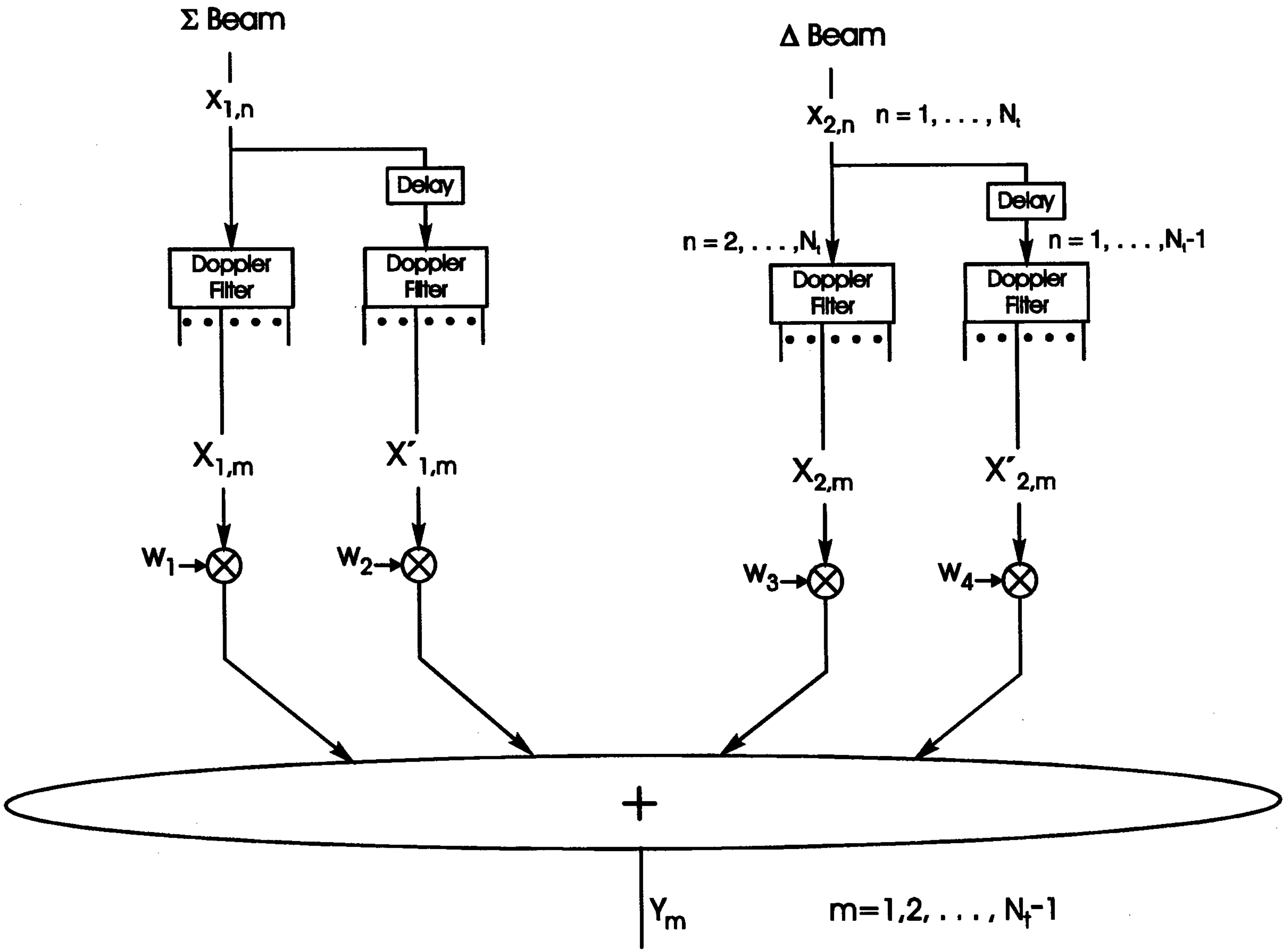

Figure 2-4: ΣΔ ADPCA

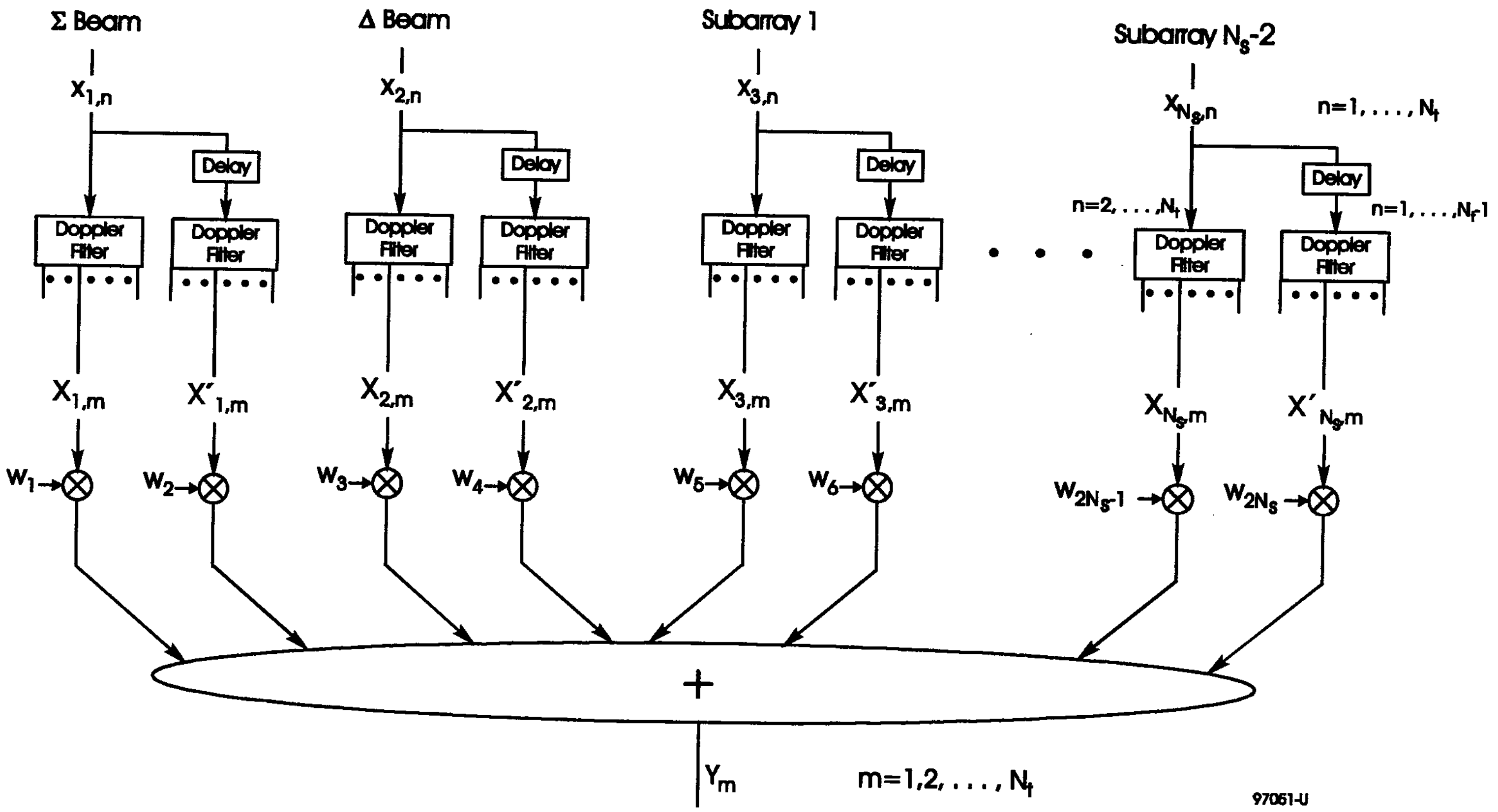

Figure 2-5: ΣΔ Subarrays ADPCA (N_s = No. Spatial Channels)

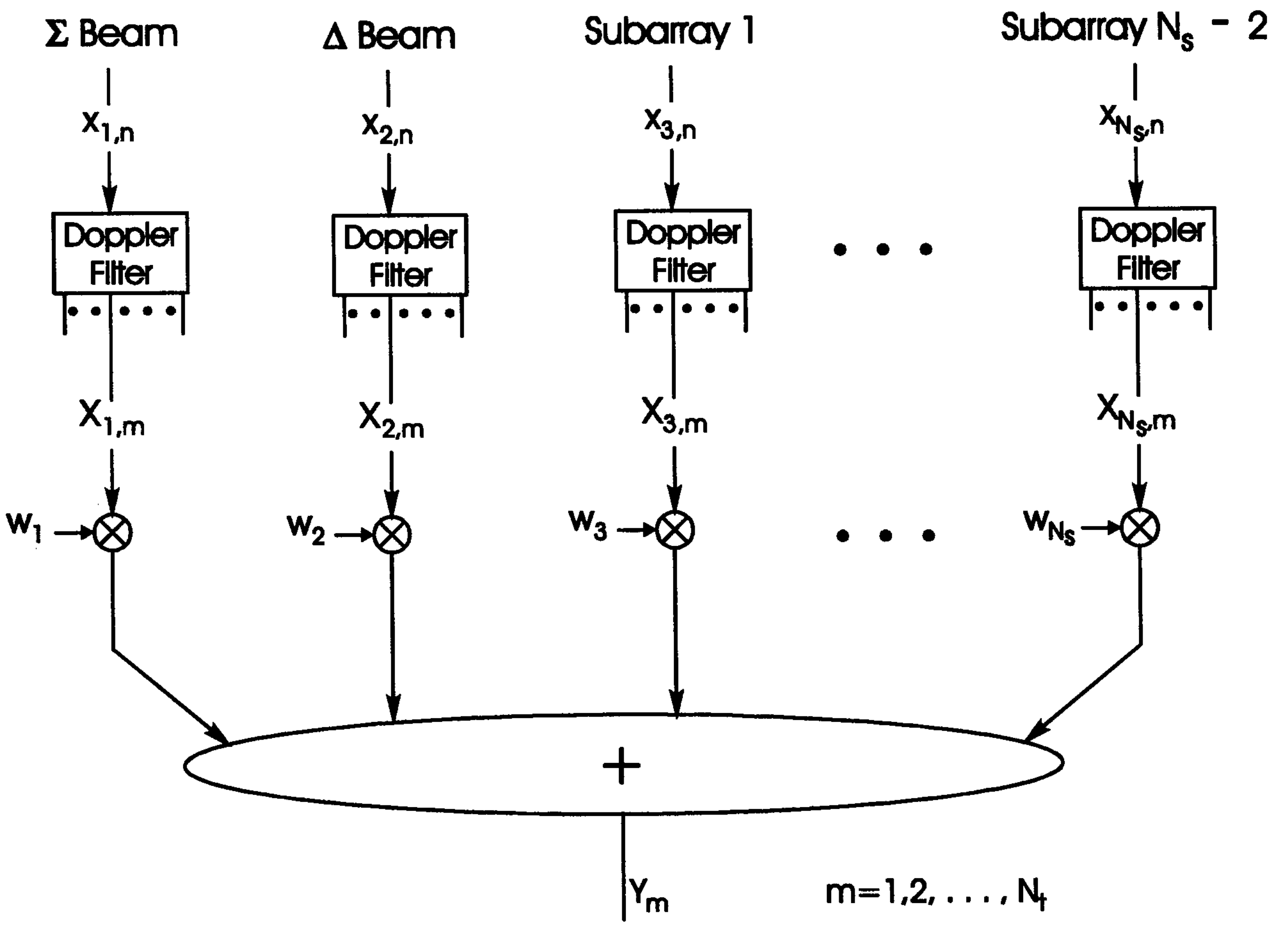

Figure 2-6: ΣΔ Subarrays Factored

2.4 Array Notching Plus Spatial Only Adaptivity (Antijam) (Rule 4)

Deterministic pattern notching in space (and in time, although only spatial notching is considered here) can be effective in supporting STAP in two ways. False alarms are fewer because discrete interference arising from moving scatterers that fall within the test range/Doppler cell is suppressed. (STAP is only effective against clutter aligned along the clutter ridge (nonmoving scatterers).) Also, the potential for "moving discretes" in STAP reference range cells to grab degrees of freedom is lessened because interference arising from moving scatterers that fall within neighboring range cells and test Doppler cell is suppressed.

2.4.1 Data Sources

Data required by the KBC, to determine notching parameters required by the filter, are obtained from the following sources:

1. Radar parameter database (PRF, etc.)
2. Radar scheduler/controller (test range rate cell (v_t), beam position (θ_0))
3. Platform control data (drift ("crab") angle (θ_c) and platform velocity (v_0))
4. Radar tracker, cooperative sensors (aircraft ranges, angles, headings, speeds)
5. Mapping data (highway locations, orientations, and maximum expected traffic speeds)
6. Result of Rule 3 (decision whether to apply STAP)

2.4.2 Filter Parameters

The following parameters are determined by the KBC and transmitted to the filter:

1. Decision whether to notch
2. Prioritization of interference to be notched
3. Notch locations and widths
4. Indication of sidelobe jamming

2.4.3 Decision Process

If STAP is not feasible (Rule 3), notching is not required. Otherwise, first the presence of air and/or ground traffic that lie in the vicinity of the test range/Doppler cell is determined. If absent, no deterministic notching. If present, the interference is prioritized according to estimated strength, and appropriate notching widths are estimated. Jamming is sensed by comparing either a low gain channel (element, column, or subarray) receiver output or a separate low gain antenna receiver output when not transmitting to receiver noise. If the receiver output is

3 dB above the noise, sidelobe radiative interference such as jamming can be assumed. Actually, the low gain antenna signal should be compared with a sum beam signal to rule out mainlobe noise jamming.

2.4.3.1 Discrete Identification

Highway traffic is a potential interference source if the highway crosses test or reference range cells and the radial velocity of the traffic lies within the test Doppler cell (radial velocity with respect to ground v_t). Range and Doppler foldover cells must be considered, as well. The requirement is that

$$\begin{aligned}\left[v_t - v_{dw}, v_t + v_{dw}\right] \;\cap\; \Big[& v_o\left(\sin\left(\theta_d + \theta_c\right) - \sin\left(\theta_o + \theta_c\right)\right) - v_d\left|\sin\alpha\right|, \\ & v_o\left(\sin\left(\theta_d + \theta_c\right) - \sin\left(\theta_o + \theta_c\right)\right) + v_d\left|\sin\alpha\right|\Big]\end{aligned} \qquad (2\text{-}20)$$

is nonempty where:

θ_0 = beam position azimuth angle (see Figure 2-1)

θ_c = drift (crab) angle (see Figure 2-1)

v_0 = platform velocity

v_t = test radial velocity w/to ground

θ_d = angle to highway crossing

v_d = maximum expected highway traffic speed

α = angle subtended by highway and range cell

Also, v_{dw} is the velocity (Doppler) filter beamwidth given by

$$v_{dw} = \beta_d \lambda / 2T_{CPI} \qquad (2\text{-}21)$$

where:

β_d = Doppler filter beam broadening factor (Figure 2-2)

λ = wavelength

T_{CPI} = coherent processing interval

An illustrative geometry is shown in Figure 2-7. Three highways cross the test range cell; a forth crosses the foldover cell. The θ and α angles all lie in the horizontal cardinal plane of the antenna; necessary projections are assumed that account, for example, for antenna tilt angle. A 5.7° tilt is shown in the inset of the figure. A broadside beam is indicated.

The angle/Doppler diagram for the test range cell is shown in Figure 2-8. (The foldover clutter ridge and foldover range cell discrete corresponding to Highway 3 are included as dashed lines.) A Doppler ambiguity lobe is shown as would result from a Doppler ambiguous waveform. The notched antenna pattern is indicated, as well. Clearly only Highways 1, 3, and 4 are candidates for notching.

A very small value of α may result in the associated highway exciting a distributed type of clutter. This effect would cause the associated horizontal line in Figure 2-8 to broaden. In this case, however, the line also would shorten dramatically and the highway traffic scattering would appear to nearly reside on the clutter ridge: i.e., appear nearly motionless, or, as is more likely, simply be masked by intrinsic clutter motion.

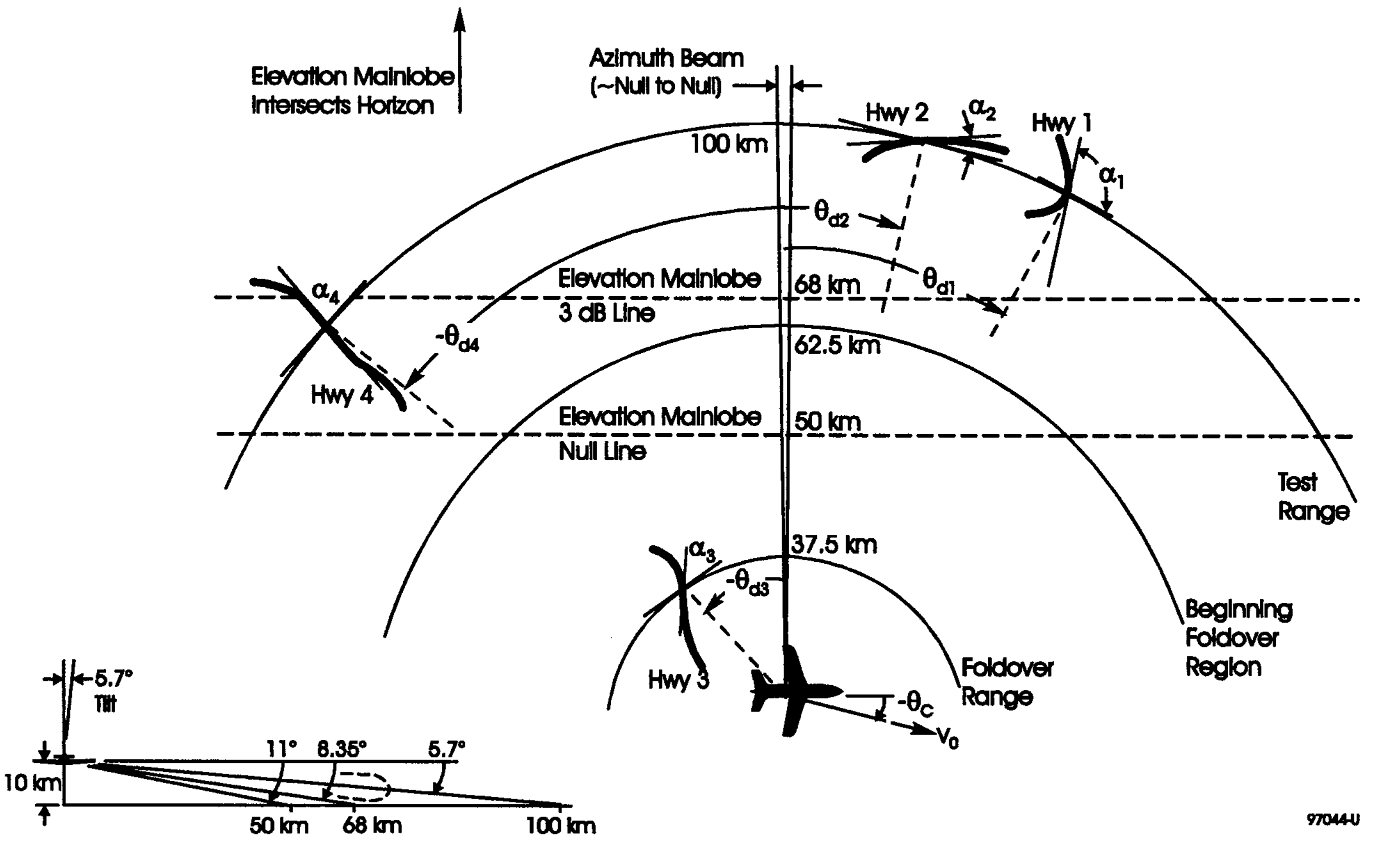

Figure 2-7: Interference Identification (Geometry)

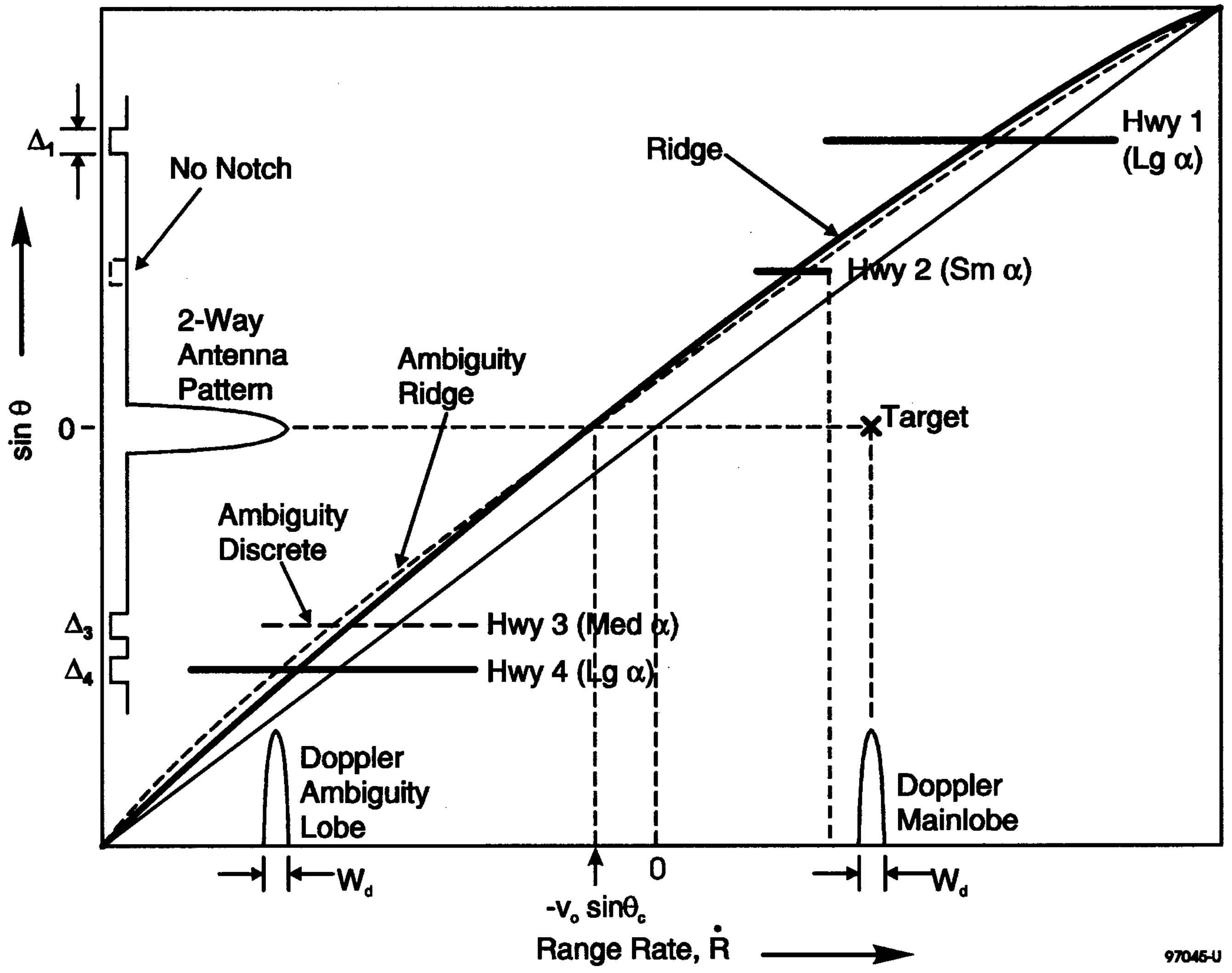

Figure 2-8: Interface Identification (Notching)

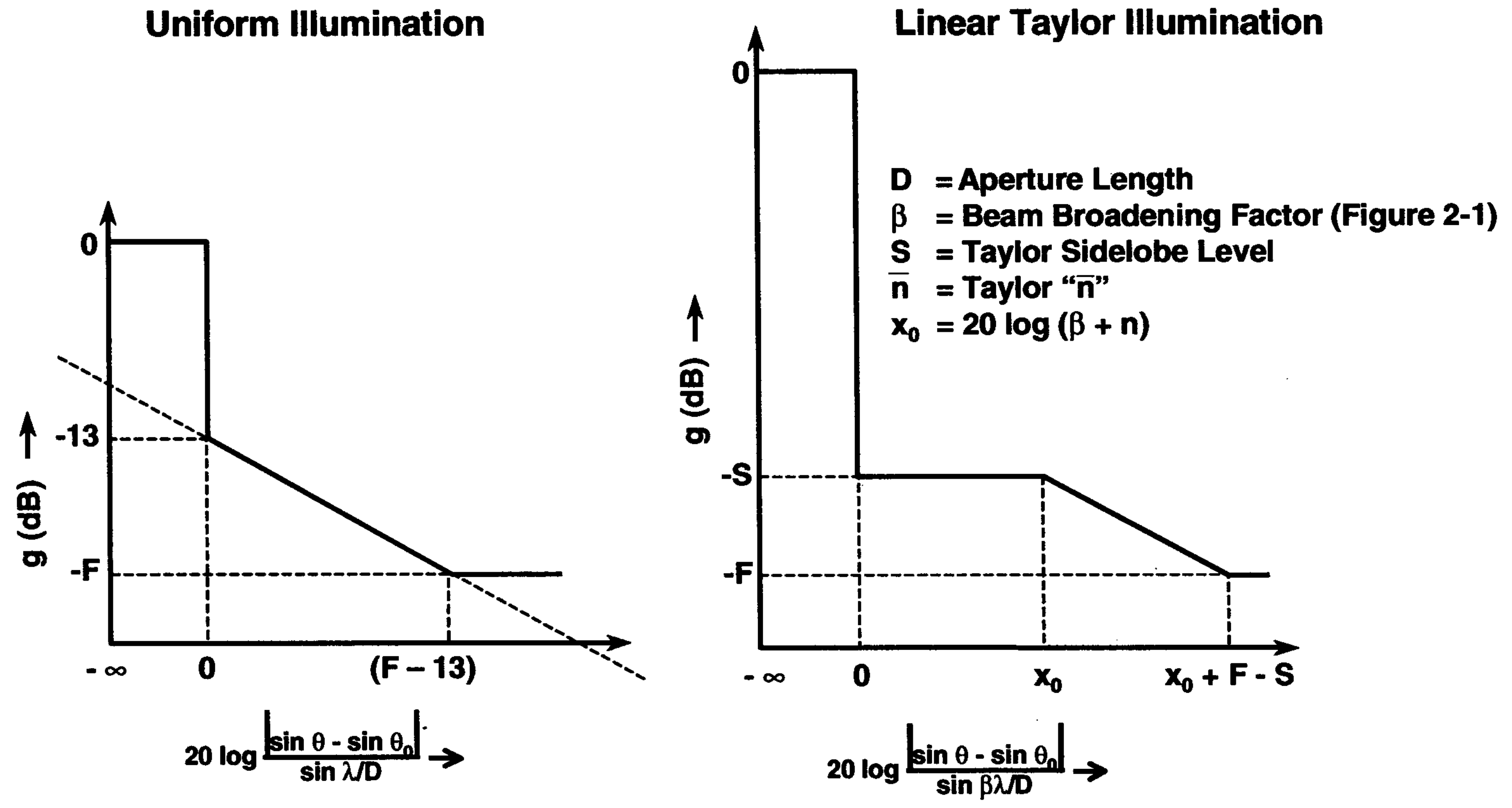

Figure 2-9: Antenna Gain Models

2.4.3.2 Notching Prioritization

With a limited number of spatial channels available for forming notched antenna patterns, rules for prioritizing the discretes that are candidates for notching are required. Rules for determining the widths and depths of the notches also must be determined. Potential discretes that can strongly impact the test range/Doppler cell can occur at foldover ranges and angles as well. For example, a discrete at angle θ_d in a near foldover range R_d' would have an $(R_t/R_d')^4$ power advantage over a discrete at angle θ_o at the test range R_t. This foldover discrete, however, is likely to reside in the very low sidelobe intercardinal plane of the two way gain pattern. The relative impact of antenna gain pattern and slant range must be considered in ordering the discretes according to their potential for degrading performance.

The priority rules applied here are based solely on slant range and antenna gain. Moving scatterer discretes, as from ground vehicles and air traffic, do not exhibit well-defined "grazing angle" dependence as does distributed clutter. The intensities of the discretes, however, could be strongly influenced by the orientation of the highway in the range cell, but this dependence is not considered in this first design. (The orientation, however, does strongly influence the range of Doppler velocities associated with a highway, and so is a necessary parameter in determining whether a discrete is coincident with a test range/Doppler cell as discussed in Section 2.4.3.1.) The moving discretes are likely to behave as point scatterers with a R^{-4} range dependence, in contrast with distributed clutter that is likely to exhibit a range dependence closer to R^{-2} or R^{-3}.

Consider, therefore, a notching priority parameter, μ, such that the larger the μ the more important the notch. This parameter is given by

$$\mu = R^{-4}(\theta,\phi)\, G_t(\theta,\phi,\theta_o,\phi_o)\, G_r(\theta,\phi,\theta_o,\phi_o) \tag{2-22}$$

where θ,ϕ are antenna coordinates of the discrete with θ = antenna zenith angle and ϕ = antenna azimuth angle, R = slant range, and G_t, G_r are the transmit and receive gain patterns. Note that G_t and G_r depend also on scan direction, θ_o, ϕ_o. Approximate pattern envelope models of the gain patterns are adequate here. Assume a rectangular aperture with "row, column" weighting. Let x denote the horizontal axis and y the vertical axis, and let θ_x, ϕ_y denote the cardinal plane pattern angles and θ_{x0}, ϕ_{y0} denote the cardinal plane scan angles. Then,

$$G_t = g_{tx}\, g_{ty},\ G_r = g_{rx}\, g_{ry} \tag{2-23}$$

where g_{tx}, g_{rx} are horizontal plane gain patterns and g_{ty}, g_{ry} are vertical plane gain patterns. For a uniformly weighted aperture, the gain pattern (in dB) is given by

$$g(x) = \begin{cases} 0 & \text{for } -\infty < x \le 0 \\ -13 - x & \text{for } 0 < x \le F\text{-}13 \\ -F & \text{otherwise} \end{cases} \tag{2-24}$$

where

$$x = 20\,log\frac{|sin\,\theta - sin\,\theta_0|}{sin(\lambda / D)} \tag{2-25}$$

D = aperture extent, and F = antenna sidelobe noise floor. Also, θ here is a cardinal plane zenith angle for scanning in half the plane only and θ_0 the corresponding scan angle. The pattern is assumed to be symmetric. The pattern for a linear Taylor distribution of sidelobe level S, n uniform sidelobes, and beam broadening coefficient β (Figure 2-2) is given by

$$g(x) = \begin{cases} 0 & for\ \ -\infty < x' \le 0 \\ -s & for\ 0 < x' \le x_0 \\ -x' + x_0 - S & for\ x_0 < x' \le x_0 + F - S \\ -F & otherwise \end{cases} \tag{2-26}$$

where

$$x_0 = 20\ \log\left(\beta + \bar{n}\right)$$

$$x' = 20\ \log\frac{|\sin\theta - \sin\theta_o|}{\sin\left(\beta\lambda/D\right)}$$

These expressions are plotted in Figure 2-9.

2.4.3.3 Notch Width

The choice of width of an antenna pattern notch for suppressing highway traffic discretes is governed primarily by the angle α and the depth, typically given in "dB below the quiescent sidelobe level" (denoted A) is limited, in turn, by antenna errors or noise floor "F." In some cases, a notch width larger than that required to suppress a discrete in the vicinity of the test cell may be desired so that the corresponding highway is notched as well in near range cells. These near cells then are likely to function better as reference cells.

A rough relation between number of spatial channels devoted to forming a notch (N_s), null (notch) depth (A), null angular location from broadside in the cardinal horizontal plane (θ_d), aperture extent in horizontal plane (D), wavelength (λ), and notch width (Δ) is given by

$$\Delta = \frac{2N_s\lambda}{\pi D\cos\theta_d}10^{-A/20} \tag{2-27}$$

Equation 2-27 was derived by assuming a standard model for a null, applying this model to determine the null width corresponding to a specified notch depth, dividing that width into the specified notch width, and equating the result to the required number of spatial channels. Preliminary computations demonstrate that this relation is quite "rough" and in need of refinement. It, however, serves as a convenient starting point.

2.5 Sample Selection/Shadowing (Rule 5)

Several sample selection methods were investigated by application to MCARM clutter data with an injected target. Conclusions were based on only one CPI of data so that the conclusions should be considered preliminary at this time. Also, since most methods demonstrated comparable performance with this limited data, a selection of "best method" was made somewhat arbitrarily. In particular, a "two pass method" labeled GIP/SMI (Generalized Inner Product/Sample Matrix Inversion), was found to perform about as well or better than the others. Although the Generalized Likelihood Ratio Test (GLRT) method performed at least as well as GIP/SMI, it was conjectured that GIP/SMI would be superior to GLRT in a complex environment.

In the GIP/SMI two pass method, GIP first is applied as a nonhomogeneity detector (NHD pass). A sliding window is used in that pass for obtaining reference cells. A target detection pass then follows. Here SMI is applied with a fixed window of reference cells. Range cells in the fixed window that are identified during the first pass as nonhomogeneities are deleted from the covariance matrix estimation as are the test cell and guard cells.

A very limited amount of testing with shadowing was carried out as well with the same MCARM data. Shadowing was simulated in the data by replacing a portion of the data cube corresponding to a section of range cell data with simulated receiver noise. A small benefit was observed if the sample selection rule for GIP/SMI was adjusted to account for the shadowed cells.

2.5.1 Data Sources

Data required by the KBC, to determine the sample selection parameters required by the filter, are obtained from the following sources:

1. Result of Rule 3 (decision to apply STAP, number of degrees of freedom (N_{DOF}))
2. Radar parameter data base (target range window (ambiguous range interval?))
3. Radar scheduler/controller (test range cell (R_t), beam position (θ_0))
4. Mapping data (terrain elevations, tall structures)
5. Platform control data (altitude)
6. Result of Rule 6 (minimum diagonal loading)

2.5.2 Filter Parameters

The following parameters are determined by the KBC and transmitted to the filter:

1. GIP lower/upper thresholds
2. Sliding window width (in NHD pass)

3. Number guard cells (in NHD pass)

4. When to shift sliding window to avoid sampling shadowed region (in NHD pass)

5. Diagonal loading

2.5.3 Decision Process

If a decision has been made to apply STAP (Rule 3), the following rule applies for selecting range cells from which the necessary STAP reference data is obtained. The rule applies only if pulse compression follows STAP. If processing limitations limit the filtering architectures to precompression STAP, a single pass SMI weight generation STAP or GLRT test statistic STAP is recommended (no NHD pass). In such cases, the entire range window comprised of ranges corresponding to an interpulse period less the transmit on time (and diplexer/receiver transient times) is applied in sample selection. (For low PRF radars, the window extends to the maximum range of the radar.) A single set of weights (SMI) or test statistic (GLRT) is determined in this case for the entire window. The test cell and guard cells are not removed from the filtering process. Diagonal loading rules apply, however, (Rule 6) to prevent target gain loss.

If STAP follows pulse compression, the STAP process of the filter would begin by applying GIP (in the GIP/SMI two pass method) with a sliding window in a NHD pass. The KBC directs the filter to determine the lower/upper GIP thresholds, for "nonhomogeneity exclusion," such that the number of range cells applied to covariance matrix estimation for the subsequent target detection pass is roughly $3N_{DOF}$. This number has been found (by analysis of a very limited sample of measured data) to optimize the number of nonhomogeneous cells discarded while retaining a sufficient number of cells for accurate estimation. SMI would then be applied in the target detection pass with a fixed window equal to the entire range window as defined above with the exception that range cells in the fixed window that are identified during the first pass as nonhomogenities are deleted from the covariance matrix estimation as are the test cell and guard cells. Also, diagonal loading is set to the minimum value determined under Rule 6.

Terrain shadowing causes receiver noise to dominate the data corresponding to the shadowed range cells. Consequently, it was found that GIP/SMI performance can be improved if the sample selection rules are modified slightly to account for shadowing. Simply, the GIP sliding window (NHD pass) is shifted in the vicinity of shadowed regions to avoid including shadowed cells in the window. The GIP lower threshold then is reduced such that the number of samples accepted for the target detection pass is again $\sim 3N_{DOF}$.

2.6 Diagonal Loading (Rule 6)

Diagonal loading can be viewed as the addition of noise to the STAP weight generation process. One purpose of diagonal loading is to prevent extraneous near zero eigenvalues from characterizing the estimated covariance matrix and rendering the matrix nearly singular, a state referred to as "ill conditioned." This state is a consequence of the estimation process because the exact matrix is never singular. The more independent reference data samples available for estimation, the less likely the matrix will be ill conditioned. The GIP/SMI sample selection method (Rule 5) has been found to require only a very minimal amount of diagonal loading for this purpose.

Another purpose of diagonal loading is to desensitize the STAP from suppressing the target response ("mainlobe gain loss"). This suppression occurs because the target signal to noise ratio (SNR) in the reference data is sufficient to impact weight determination. The "steering vector" cannot compensate for this loss. Diagonal loading, in this case, serves to reduce target SNR levels in the reference data at the expense of reduced clutter suppression. The minimum amount of diagonal loading required to prevent severe mainlobe gain loss is determined here.

An alternative to diagonal loading is to apply mainlobe constraints in the weight generation process. (Such constraints are sometimes referred to as "hard constraints" to distinguish them from steering vector, or "soft," constraints.) A disadvantage of applying hard constraints is that it requires the transference of some degrees of freedom from clutter suppression to filtering the target signal from weight generation. Mainlobe constraints are not considered here. They are discussed further in [1].

2.6.1 Data Sources

1. Radar parameter data base (including pulse compression ratio, pulse compression sidelobe level, receive beamformer nominal gain, Doppler filter gain)
2. Radar scheduler/controller (test range cell (R_t))
3. Mission data base (minimum target cross section (σ_t))
4. Result of Rule 3 (decision whether to apply STAP)

2.6.2 Filter Parameters

1. Minimum diagonal loading for STAP.

2.6.3 Decision Process

If, in accordance with Rule 3, a decision to not apply STAP is made, no further action is required here. If STAP is to be applied, a minimum amount of diagonal loading may be desirable to prevent target signal suppression (gain loss) in the STAP process. The rule for determining that amount requires estimating the minimum signal to noise level at the element (subarray or column) output prior to pulse compression or Doppler processing (SNR_e). This value is estimated from the radar parameters, test range cell (R_t), and minimum target cross section (σ_t) in accordance with the radar range equation similar to the method applied for estimating SNR_{max} in Rule 1. Thus,

$$SNR_e = \frac{P_t G_t G_e \sigma_t \lambda^2}{(4\pi)^3 R_t^4 k_b T_0 BFL} \tag{2-28}$$

where,

P_t = transmitter radiated power (W)

G_t = transmit antenna directive gain

G_e = element (subarray or column) directive gain

λ = wavelength (m)

k_b = Boltzmann's Constant ($W/Hz/K$)

T_0 = 290 K ($kT_0 = 4 \cdot 10^{-21}$ W/Hz)

F = receiver noise figure

B = bandwidth (Hz)

L = receive antenna loss

Consider the following definitions:

PCR = pulse compression ratio (dB)

$PCSL$ = pulse compression sidelobe level (dB)

DNR = minimum diagonal loading (plus noise) to noise ratio (dB); (0 dB → 3 dB increase in "noise" in STAP weight generation process)

RGB = receive beamformer gain (dB)

DFG = Doppler filter gain (dB)

The value of DNR depends on the order of processing. Eight possibilities are pertinent. These follow with the associated equation for determining DNR.

1. Pulse compression → Element space STAP → Doppler filtering

$$DNR = SNR_e + PCR - PCSL$$

2. Pulse compression → Beam space STAP → Doppler filtering

   $DNR = SNR_e + PCR + RBG - PCSL$

3. Pulse compression and Doppler filtering → Element space STAP

   $DNR = SNR_e + PCR + DFG - PCSL$

4. Pulse compression and Doppler filtering → Beam space STAP

   $DNR = SNR_e + PCR + DFG + RGB - PCSL$

5. Element space STAP → Pulse compression and Doppler filtering

   $DNR = SNR_e$

6. Beam space STAP → Pulse compression and Doppler filtering

   $DNR = SNR_e + RBG$

7. Doppler filtering → Element space STAP → Pulse compression

   $DNR = SNR_e + DFG$

8. Doppler filtering → Beam space STAP → Pulse compression

   $DNR = SNR_e + DFG + RBG$

References

1. H. K. Schuman and Ping Li, "Airborne Radar Filtering," in preparation.
2. D. G. Bodnar, Antenna Engineering Handbook, 3rd Edition, R.C. Johnson, ed., McGraw-Hill, sec. 46-5, 1993.

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