雷达信号处理及MATLAB仿真

第四章 杂波抑制与动目标检测

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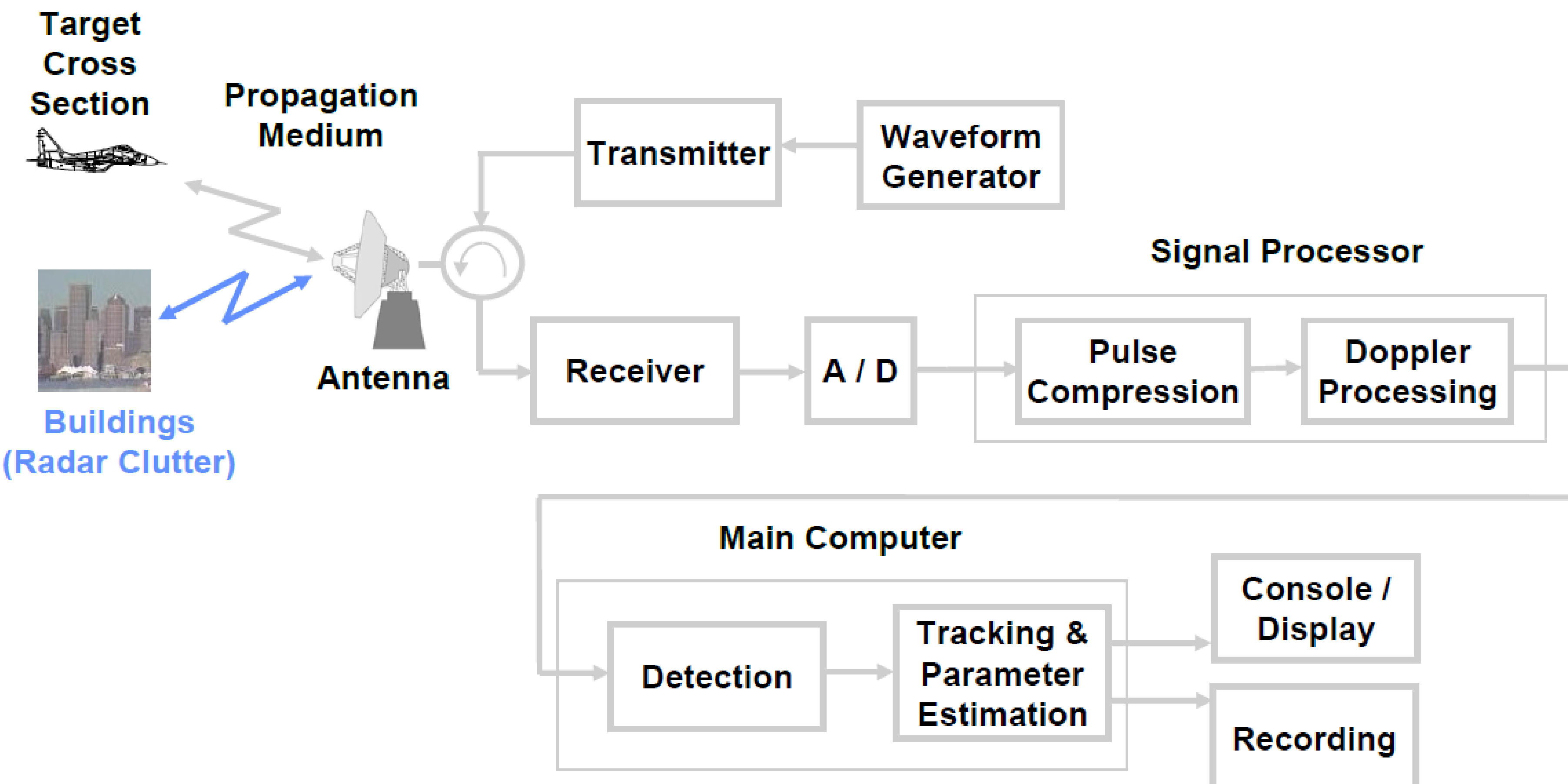
杂波抑制与动目标检测

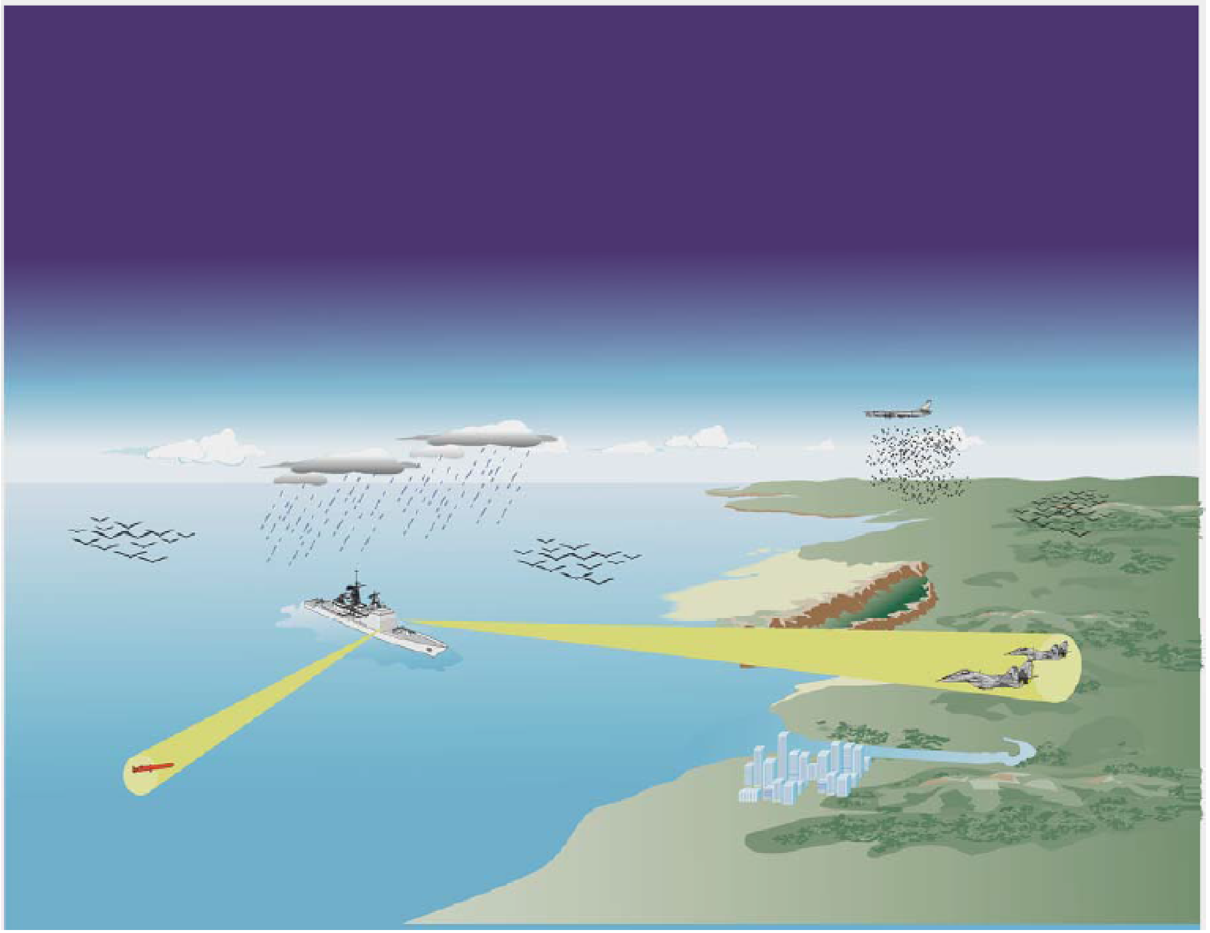
- 杂波的定义
- 杂波抑制技术
- 动目标检测
- 本章小结

一、杂波的定义


Target
Cross
Section
Propagation
Medium
Transmitter
Waveform
Generator
Signal Processor
Buildings
(Radar Clutter)
Antenna
Receiver
A / D
Pulse
Compression
Doppler
Processing
Main Computer
Console /
Display
Detection
Tracking &
Parameter
Estimation
Recording

一、杂波的定义

Naval Air Defense Scenario



Radar echo is composed of:

- Backscatter from target of interest
- Receiver noise
- Atmospheric noise
- Interference
  - From other radars
  - Jammers
- Backscatter from unwanted objects
  - Ground
  - Sea
  - Rain
  - Chaff
  - Birds
  - Ground traffic

一、杂波的定义－地杂波

地面的山丘、树林、农田、沙漠、城市建筑等

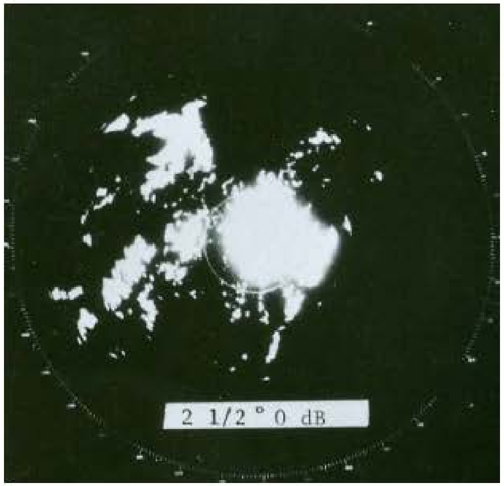
Mountainous Region of Lakehead, Ontario, Canada
PPI Set for 30 nmi.

0 dB

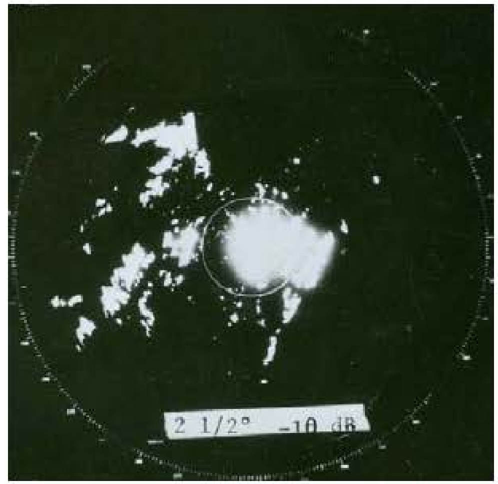
60 dB

一、杂波的定义

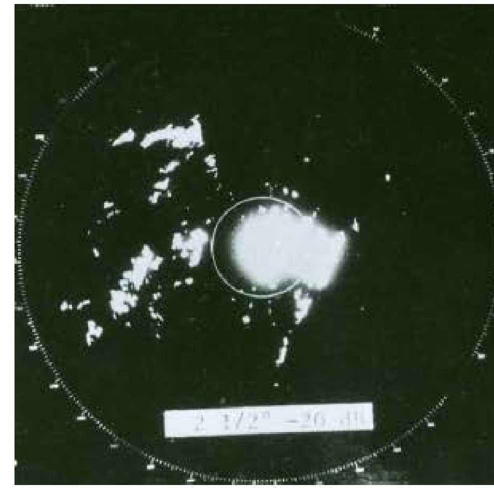
0 dB



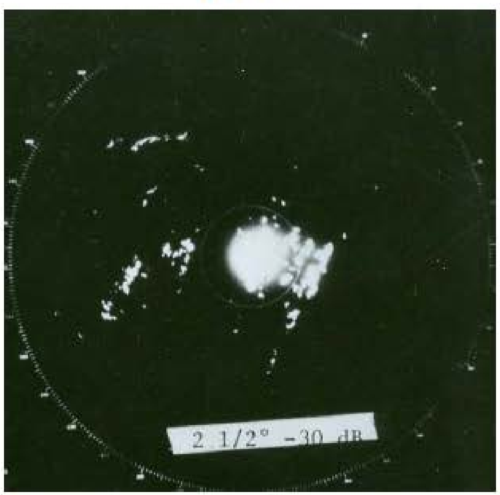
10 dB



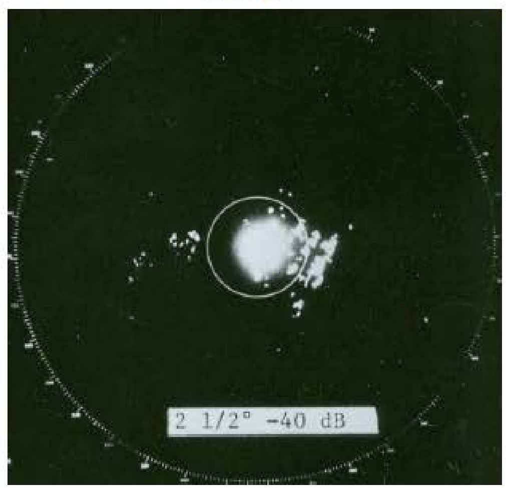
20 dB



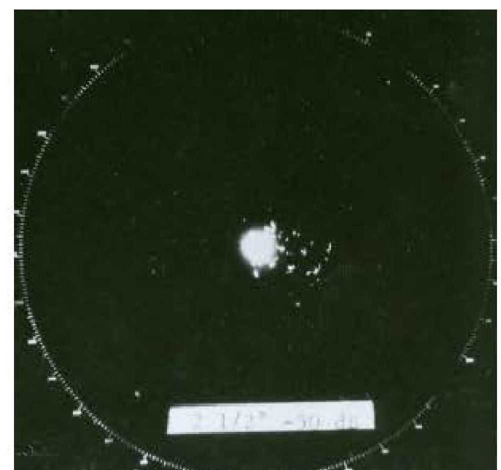
30 dB



40 dB

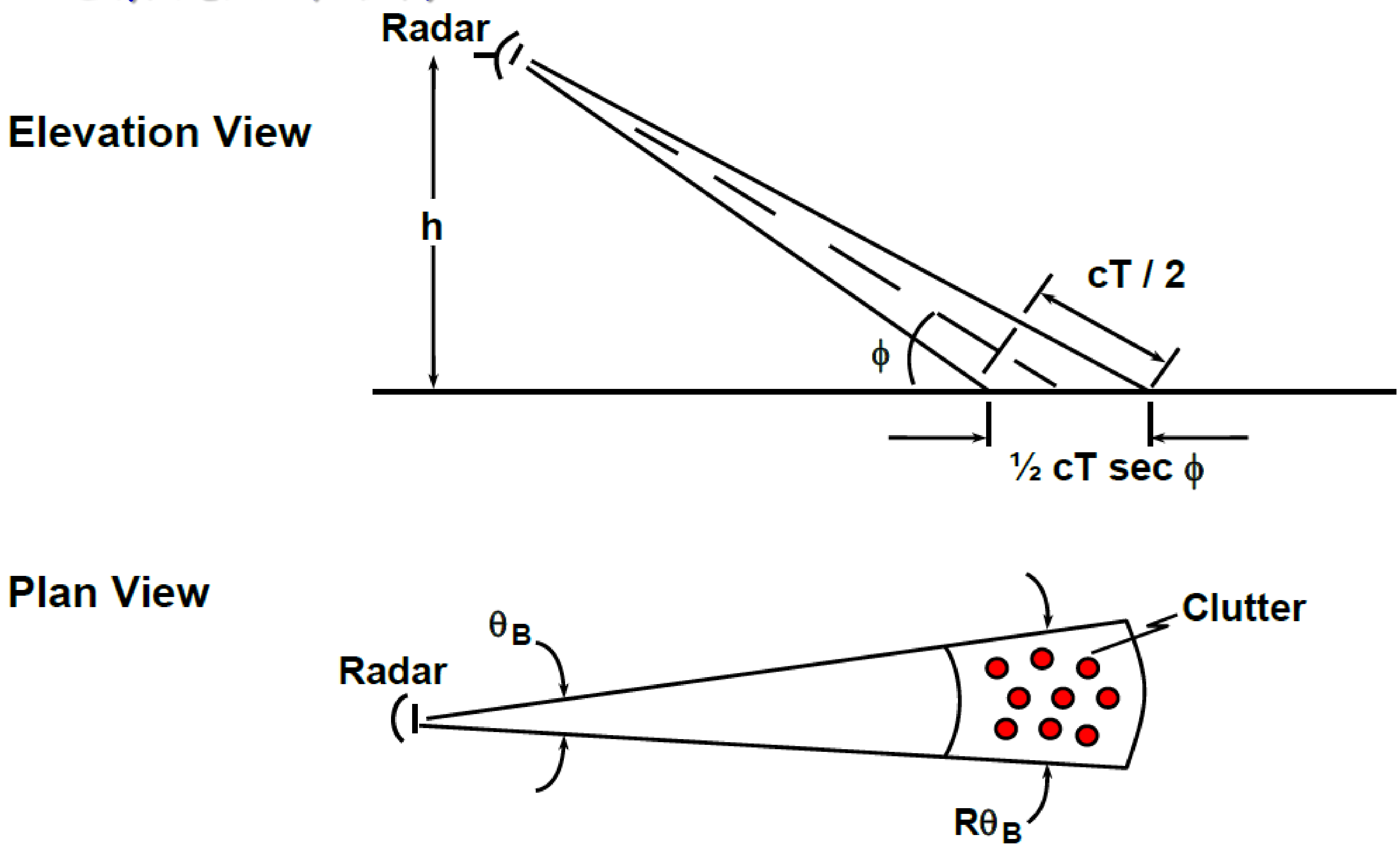


50 dB



一、杂波的定义

地杂波几何结构



$$\sigma_0 = \frac{\sigma}{A} \qquad A = R\theta_B\left[\tfrac{1}{2}cT\sec\phi\right]$$

一、杂波的定义

- Typical Value of σ_o = -20 dB = $\dfrac{0.01\ m^2}{m^2}$
- $\sigma_{Clutter} = \sigma_o A = \sigma_o \dfrac{c\,T}{2} R\,\theta_B$
  - For ASR-9 (Airport Surveillance Radar)

$$\frac{c\,T}{2} = 100\text{m} \qquad R = 60\text{ km} \qquad \theta_B = 1.5^o = 0.026\text{ radians}$$

- $\sigma_{Clutter} = \dfrac{0.01\ m^2}{m^2}$ x 100 m x 60,000 m x 0.026 radians = 1500 m^2

For $\sigma_{Target} = 1\ m^2$ ⇨ $\dfrac{\sigma_{Target}}{\sigma_{Clutter}} = \dfrac{1}{1500}$ ⇨ $\dfrac{\sigma_{Target}}{\sigma_{Clutter}} = 20$

Small single-engine aircraft

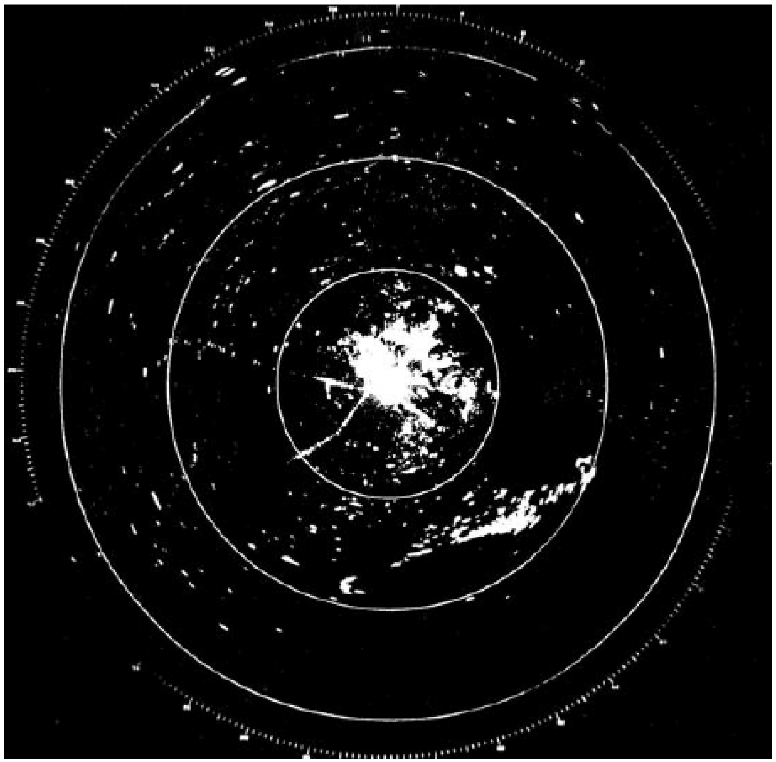
For good detection

$\therefore$ **Must suppress clutter by a factor of 1500 x 20 = 30,000 = 45 dB**

一、杂波的定义

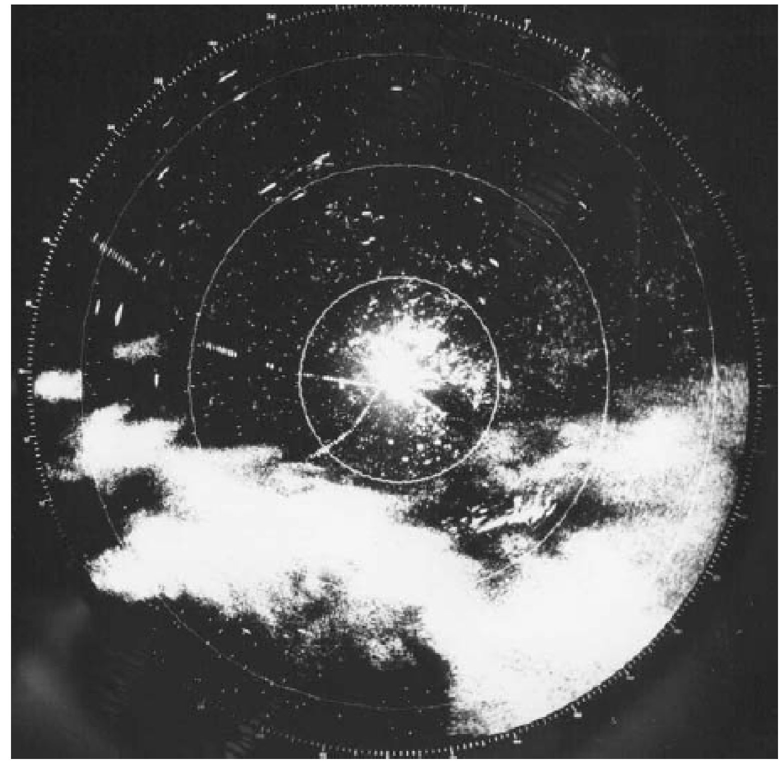
云雨杂波

Clear Day (No Rain)



Airport Surveillance Radar
S Band
Detection Range - 60 nmi on a 1 m^2 target

Day of Heavy Rain



10 nmi Range Rings on PPI Display
August 1975, FAA Test Center
Atlantic City, New Jersey

杂波抑制与动目标检测

- 杂波的定义
- **杂波抑制技术**
- 动目标检测
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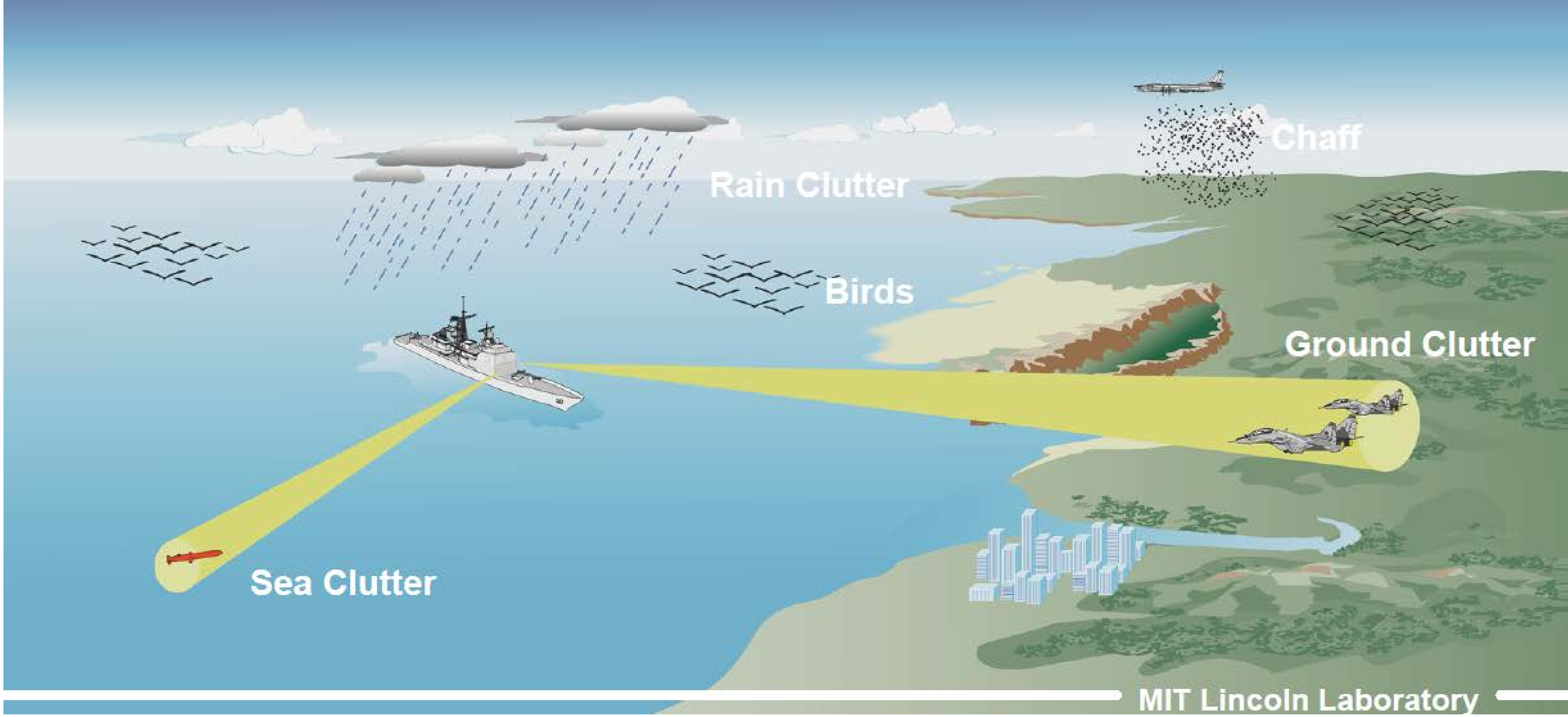
二、杂波抑制

- Moving Target Indicator (MTI) and Pulse-Doppler (PD) processing use Doppler to reject clutter and enhance detection of moving targets
- Smaller targets require more clutter suppression



二、杂波抑制

Moving Target Indicator (MTI) Techniques

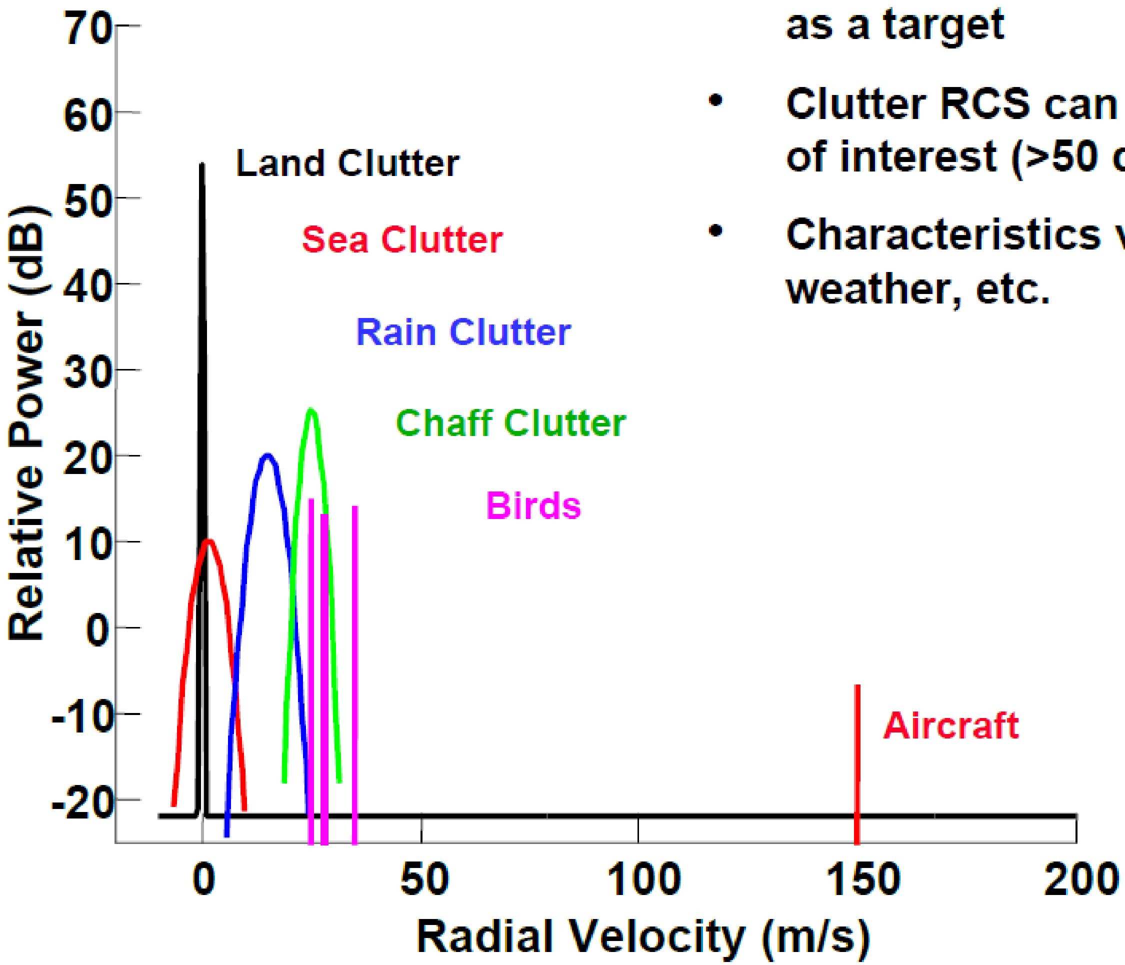
- Just separate moving targets from clutter
- Use short waveforms (two or three pulses)
- Do not provide target velocity estimation

Pulsed Doppler (PD) Techniques

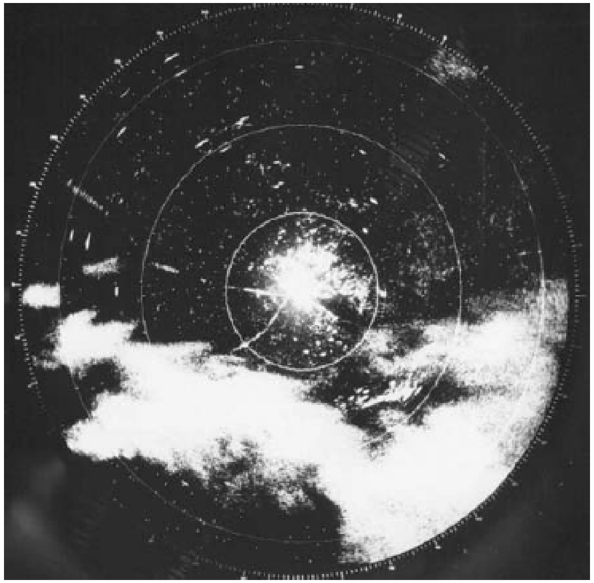
- Separate targets into different velocity regimes in addition to canceling clutter
- Provide good estimates of target velocity
- Use long waveforms -- (many pulses, tens to thousands of pulses)

二、杂波抑制

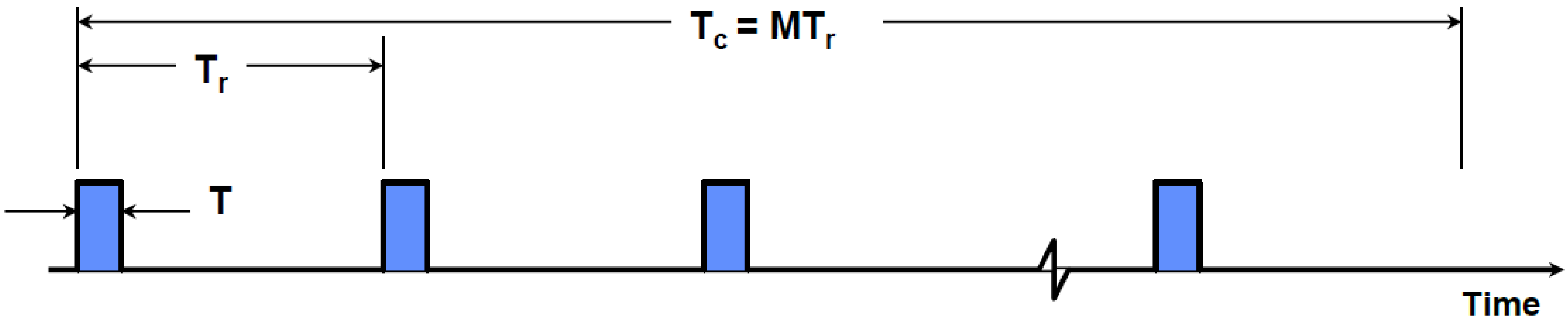
- Clutter comes from same range/angle cell as a target
- Clutter RCS can be much larger than targets of interest (>50 dB)
- Characteristics vary with terrain (land/sea), weather, etc.



PPI Display of Heavy Rain

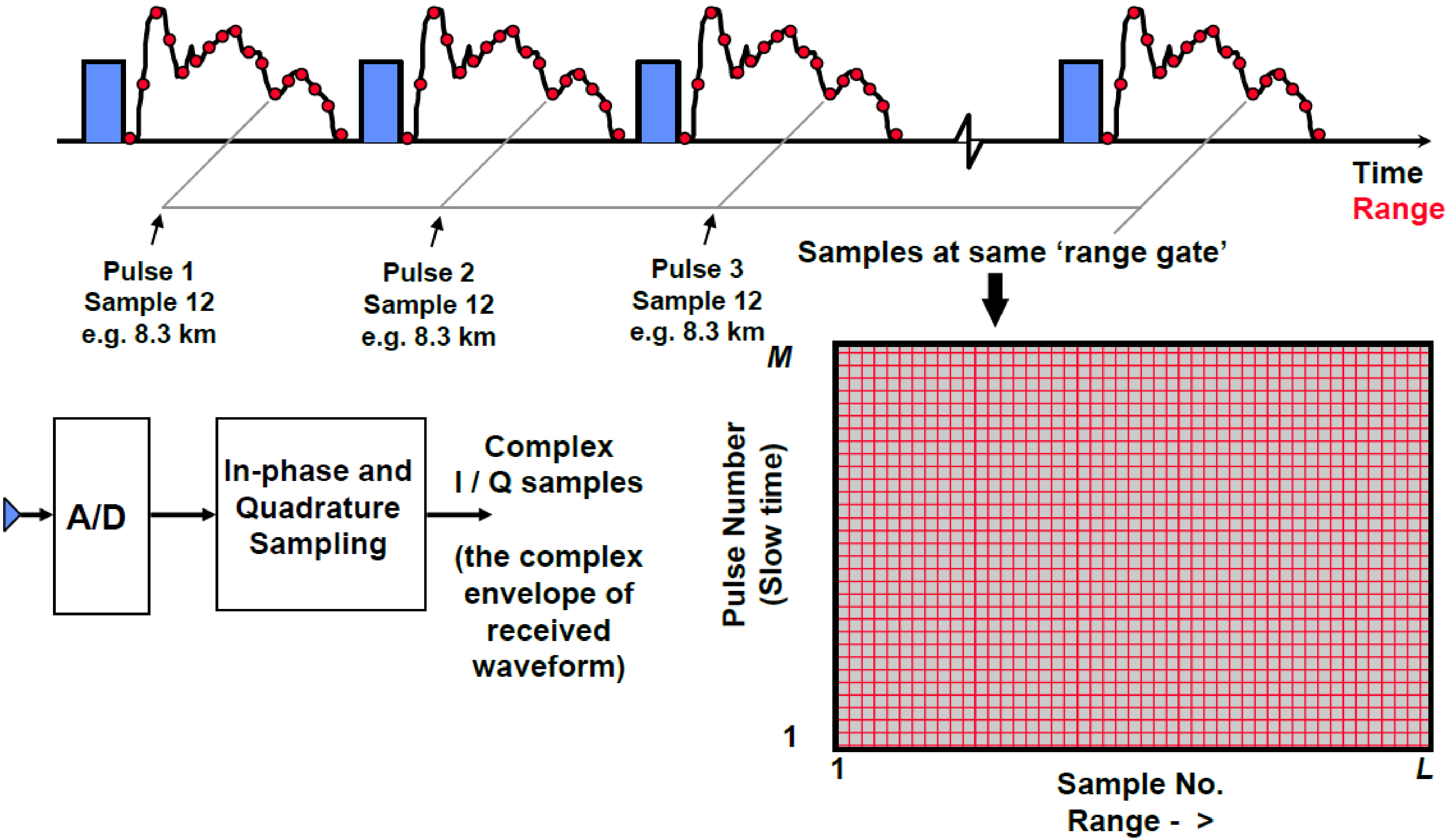


二、杂波抑制



T	=	Pulse length
B	$= 1/T$	Bandwidth
T_r	=	Pulse repetition interval (PRI)
f_r	$= 1/T_r$	Pulse repetition frequency (PRF)
δ	$= T/T_r$	Duty Factor
T_c	$= MT_r$	Coherent processing interval (CPI)
M	=	Number of pulses in the CPI
		M = 2, 3, or sometimes 4 for MTI
		M usually much greater for Pulse Doppler

二、杂波抑制

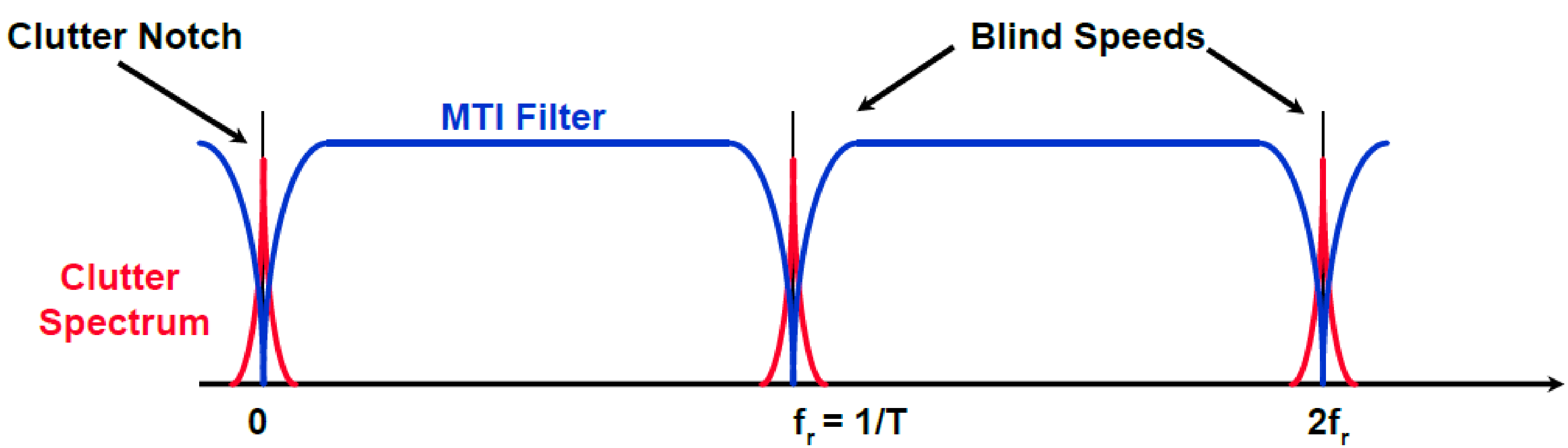


Time
Range
Pulse 1
Sample 12
e.g. 8.3 km
Pulse 2
Sample 12
e.g. 8.3 km
Pulse 3
Sample 12
e.g. 8.3 km
Samples at same ‘range gate’
A/D
In-phase and Quadrature Sampling
Complex I / Q samples
(the complex envelope of received waveform)
M
Pulse Number (Slow time)
1
1
L
Sample No.
Range - >

二、杂波抑制 － Moving Target Indictor (MTI)

动目标显示指利用杂波抑制滤波器抑制各种杂波，提高雷达的信杂噪比（SCNR），以利于运动目标检测的技术。

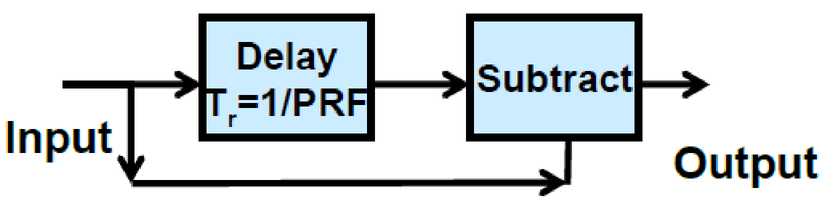
- Notch out Doppler spectrum occupied by clutter
- Provide broad Doppler passband everywhere else
- Blind speeds occur at multiples of the pulse repetition frequency
  - When sample frequency (PRF) equals a multiple of the Doppler frequency



二、杂波抑制 － Moving Target Indictor (MTI)

- Fixed Clutter echoes
  - If one pulse is subtracted from the previous pulse, fixed clutter echoes will cancel and will not be detected
- Moving targets
  - Moving targets change in amplitude from one pulse to the next because of their Doppler frequency shift.
  - If one pulse is subtracted from the other, the result will be an uncancelled residue

Block Diagram



$$V_{output} = V_{i+1} - V_i$$

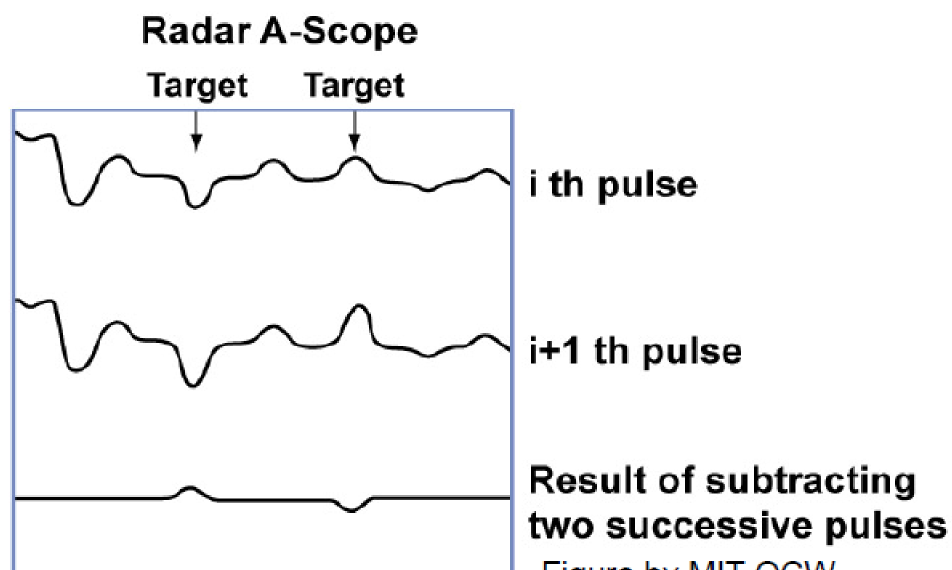
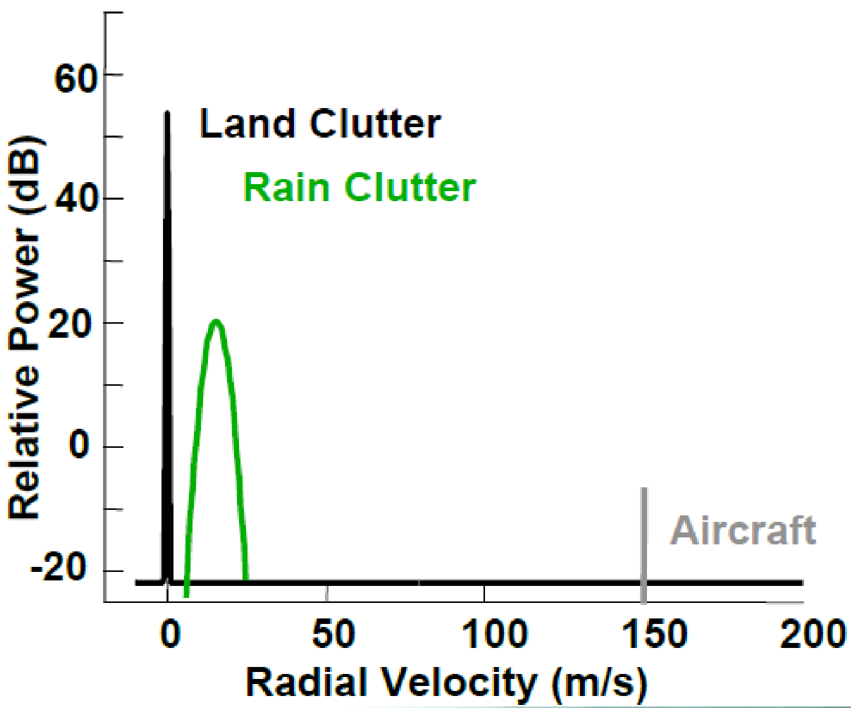


Figure by MIT OCW.

二、杂波抑制 – 评估指标 改善因子

- S_{in} and C_{in} - Input target and clutter power per pulse
- $S_{out}(f_d)$ and $C_{out}(f_d)$ – Output target and clutter power from processor at Doppler frequency, f_d
- MTI Improvement Factor = $I(f_d) = \left.\dfrac{(\text{Signal / Clutter})_{out}}{(\text{Signal / Clutter})_{in}}\right|_{f_d}$



MTI Improvement Factor

$$I(f_d) = \left.\underbrace{\frac{C_{in}}{C_{out}}}_{\text{Clutter Attenuation}} \times \underbrace{\frac{S_{out}}{S_{in}}}_{\text{Signal Gain}}\right|_{f_d}$$

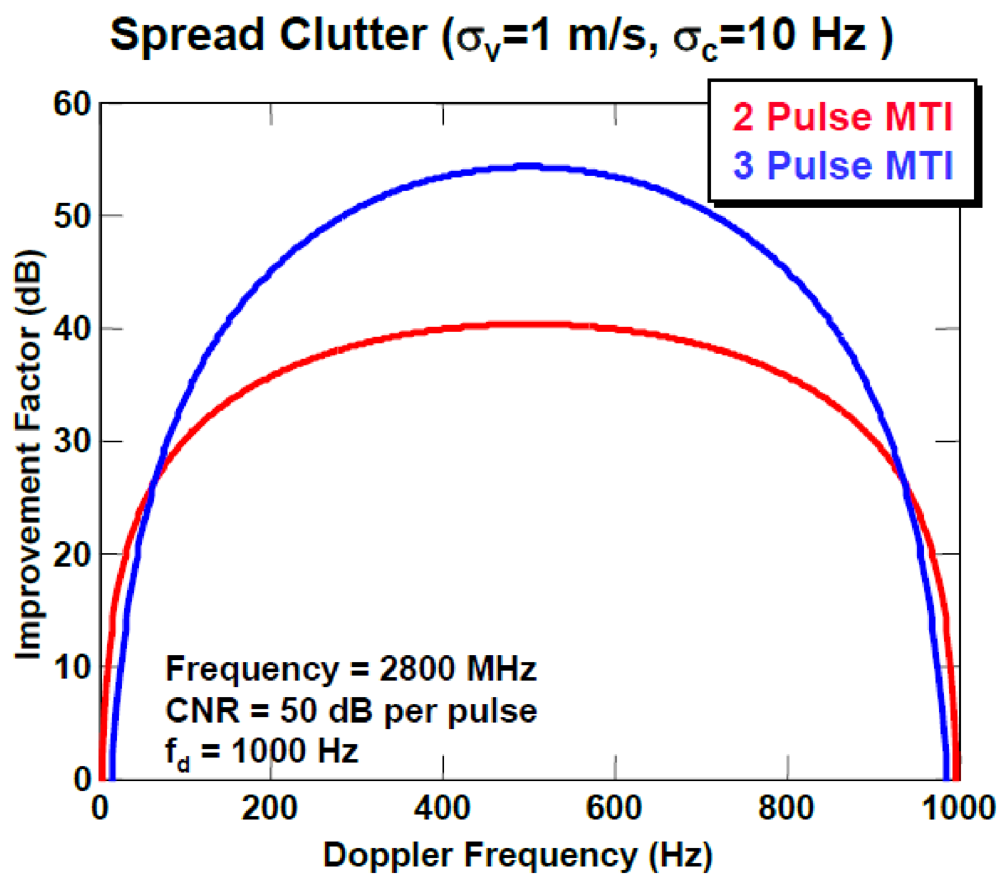
二、杂波抑制

2-Pulse MTI

$$V_{output} = V_i - V_{i-1}$$

3-Pulse MTI

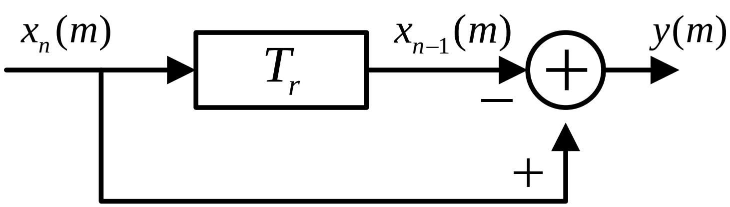
$$V_{output} = V_i - 2V_{i-1} + V_{i-2}$$



Three-pulse canceller provides wider clutter notch and greater clutter attenuation

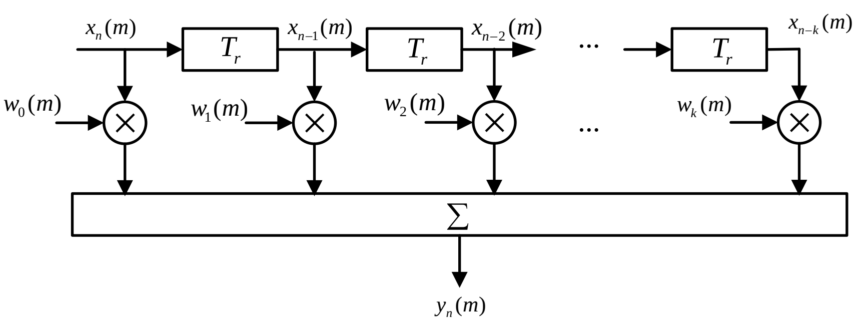
二、杂波抑制 – Moving Target Indictor (MTI)

一次对消器



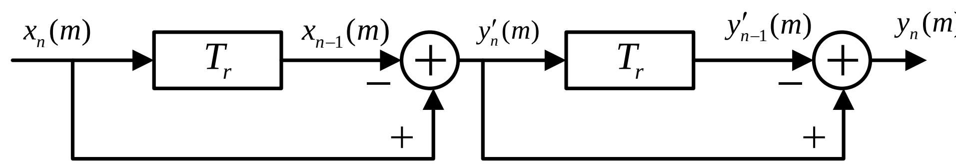
$$y_n(m) = x_n(m) - x_{n-1}(m)$$

K次对消器

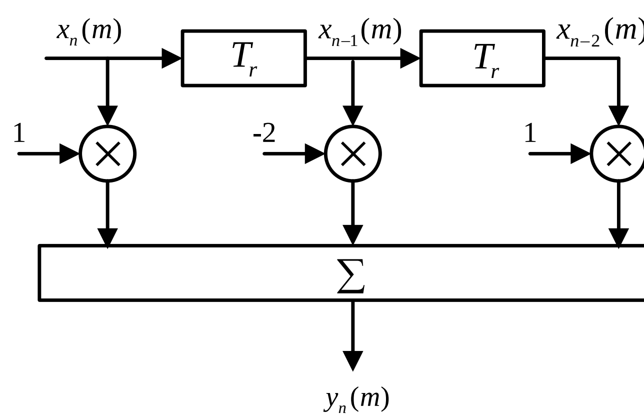


$$y_n(m) = \sum_{i=0}^{k} w_i x_{n-1}(m)$$

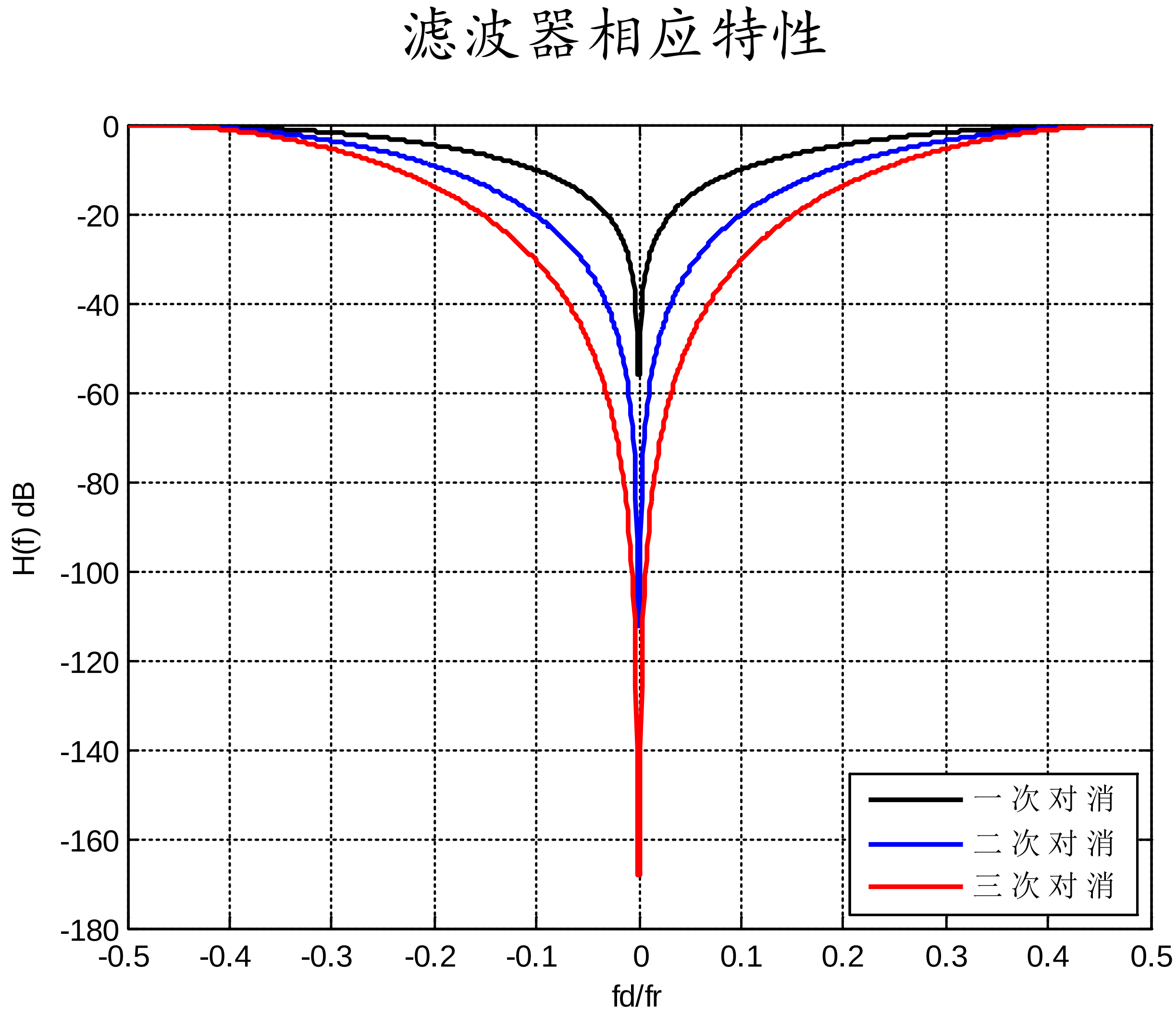
二次对消器



$$\begin{aligned} y_n(m) &= y'_n(m) - y'_{n-1}(m) \\ &= x_n(m) - x_{n-1}(m) - x_{n-1}(m) + x_{n-2}(m) \\ &= x_n(m) - 2x_{n-1}(m) + x_{n-2}(m) \end{aligned}$$



二、杂波抑制 － Moving Target Indictor (MTI)



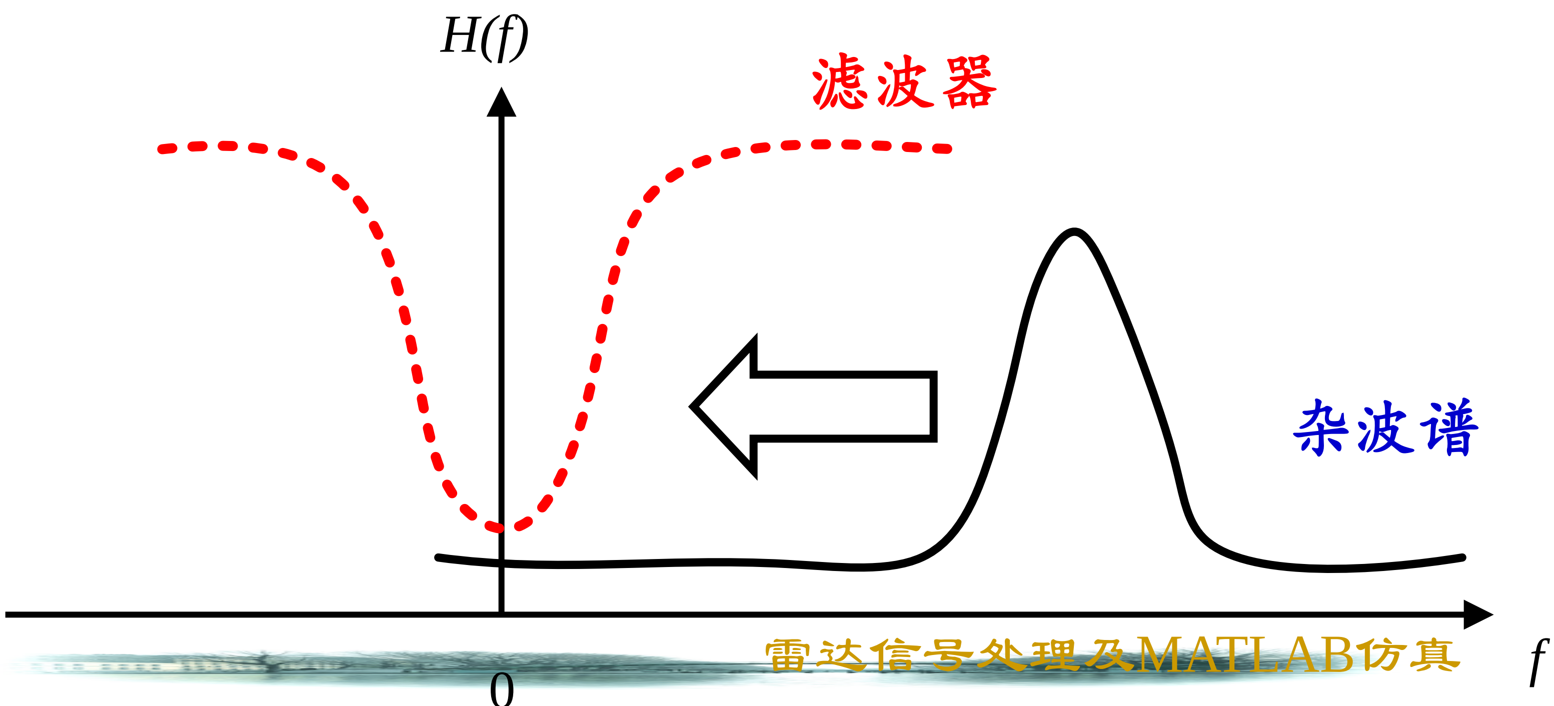
二、杂波抑制 - MTI滤波器

优点：

权值为实数权，其滤波结构为FIR滤波器，因此结构简单，计算量小。

缺点：

- 滤波器的凹口在0频处，即传统滤波器只能对消静止的杂波
- 滤波器的凹口宽度是固定的，不能根据杂波谱的宽度自适应的调节



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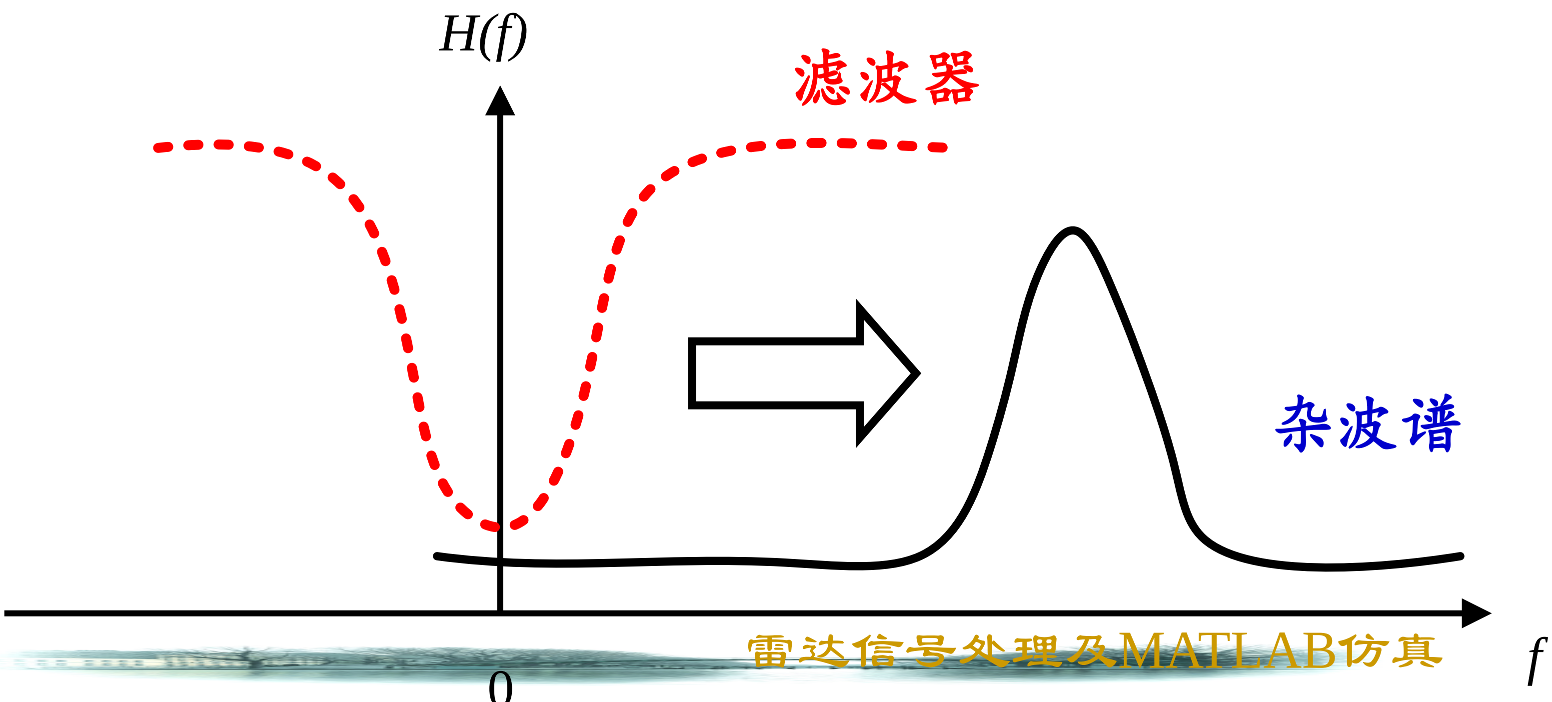


二、杂波抑制 - MTI

IIR滤波器

优点：可以用相对较少的阶数达到滤波器响应；

缺点：相位非线性 （在实际中很少采用）

FIR滤波器

优点：具有线性相位

MTI滤波器的设计

有效抑制杂波

保证目标信号能良好通过

二、杂波抑制 － 特征矢量法

假设MTI滤波器输入的杂波数据和目标数据分别为

$$\mathbf{C}=\left[c(t_1),c(t_2),\ldots,c(t_n)\right]$$

$$\mathbf{S}=\left[s(t_1),s(t_2),\ldots,s(t_n)\right]$$

→ MTI 滤波器 →

$$C_0=E\left[\left|\mathbf{C}^{\mathbf{H}}W\right|^2\right]=C_{in}\mathbf{W}^{\mathbf{H}}\mathbf{R}_{\mathbf{c}}\mathbf{W}$$

$$S_0=E\left[\left|\mathbf{S}^{\mathbf{H}}W\right|^2\right]=C_{in}\mathbf{W}^{\mathbf{H}}\mathbf{R}_{\mathbf{s}}\mathbf{W}$$

根据MTI改善因子的定义

$$I=\frac{S_o/C_o}{S_{in}/C_{in}}=\frac{S_o}{S_{in}}\times\frac{C_{in}}{C_o}$$

$$=\frac{S_{in}\mathbf{W}^{\mathbf{H}}\mathbf{R}_{\mathbf{s}}\mathbf{W}}{S_{in}}\times\frac{C_{in}}{C_{in}\mathbf{W}^{\mathbf{H}}\mathbf{R}_{\mathbf{c}}\mathbf{W}}$$

$$=\frac{\mathbf{W}^{\mathbf{H}}\mathbf{R}_{\mathbf{s}}\mathbf{W}}{\mathbf{W}^{\mathbf{H}}\mathbf{R}_{\mathbf{c}}\mathbf{W}}$$

对于目标回波，假设在区间（-B/2，B/2）上均匀分布

$$S(f)=\begin{cases}1 & -B/2\le f\le B/2\\ 0 & \text{其它}\end{cases}$$

目标信号的自相关函数

$$r_s(i,j)=\frac{1}{B}\int_{-B/2}^{B/2}e^{-j2\pi f\tau_{ij}}df$$

$$=\frac{\sin\left(\pi B\tau_{ij}\right)}{\pi B\tau_{ij}}$$

$$\tau_{ij}=t_i-t_j$$

$$r_s(i,j)=\begin{cases}1 & i=j\\ 0 & i\ne j\end{cases}$$

$$I=\frac{\mathbf{W}^{\mathbf{H}}\mathbf{R}_{\mathbf{s}}\mathbf{W}}{\mathbf{W}^{\mathbf{H}}\mathbf{R}_{\mathbf{c}}\mathbf{W}}=\frac{\mathbf{W}^{\mathbf{H}}\mathbf{W}}{\mathbf{W}^{\mathbf{H}}\mathbf{R}_{\mathbf{c}}\mathbf{W}}$$

二、杂波抑制

假设杂波具有高斯分布

$$C(f)=\frac{1}{2\pi\sigma_f}\exp\left\{-\frac{(f-f_0)^2}{2\sigma_f^2}\right\}$$

傅里叶逆变换

$$r_c(i,j)=\int_{-\infty}^{\infty}C(f)e^{j2\pi f(t_i-t_j)}df$$
$$=\int_{-\infty}^{\infty}\frac{1}{2\pi\sigma_f}\exp\left[-\frac{(f-f_0)^2}{2\sigma_f}\right]e^{j2\pi f(t_i-t_j)}df$$
$$=e^{-2\pi\sigma_f^2\tau_{ij}^2}\left[\cos(2\pi f_0\tau_{ij})+j\sin(2\pi f_0\tau_{ij})\right]$$

Step1:构建杂波协方差矩阵

$$R_c=\begin{bmatrix} r_c(0,0) & r_c(0,1) & \cdots & r_c(0,N) \\ r_c(1,0) & r_c(1,1) & \cdots & r_c(1,N) \\ \vdots & \vdots & \vdots & \vdots \\ r_c(N,0) & r_c(N,1) & \cdots & r_c(N,N) \end{bmatrix}$$

Step2:特征值分解

$$\lambda_1<\lambda_2<\lambda_3<\cdots\lambda_N$$

W_1、W_2、$W_3\cdots W_N$

Step3: MTI权值确定

准则:最小特征值所对应的特征矢量作为MTI滤波器的权系数矢量

二、杂波抑制 － 特征矢量法

改善因子最大准则

$$I=\frac{S_o/C_o}{S_{in}/C_{in}}=\frac{S_o}{S_{in}}\times\frac{C_{in}}{C_o}$$

$$C_o=E\left[\left\lfloor C^H W\right\rfloor^2\right]=C_{in}W^H R_c W$$

$$S_o=E\left[\left\lfloor S^H W\right\rfloor^2\right]=S_{in}W^H R_s W$$

$$I=\frac{S_{in}W^H R_s W}{S_{in}}\times\frac{C_{in}}{C_{in}W^H R_c W}=\frac{W^H R_s W}{W^H R_c W}$$

$R_s=I$(单位阵)

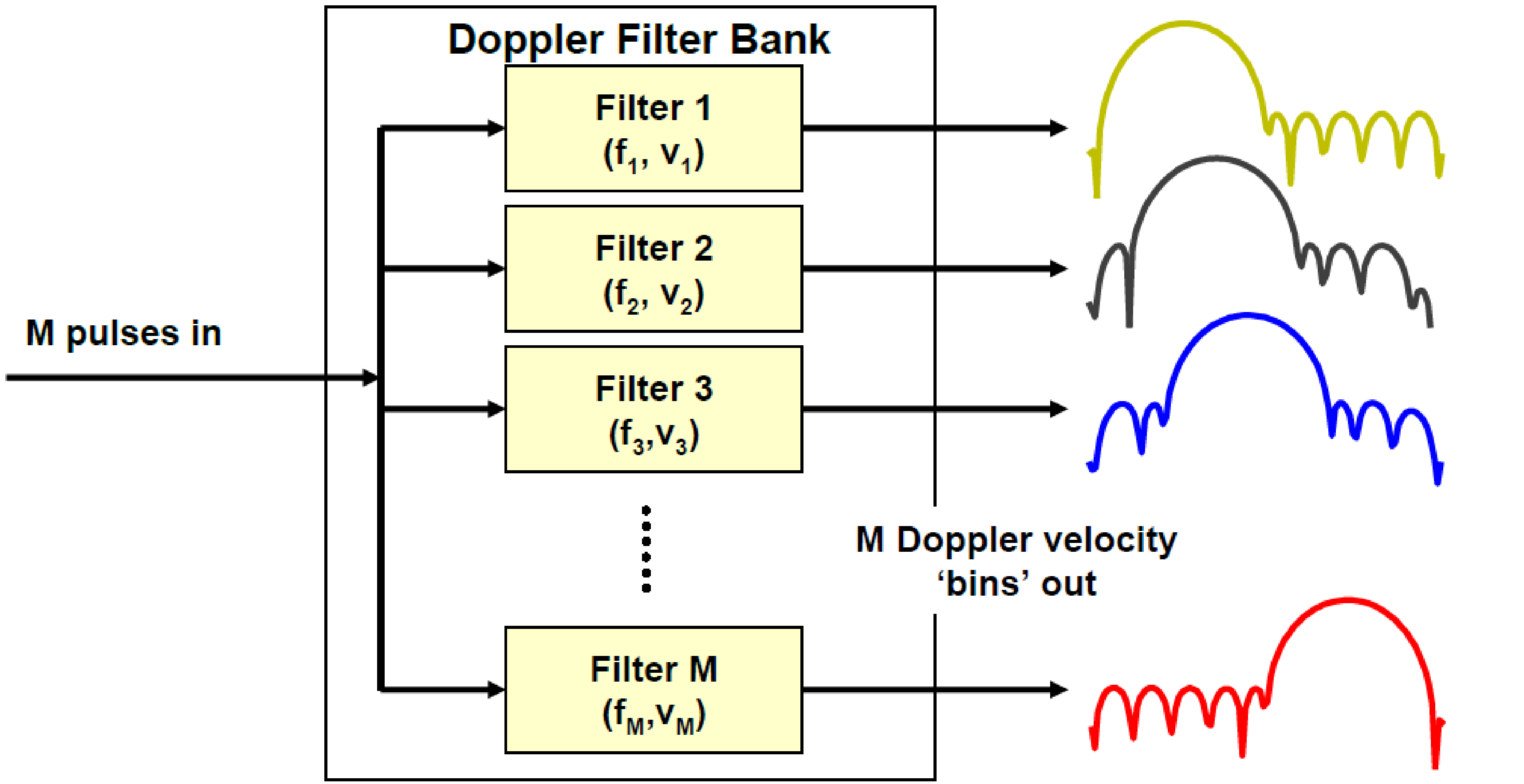
$R_c W_i=\lambda_i W_i \quad i=1,2,\cdots N$

$$I=\frac{W_i^H W_i}{W_i^H\lambda_i W_i}=\frac{W_i^H W_i}{\lambda_i W_i^H W_i}=\frac{1}{\lambda_i}$$

$$I\rightarrow MAX\Rightarrow\lambda\rightarrow MIN$$

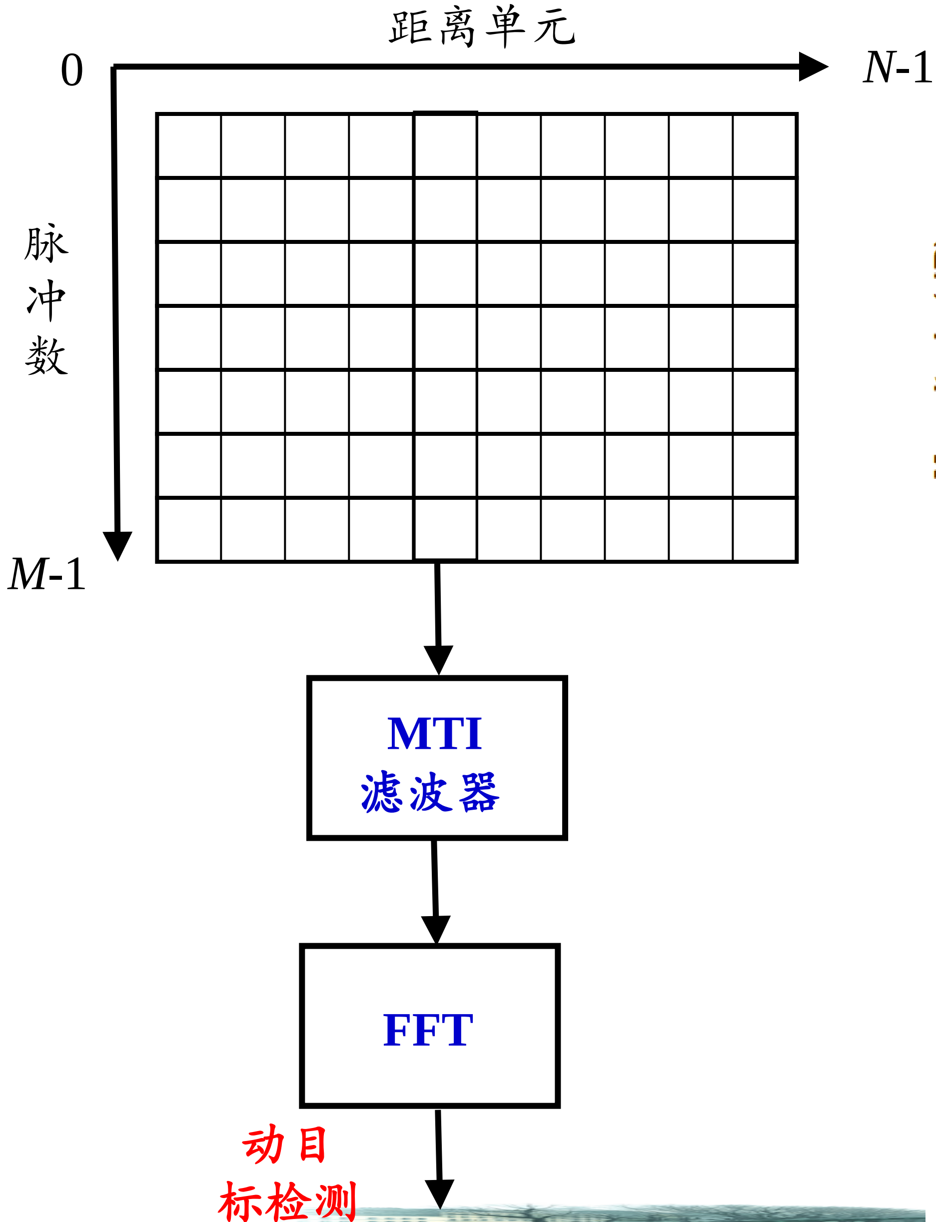
噪声子空间和信号子空间是正交的，所以最小特征值所对应的特征向量作为MTI权系数矢量，就可以最大限度的抑制杂波

二、杂波抑制 – 动目标检测（MTD）

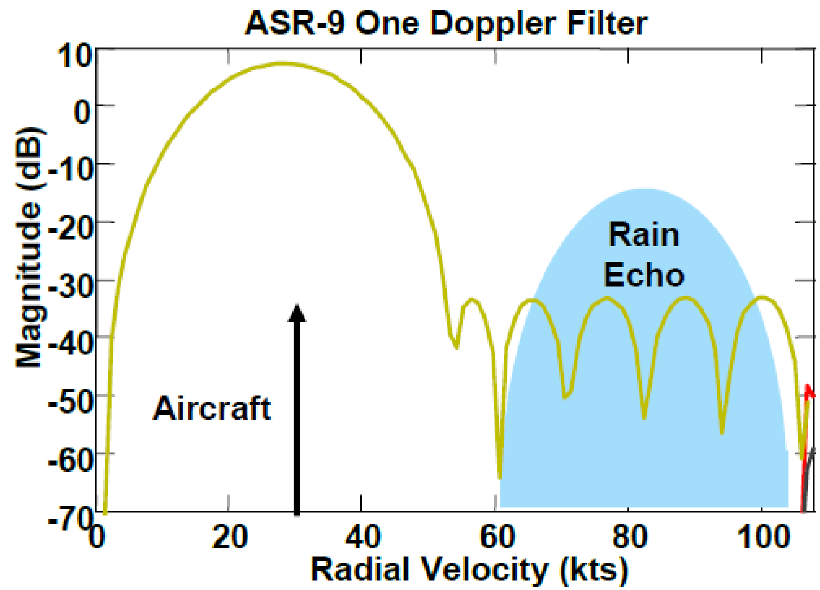


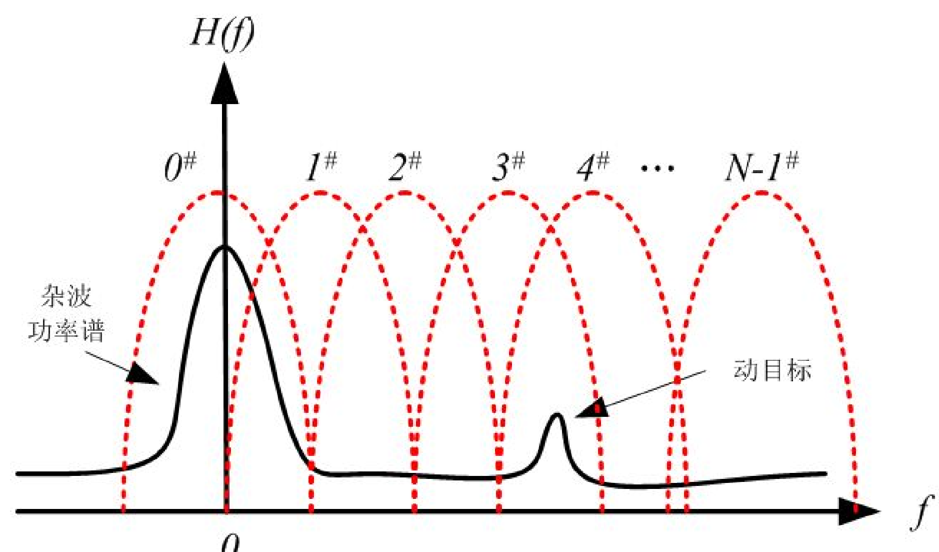
- Coherent integration of all pulses of a CPI
- Clutter rejection
- Resolving targets into different velocity segments and allowing for fine-grain target radial velocity estimation

二、杂波抑制



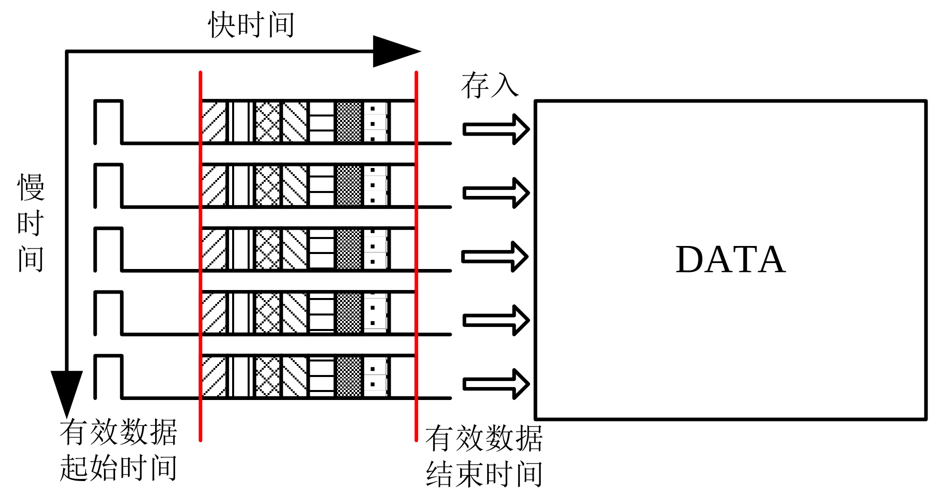
$$X(k)=\sum_{n=0}^{N-1}x(n)e^{-j2\pi nk/N}$$



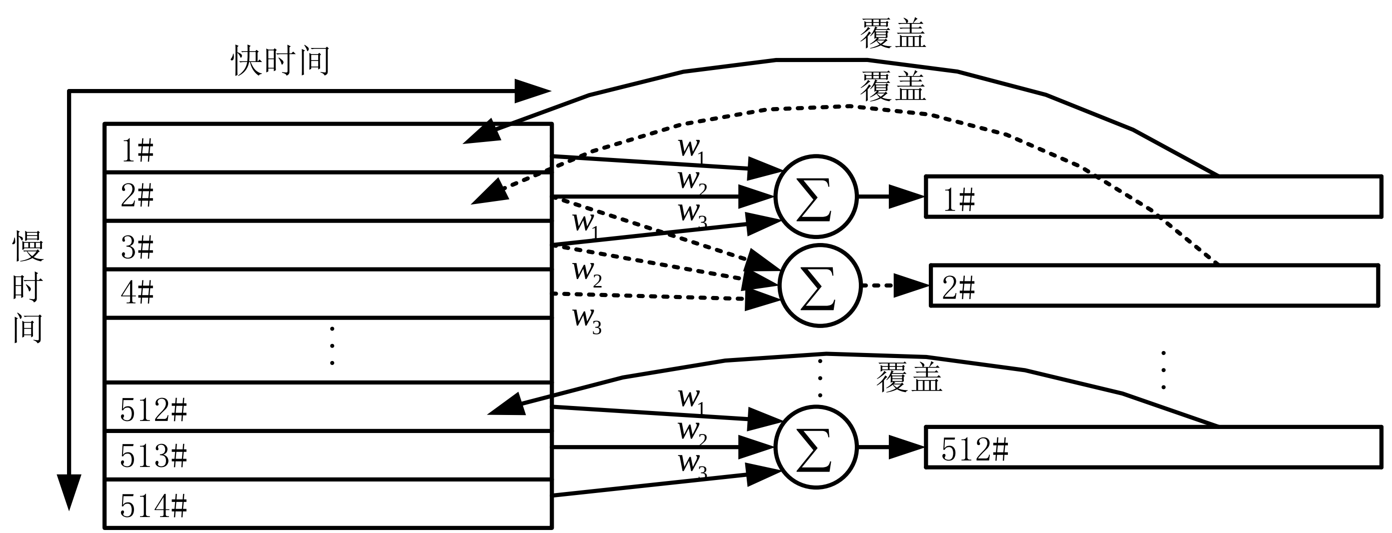


二、杂波抑制

□ 数据采集与存储阶段



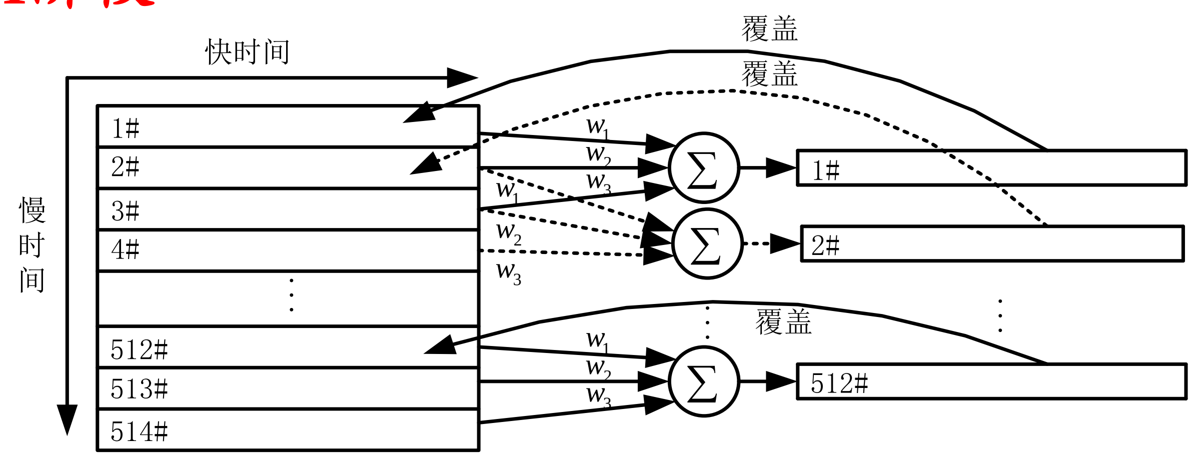
□ MTI阶段



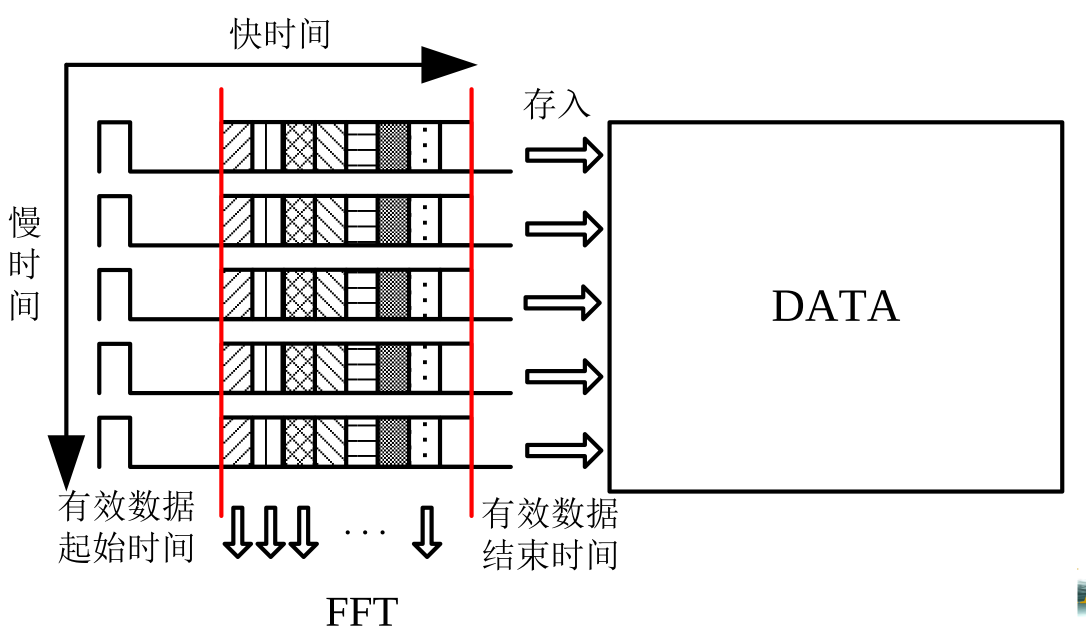
真

二、杂波抑制

□ MTI阶段

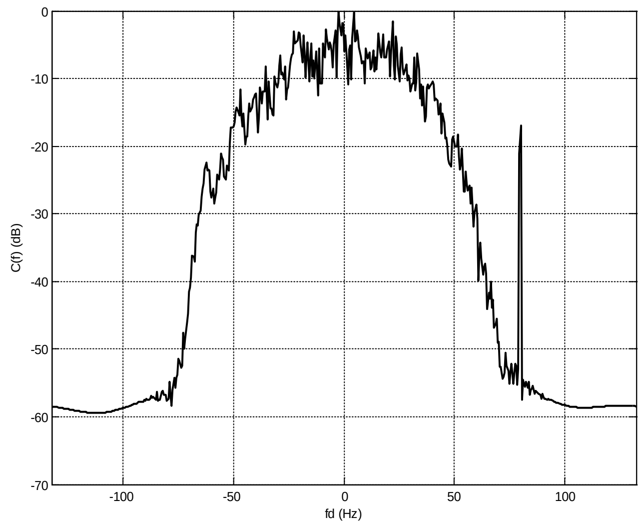


□ MTD阶段

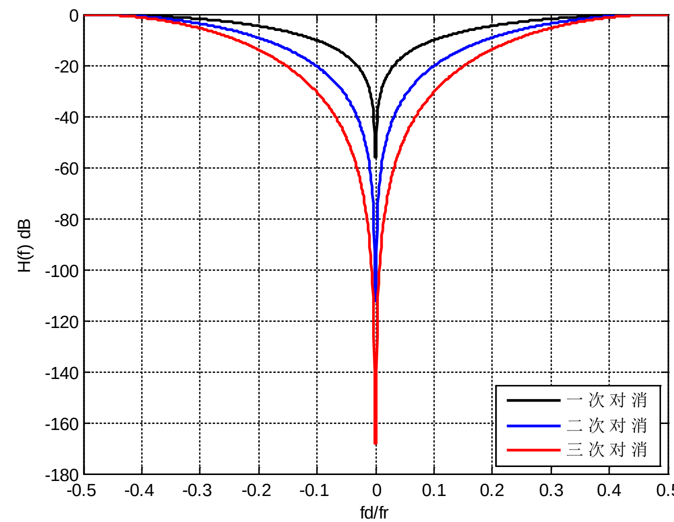


二、杂波抑制 - 传统方法

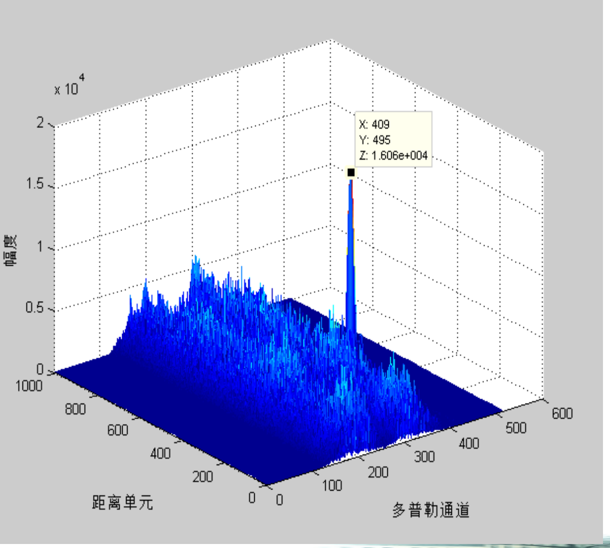
杂波频谱



滤波器相应特性



一次对消



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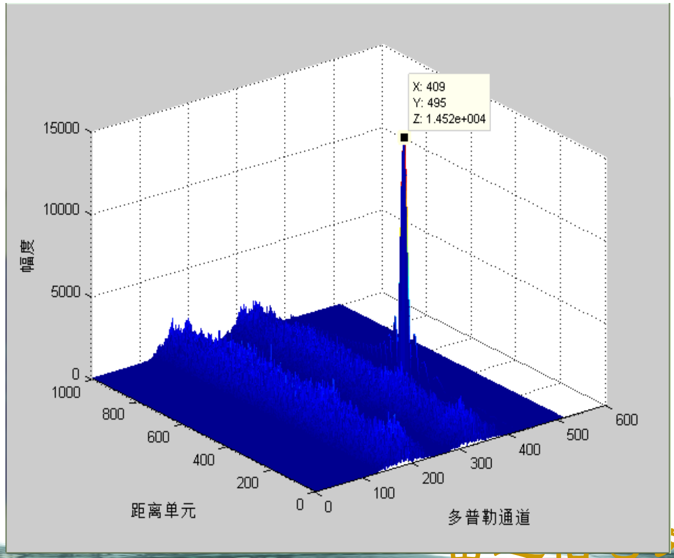
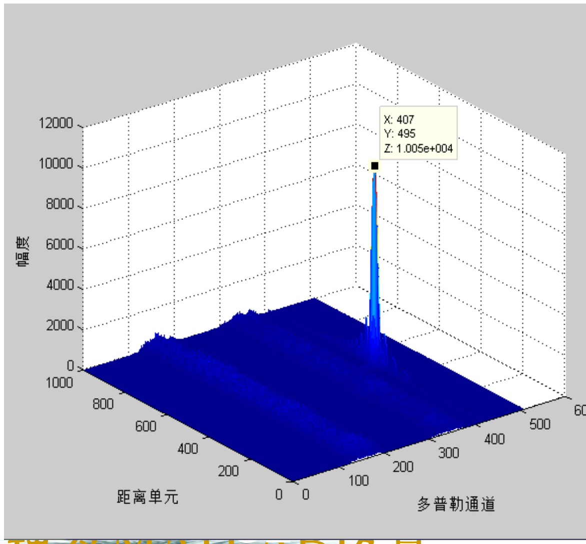
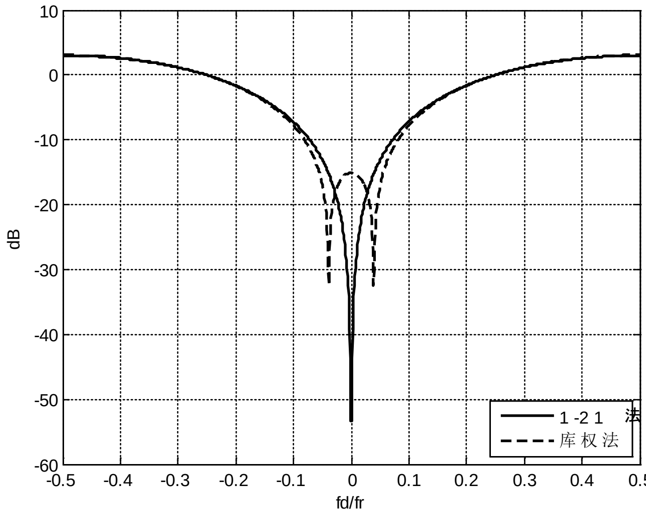
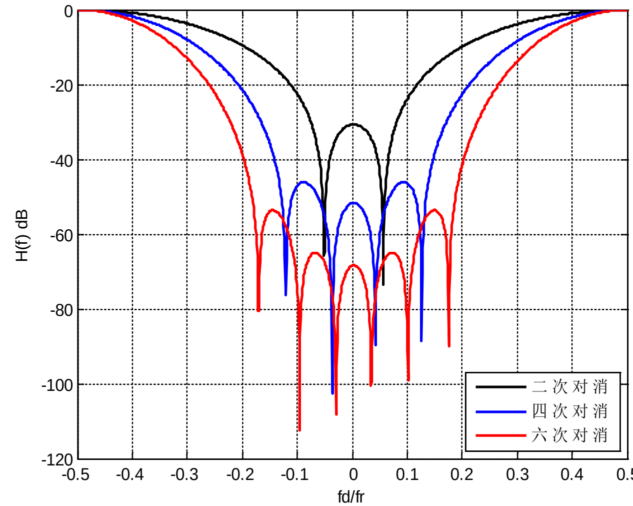


三次对消



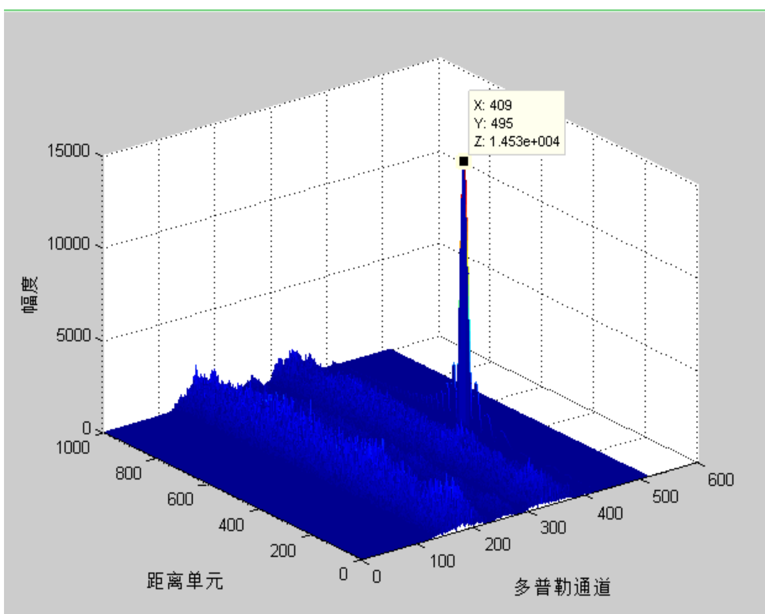
二、杂波抑制 – 特征矢量法

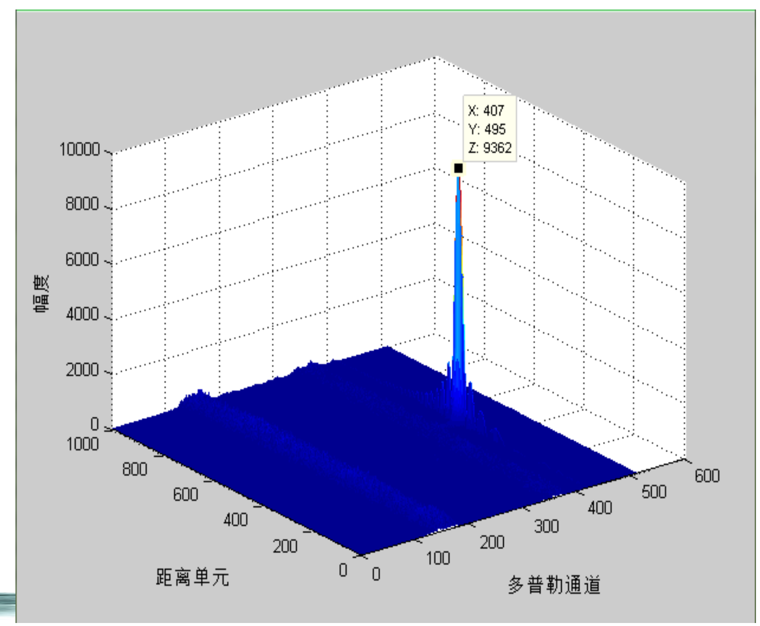




二次对消

四次对消





杂波抑制与动目标检测

- 杂波的定义
- 杂波抑制技术
- **动目标检测**
- 本章小结

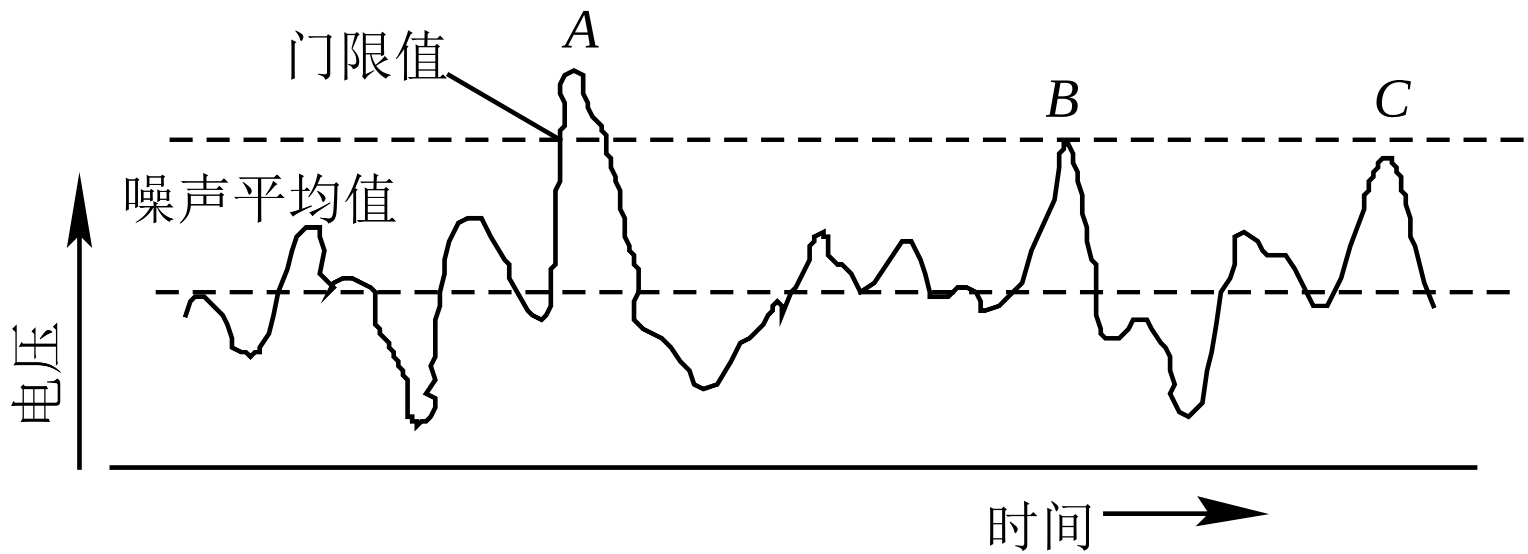
三、动目标检测

检测时门限电压的高低影响以下两种错误判断的多少: □

(1) 有信号而误判为没有信号(**漏警**); □

(2) 只有噪声时误判为有信号(**虚警**)。 □

应根据两种误判的影响大小来选择合适的门限。



三、动目标检测

门限检测是一种统计检测，由于信号叠加有噪声，所以总输出是一个随机量。在输出端根据输出振幅是否超过门限来判断有无目标存在，可能出现以下四种情况：□

(1)发现概率P_d： 存在目标时，判为有目标；

(2)漏报概率P_{la}： 存在目标时，判为无目标；□

(3)正确不发现概率P_{an}： 不存在目标时判为无目标；□

(4)虚警概率P_{fa}： 不存在目标时判为有目标；□

$$P_d+P_{la}=1, \quad P_{an}+P_{fa}=1$$

三、动目标检测

虚警概率P_{fa}□

通常加到接收机中频滤波器(或中频放大器)上的噪声是**宽带高斯噪声**, 其概率密度函数由下式给出:

$$p(v)=\frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{v^2}{2\sigma^2}\right)$$

包络检波器输出端**噪声电压振幅**的概率密度函数为瑞利分布:

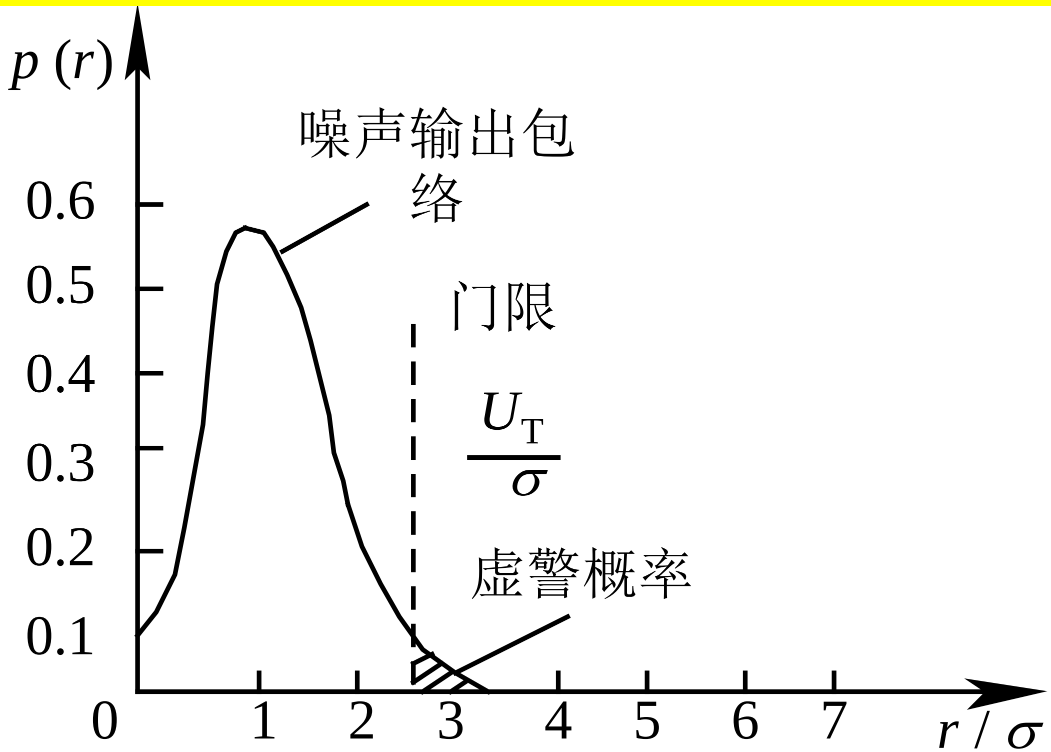
$$p(r)=\frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right)\qquad r\geq 0$$

三、动目标检测

虚警概率P_{fa}□

设置门限电平U_T, 噪声包络电压超过门限电平的概率就是虚警概率P_{fa}, 它可以由下式求出:

$$P_{fa} = P(U_T \le r < \infty) = \int_{U_T}^{\infty} \frac{r}{\sigma^2} \exp\left(\frac{r^2}{2\sigma^2}\right) dr = \exp\left(-\frac{U_T^2}{2\sigma^2}\right)$$



仿真

三、动目标检测

为获得可预知且稳定的检测性能，雷达系统一般倾向于设计雷达具有恒定的虚警概率。因此，实际干扰噪声功率电平必须实时的从数据中估计，从而调整雷达检测门限以获得期望的虚警概率。

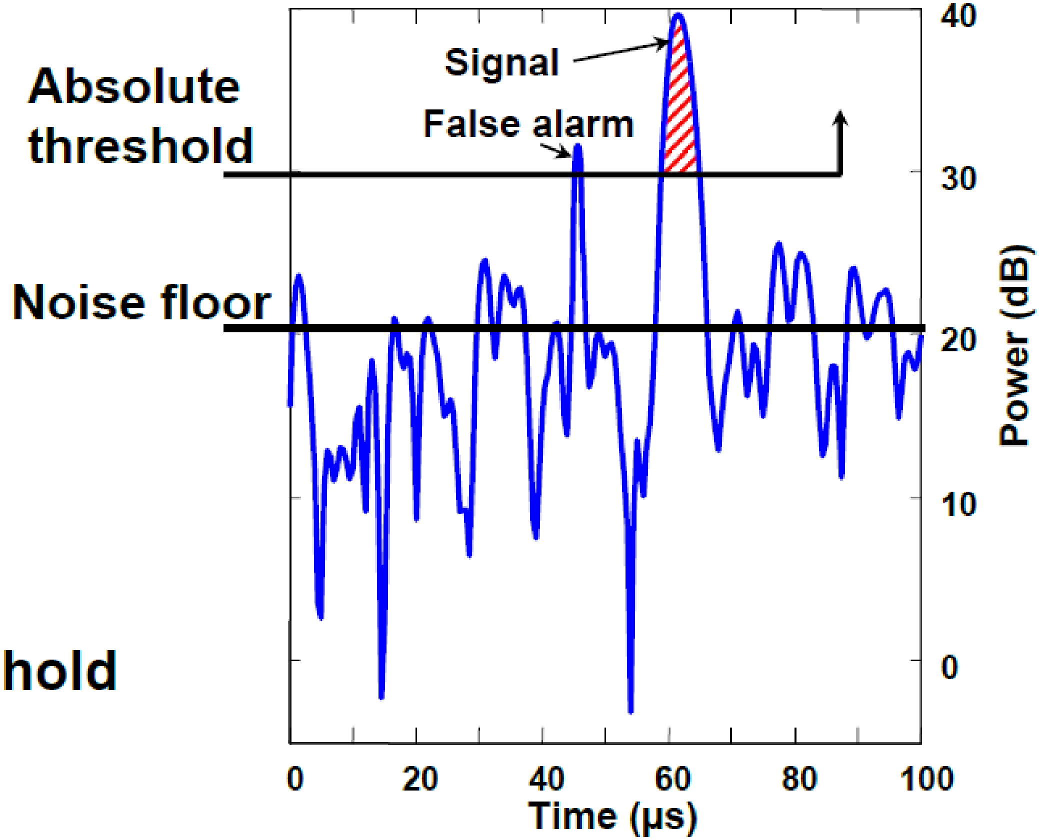
可保持**恒定虚警概率**的检波处理器——**恒虚警检测(CFAR)**

恒虚警检测的方法就是采用自适应门限代替固定门限，因此自适应门限能随着被检测点的背景噪声、杂波和干扰的大小自适应调整。

三、动目标检测

- Problem: Must know (or estimate) noise floor to set threshold
- Solution: Estimate noise floor using noise-only samples
  - Adaptive thresholding
- CFAR thresholding:

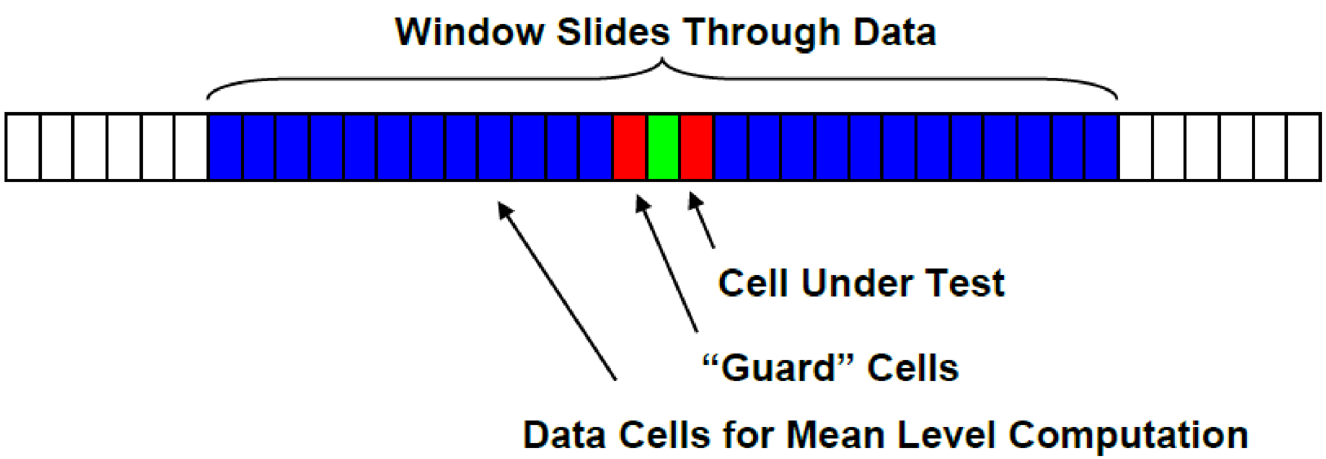
$$\frac{\text{test cell}}{\text{noise floor estimate}} > \text{threshold}$$



三、动目标检测

平均单元恒虚警检测 （CA-CFAR）

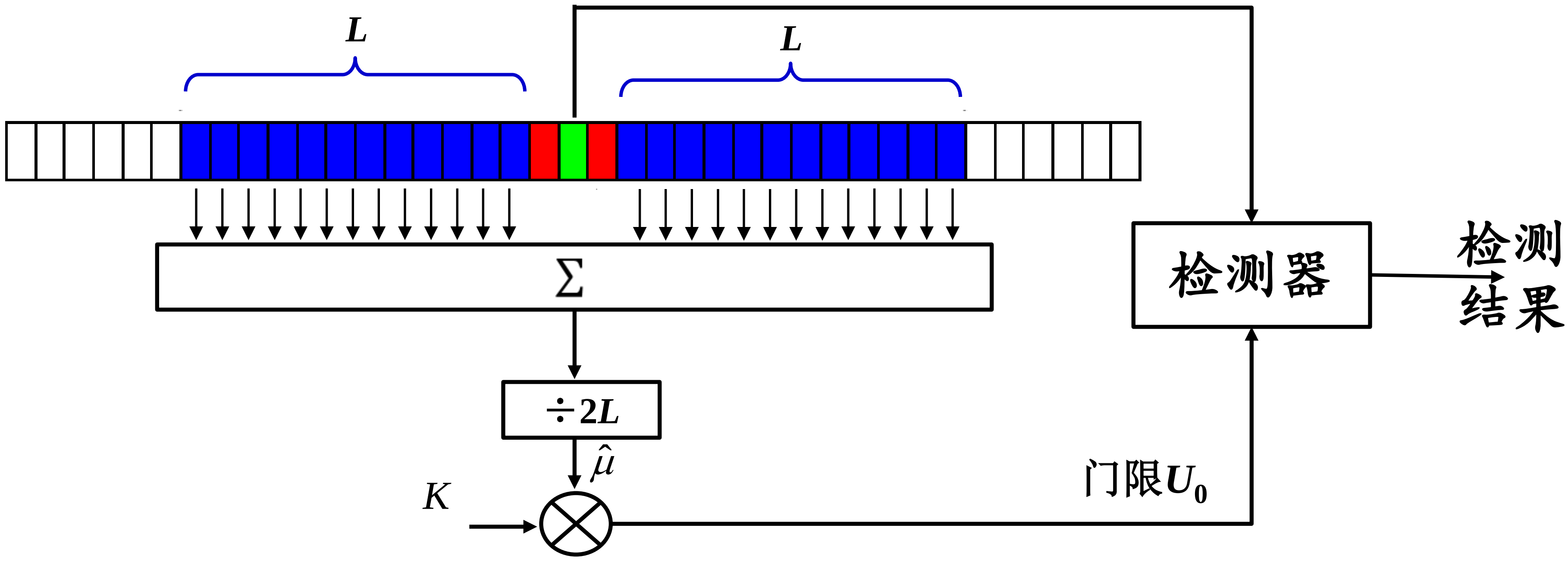
- Use mean value of surrounding range cells to determine threshold for cell under test



- Nearby targets can raise threshold and suppress detection

三、动目标检测

平均单元恒虚警检测 （CA-CFAR）

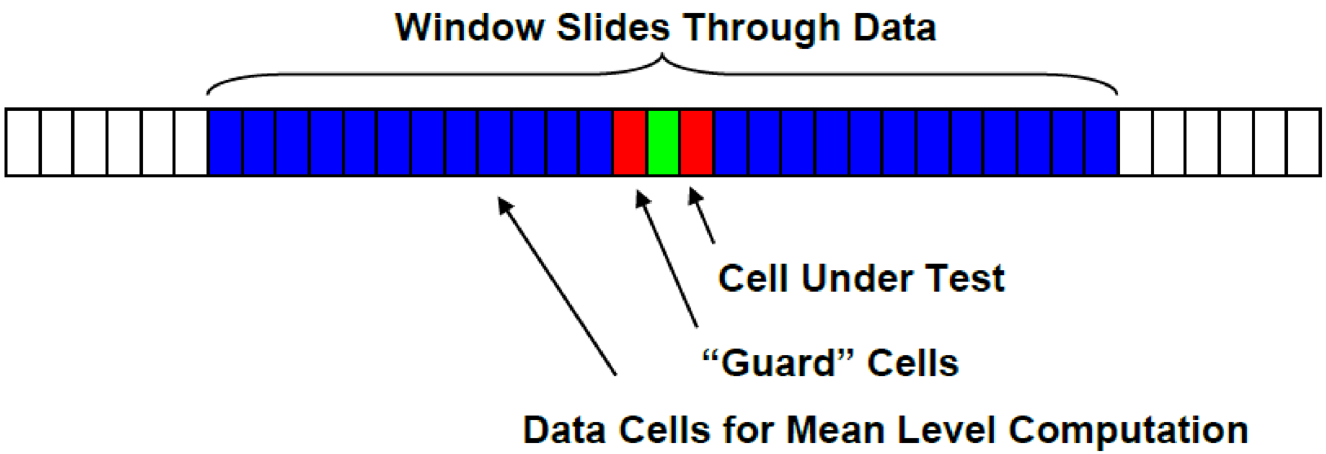


$$U_0 = K\hat{\mu}$$

三、动目标检测

平均单元恒虚警检测 （CA-CFAR）

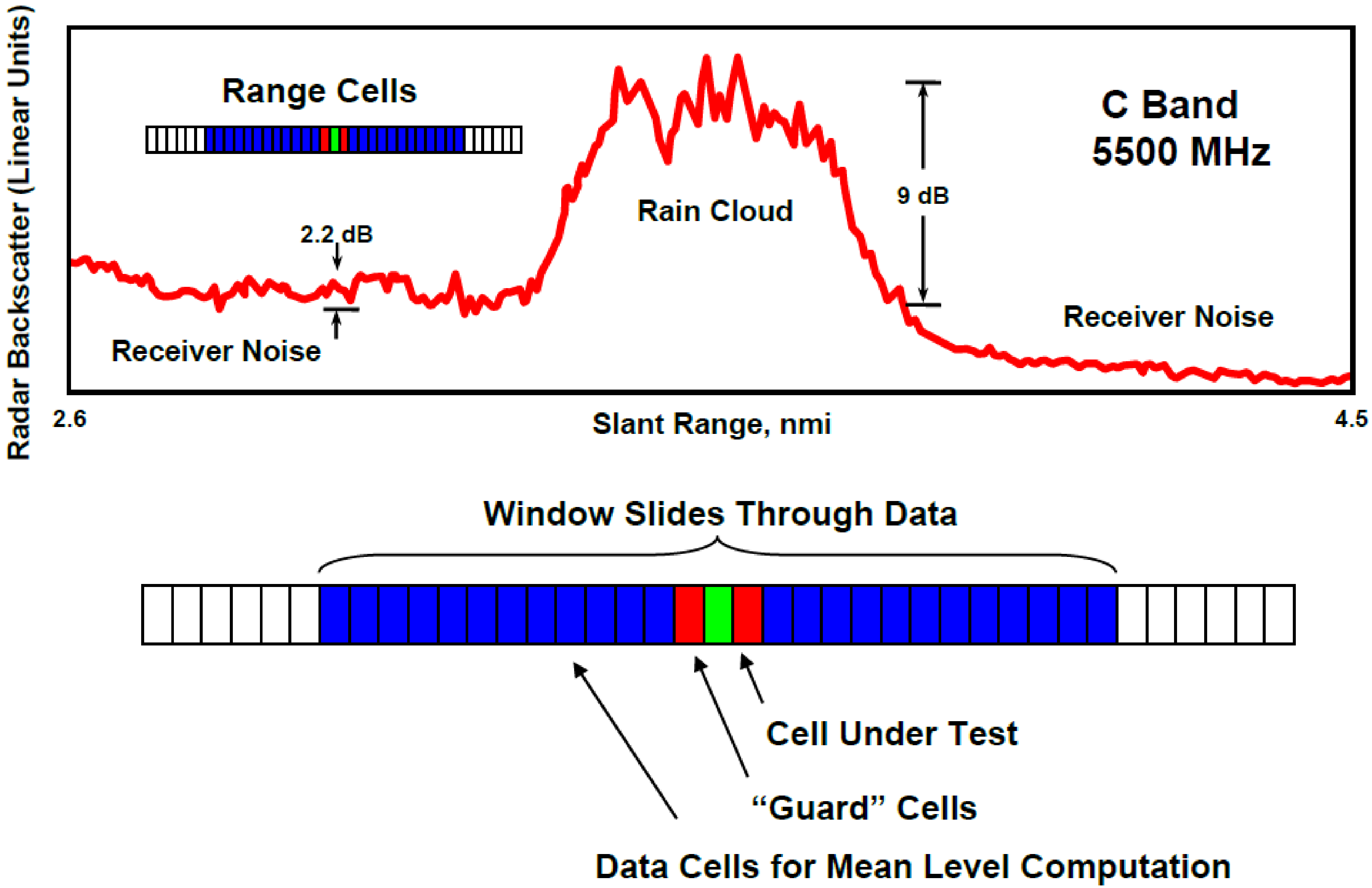
- Use mean value of surrounding range cells to determine threshold for cell under test



- Nearby targets can raise threshold and suppress detection

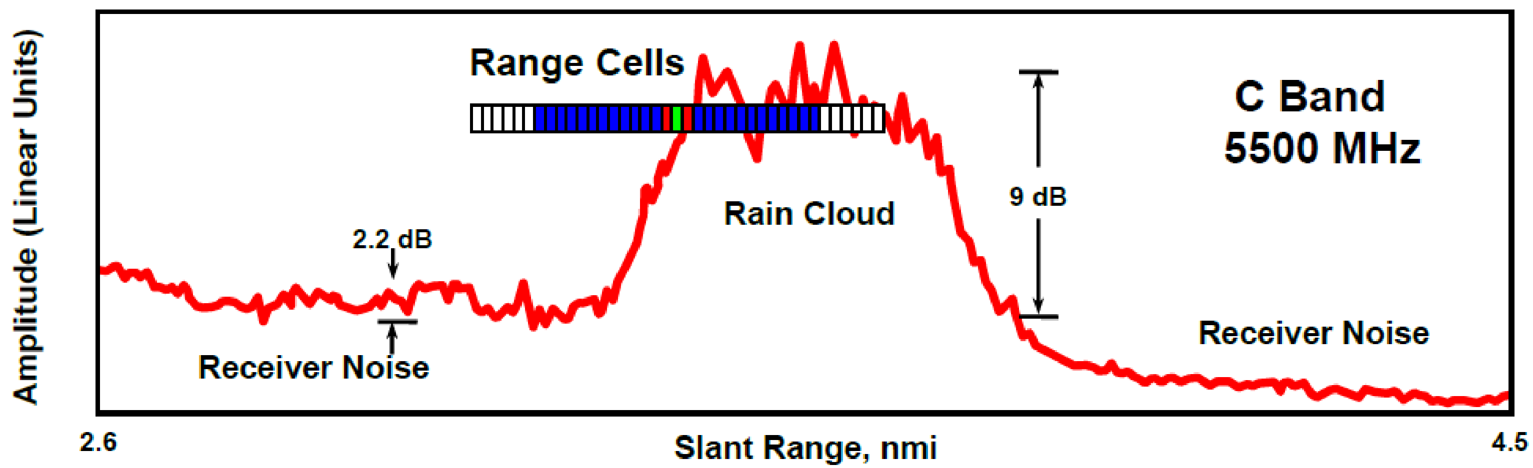
三、动目标检测

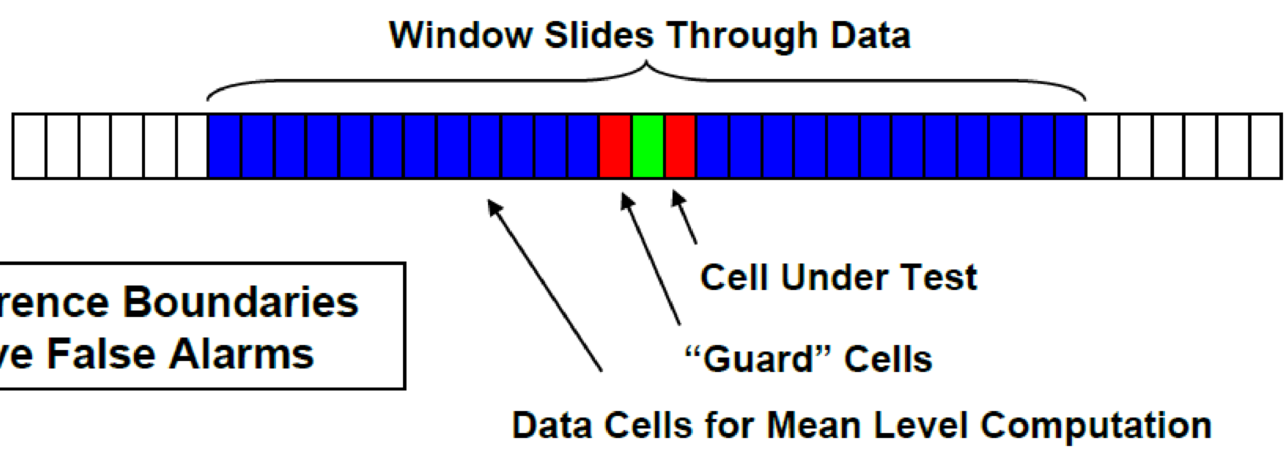
选大恒虚警（GO-CFAR）　　选小恒虚警（SO-CFAR）



三、动目标检测

选大恒虚警（GO-CFAR）　　选小恒虚警（SO-CFAR）



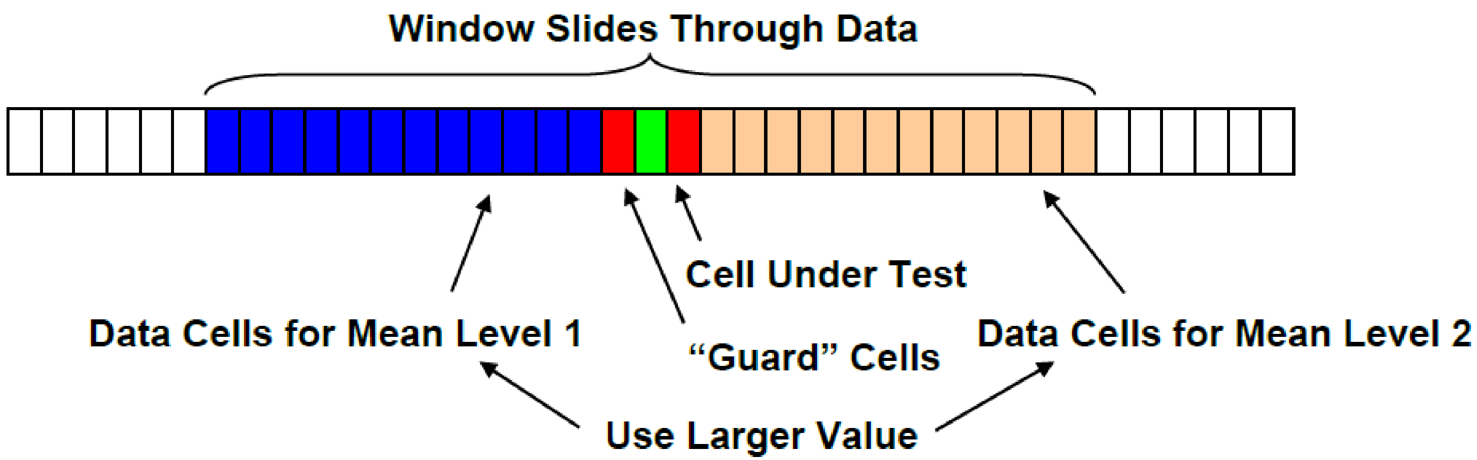


Sharp Clutter or Interference Boundaries
Can Lead to Excessive False Alarms

三、动目标检测

选大恒虚警（GO-CFAR）　　选小恒虚警（SO-CFAR）

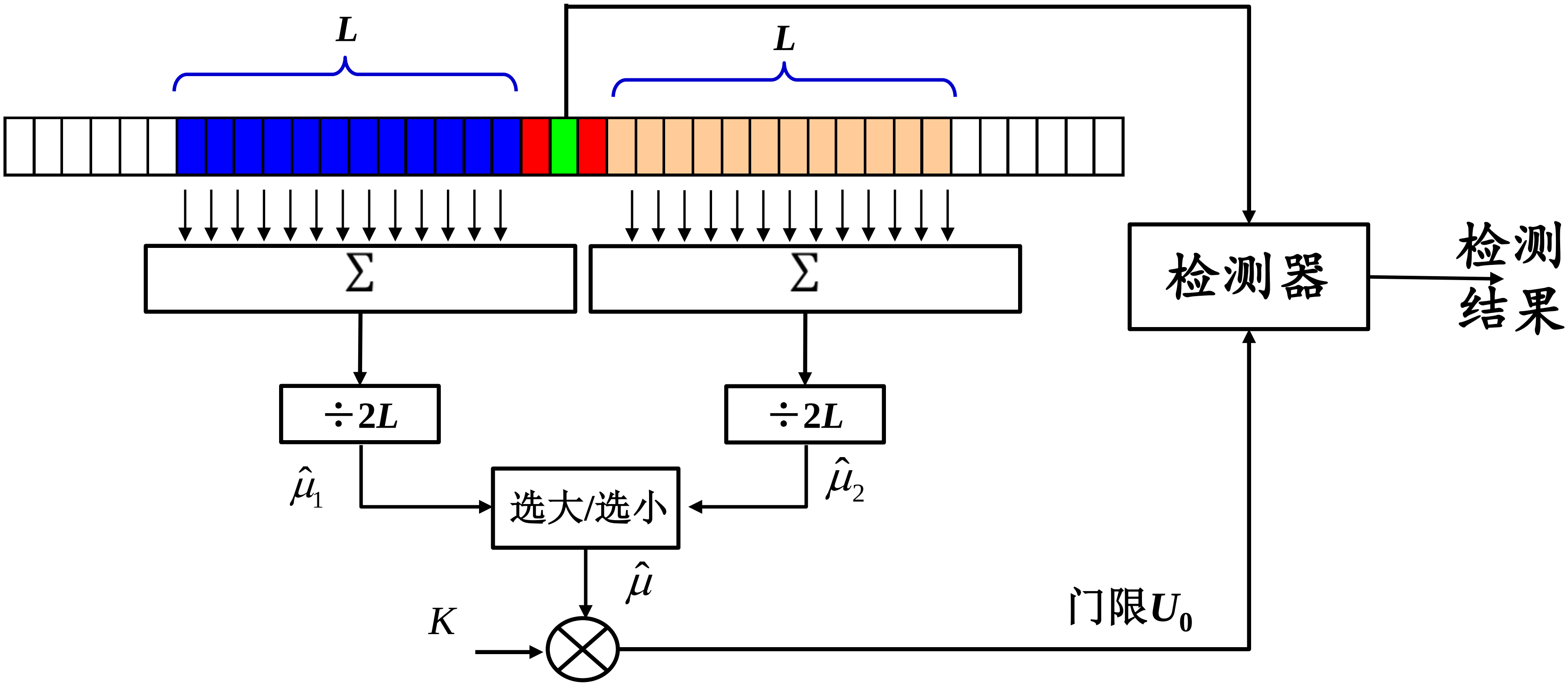
- Find mean value of N/2 cells before and after test cell separately
- Use larger noise estimate to determine threshold



- Helps reduce false alarms near sharp clutter or interference boundaries
- Nearby targets still raise threshold and suppress detection

三、动目标检测

选大恒虚警（GO-CFAR）　　选小恒虚警（SO-CFAR）



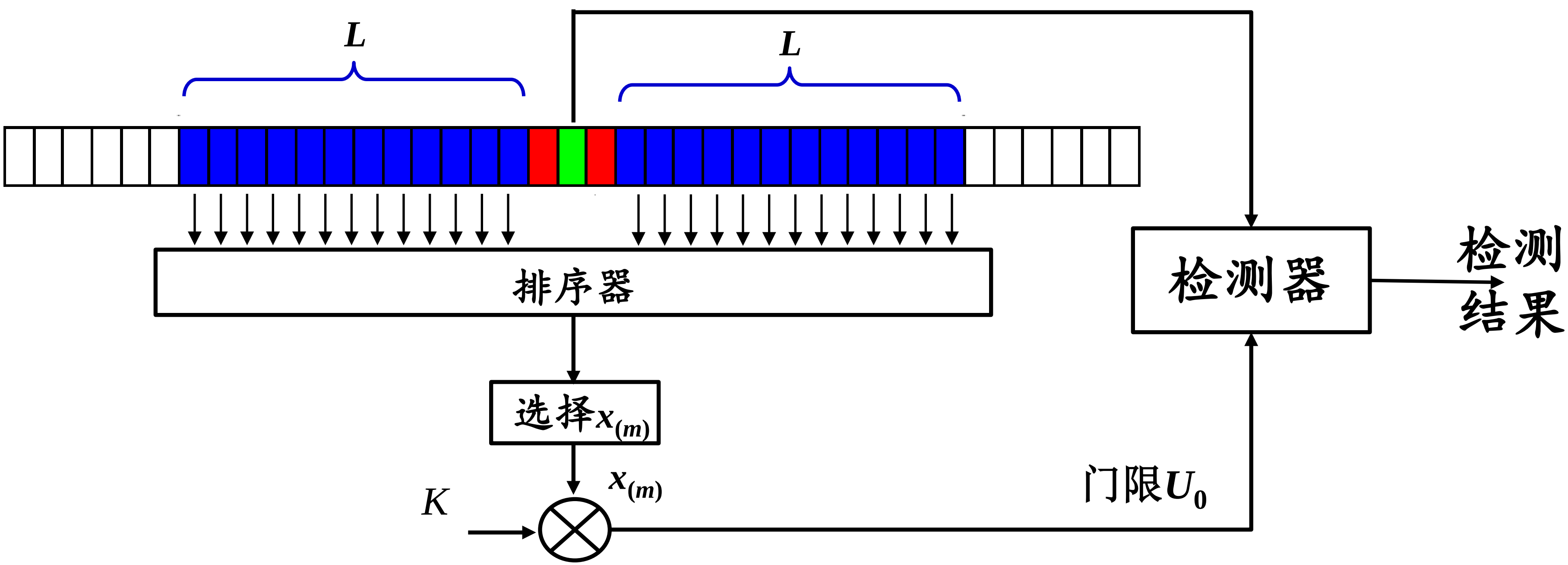
$$U_0 = K\max\{\hat{\mu}_1,\ \hat{\mu}_2\}$$

$$U_0 = K\min\{\hat{\mu}_1,\ \hat{\mu}_2\}$$

三、动目标检测

有序恒虚警检测器（OS-CFAR）

如果参考单元中出现其它信号（**干扰信号**），将引起恒虚警检测器性能的下降。为提高恒虚警抗其它干扰目标的能力——**有序恒虚警检测器**

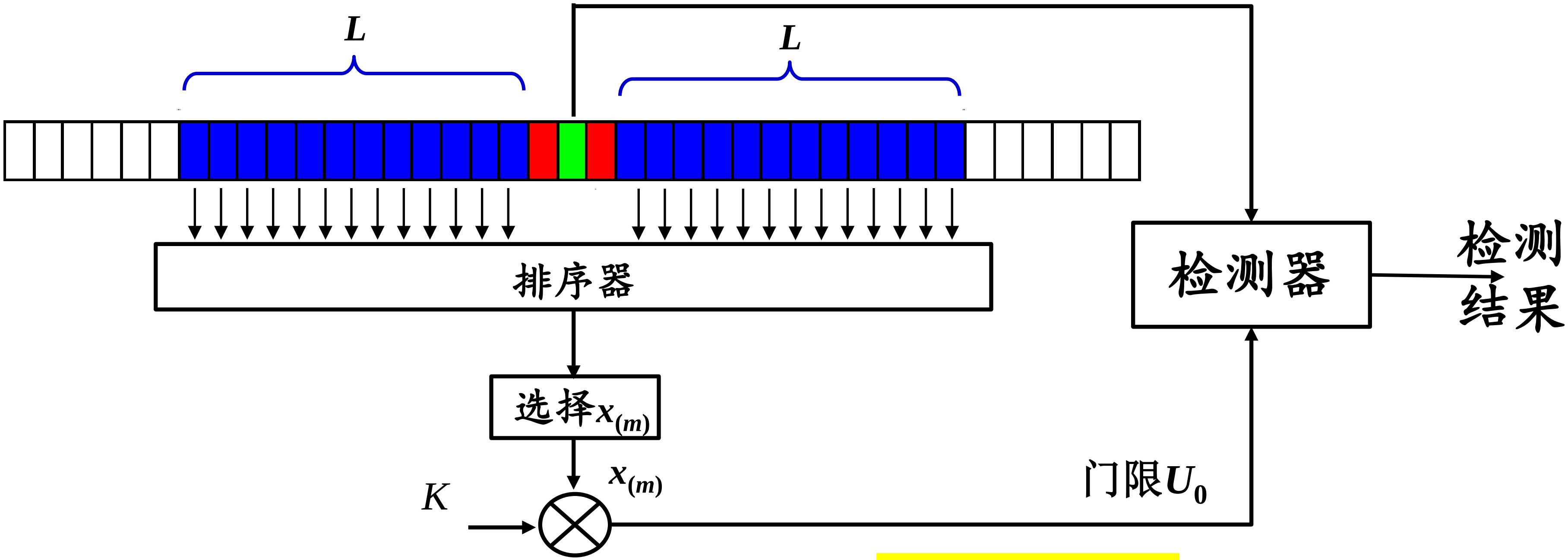


三、动目标检测

有序恒虚警检测器（OS-CFAR）

排序器对参考单元内的$2L$个x值进行排序，$x_{(1)} \le x_{(2)} \le x_{(3)} \le \cdots \le x_{(2L)}$

再选择第m个样本作为$2L$个电平的一种估计



$$U_0 = Kx_{(m)}$$

$$m = \frac{3}{4} \times 2L = 1.5L$$

当有将强的1个或多个干扰目标进入2L个参考单元时，**只会引起OS-CFAR检测器中排序结果变化**

三、动目标检测

- 剔除和平均恒虚警检测器

$$x_{(1)} \le x_{(2)} \le x_{(3)} \le x_{(4)} \le x_{(5)} \cdots\cdots\cdots\cdots \underbrace{\le x_{(2L-2)} \le x_{(2L-1)} \le x_{(2L)}}_{r}$$

剔除排序器内前r最大值，再对剩余的求平均

$$\mu = \frac{1}{2L-r}\sum_{i=1}^{2L-r} x_{(i)}$$

- 整理和平均恒虚警检测器

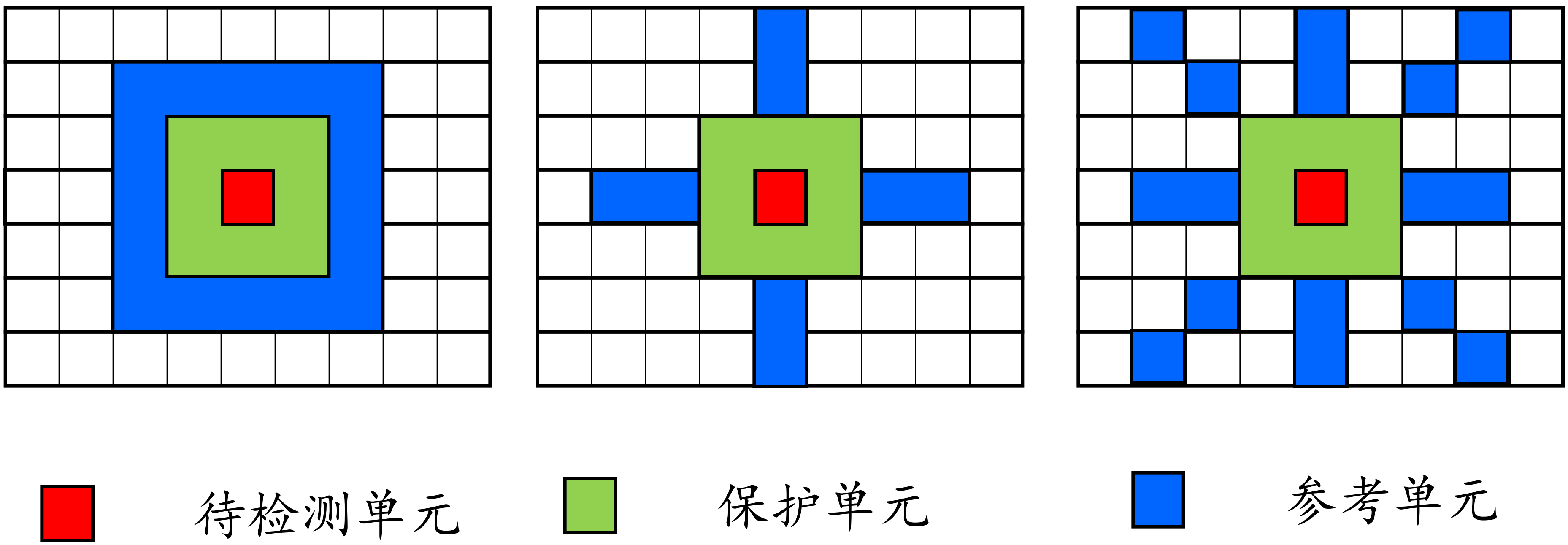
$$\underbrace{x_{(1)} \le x_{(2)} \le x_{(3)} \le x_{(4)} \le x_{(5)}}_{r_2} \cdots\cdots\cdots\cdots \underbrace{\le x_{(2L-2)} \le x_{(2L-1)} \le x_{(2L)}}_{r_1}$$

剔除排序器内前r_1最大值和后r_2个最小值，再对剩余的求平均

$$\mu = \frac{1}{2L-(r_1+r_2)}\sum_{i=r_1+1}^{2L-r_2} x_{(i)}$$

三、动目标检测

两维恒虚警检测器



杂波抑制与动目标检测

- 杂波的定义
- 杂波抑制技术
- 动目标检测
- **本章小结**

本章要点

◈基本要求

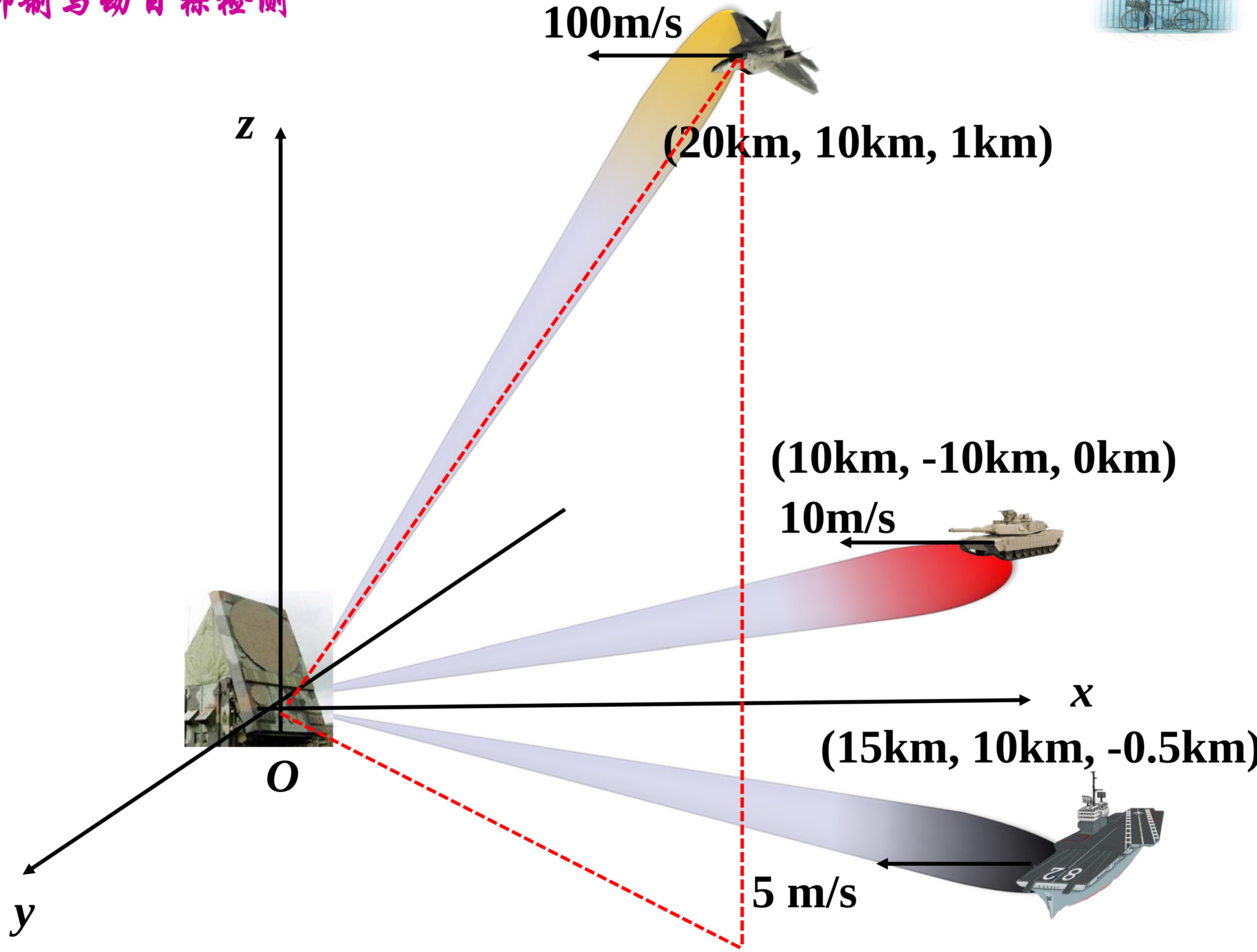
了解杂波对消器、特征矢量法以及恒虚警检测原理;

◈ 重点、难点

掌握MTI、MTD、CFAR仿真流程，能够熟练运用MATLAB工具进行仿真。

◈ 课堂作业

1，-2，1 滤波器仿真、一维CFAR 仿真。


100m/s
z
(20km, 10km, 1km)
(10km, -10km, 0km)
10m/s
x
(15km, 10km, -0.5km)
O
y
5 m/s