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Short Course 6: Flow Measurements

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Internet-site for short course:
http://www.ifbt.ntnu.no/~hanst/flowmeas02/index.html

Lecture 3: Color flow imaging

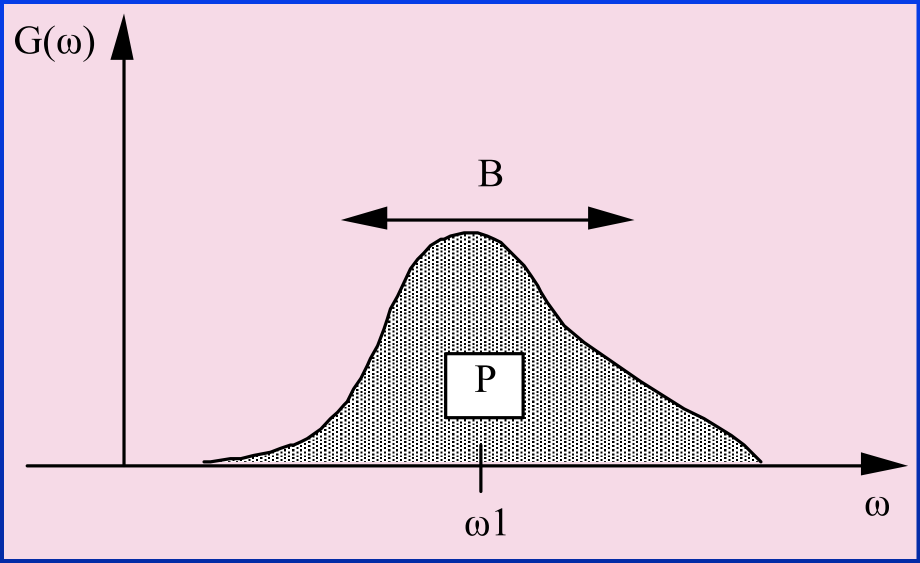
Color flow imaging

- Estimator for velocity and velocity spread
  power, mean frequeny, bandwidth
- Color mapping and visualization
- Clutter filtering
- Scanning strategies

2D Color flow imaging

1. Limited information content in the signal, i.e. short observation time, low signal-to-noise ratio, and low Nyquist velocity limit.

2. Insufficient signal processing/display. Full spectrum analysis in each point of the sector is difficult to visualize.



Signal power:

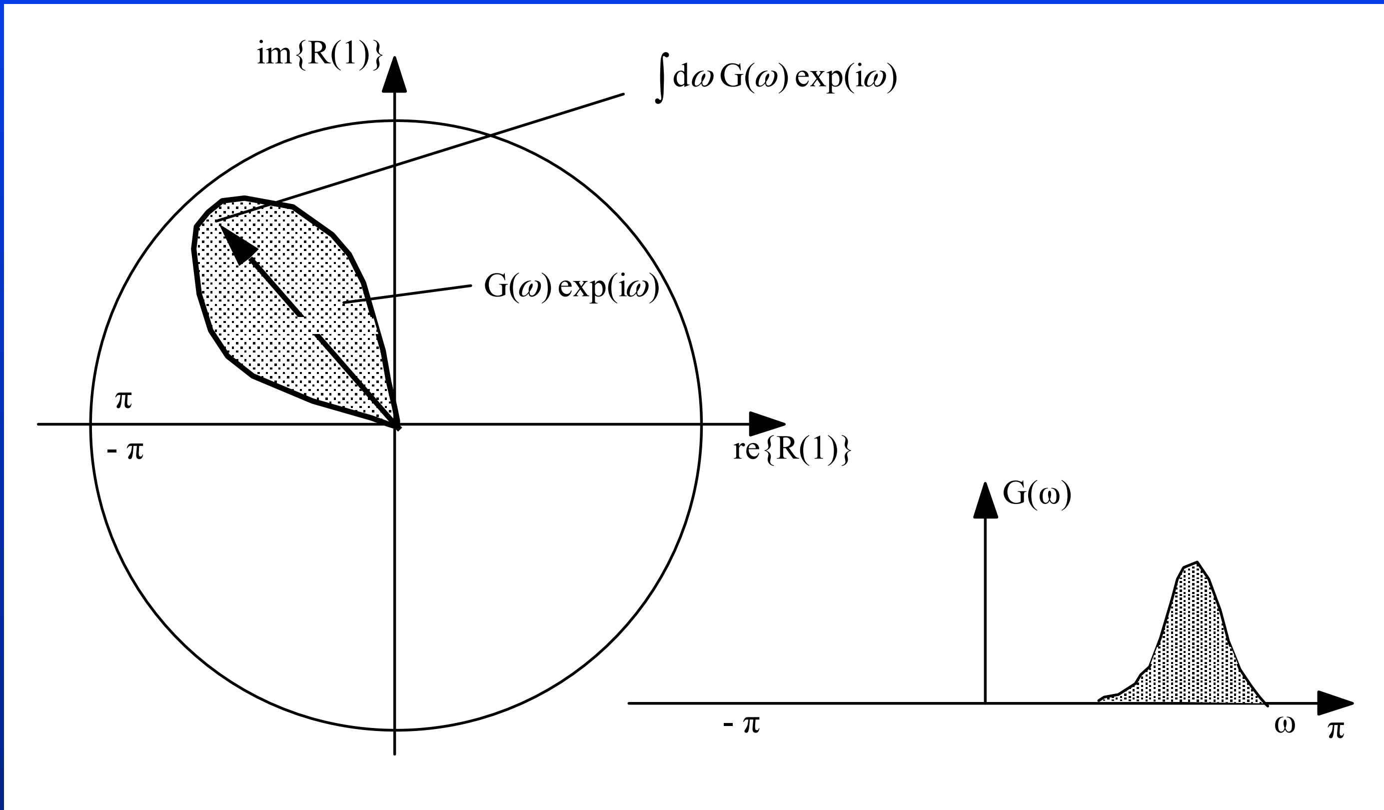
$$P = \int_{-\pi}^{\pi} d\omega G(\omega)$$

Mean frequency:

$$\omega_1 = \frac{1}{P}\int_{-\pi}^{\pi} d\omega \omega G(\omega)$$

Bandwidth:

$$B = \sqrt{\frac{1}{P}\int_{-\pi}^{\pi} d\omega (\omega - \omega_1)^2 G(\omega)}$$



$$R(1) = \int_{-\pi}^{\pi} d\omega\, G(\omega) e^{i\omega}$$

$$P = R(0) = \int_{-\pi}^{\pi} d\omega\, G(\omega)$$

$$R(1) = e^{i\omega_1} \int_{-\pi}^{\pi} d\omega G(\omega) e^{i(\omega-\omega_1)} \approx P e^{i\omega_1} \{1 - \frac{1}{2} B^2\}$$

Taylor expansion of exp-function

Autocorrelation method

$$R(1) \approx P e^{i\omega_1} \{1 - \frac{1}{2} B^2\}$$

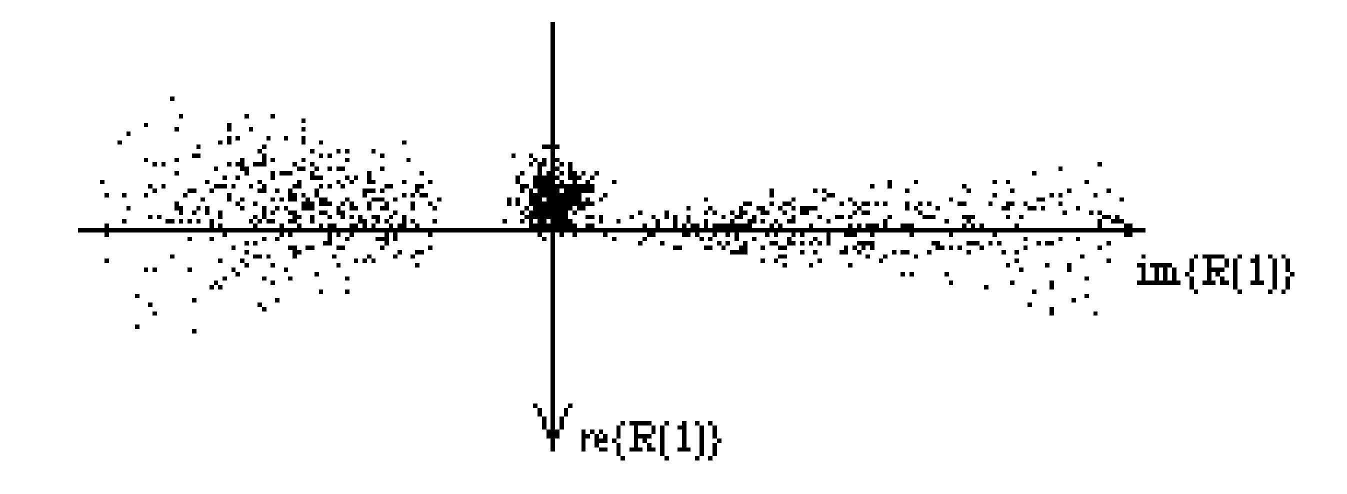
$$\hat{R}_N = \frac{1}{N} \sum_{k=1}^{N} z(k+1) z(k)^*$$

$$P = R(0)$$
$$\omega_1 \approx \arg\{R(1)\}$$
$$B \approx \sqrt{2} \cdot \sqrt{1 - \frac{R(1)}{R(0)}}$$

$$\hat{P} = \hat{R}_N(0)$$
$$\hat{\omega}_1 = \arg\{\hat{R}_N(1)\}$$
$$\hat{B} = \sqrt{2} \cdot \sqrt{1 - \frac{\hat{R}_N(1)}{\hat{R}_N(0)}}$$

Power, meanfreq., bandwidth derived from sample mean autocorrelation estimator

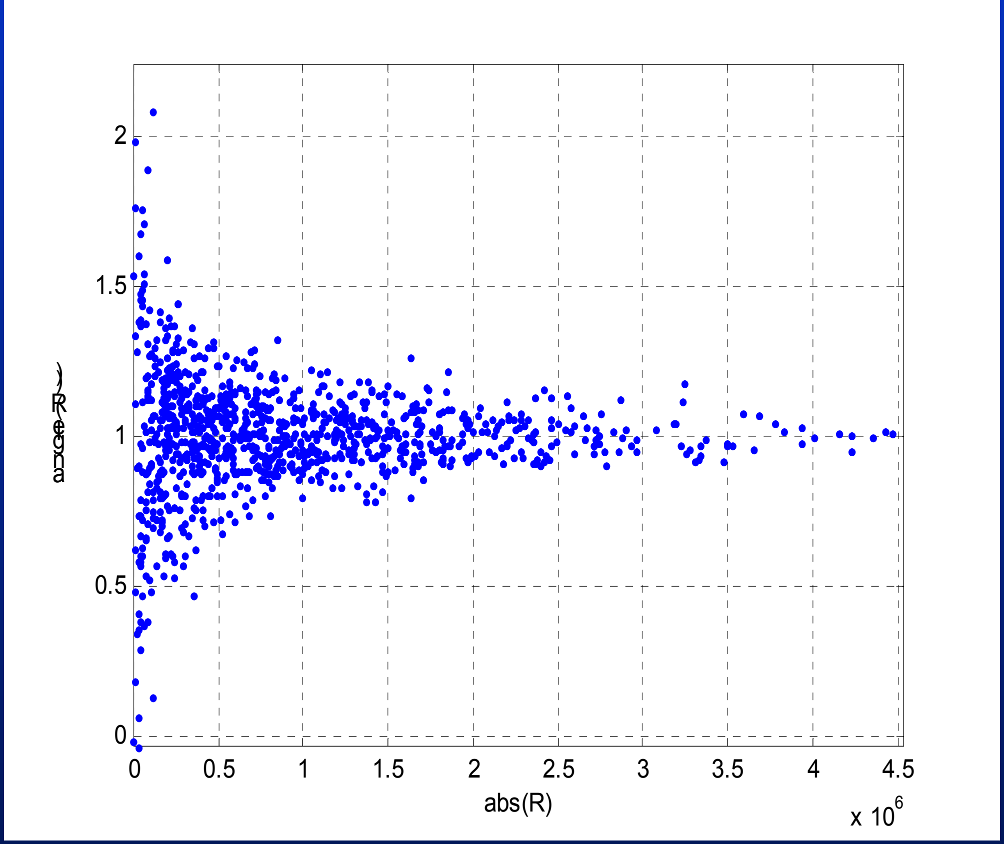
Autocorrelation method



Scatter diagram of the autocorrelation estimator with lag m=1 for three different signals. To the right, a narrow band signal with center frequency $\omega_1 = \pi/2$ *to the left, a slightly more broadband signal with* $\omega_1 = 3\pi/2$*, and in the middle, high-pass filtered white noise.*

Estimation error is minimum when correlation is maximum

Correlation angle ~Velocity



Correlation magnitude

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Matlab-demo: AcorrEst.m

Estimator properties

$$P_N = R_N(0) = \frac{1}{N}\sum_{k=1}^{N}\left|z(k)\right|^2$$

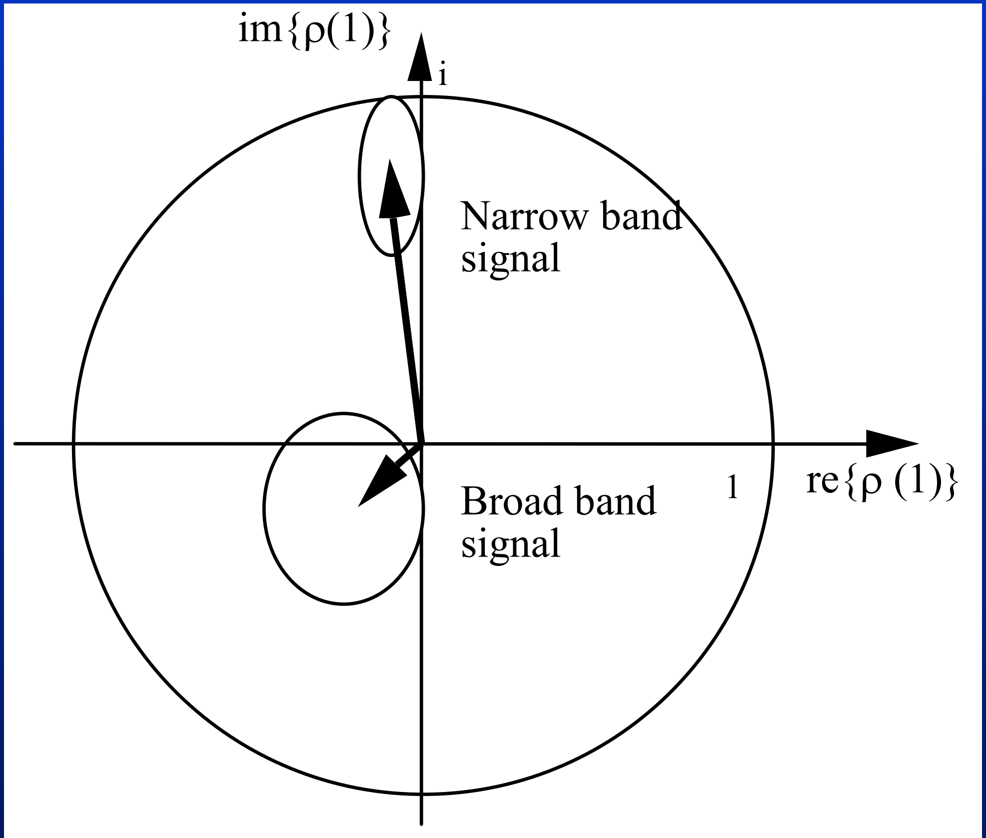
$$Var(P_N) \approx \frac{P^2}{BN}$$

$$\hat{R}_N = \frac{1}{N}\sum_{k=1}^{N} z(k+1)z(k)^*$$

$$\hat{\omega}_{1N} = angle(\hat{R}_N(1))$$

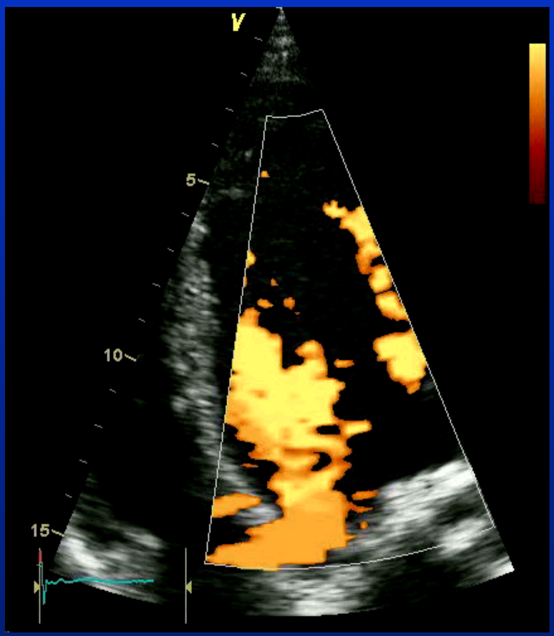
$$Var(\omega_{1N}) \approx \frac{B^2}{N}$$

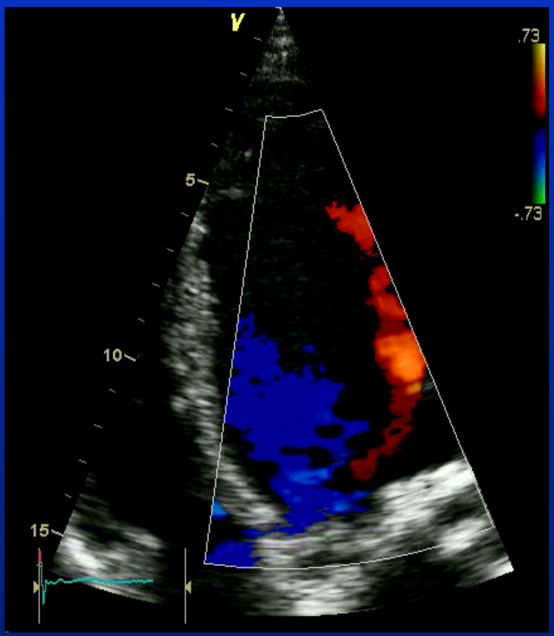
Normalized Autocorrelation function

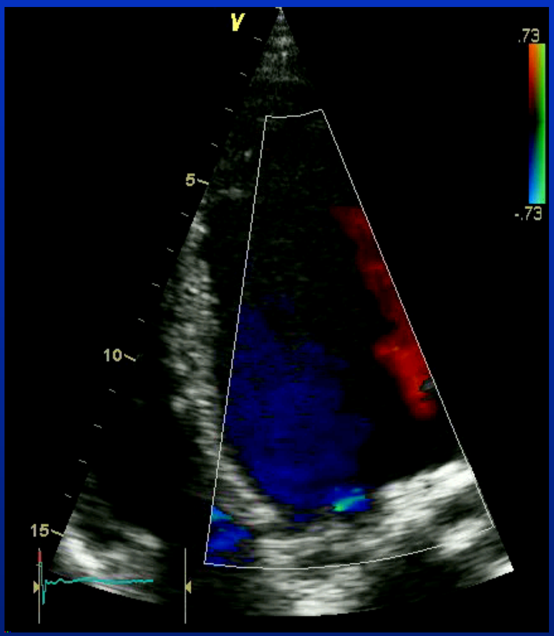


$\rho(1) = R(1) / R(0)$

Color mapping types







Power Doppler (Angio)

Brightnes ~ signal power

Color flow

Brightnes ~ signal power
Hue ~ Velocity

Color flow ”Variance map”

Hue & Brightnes ~ Velocity
Green ~ signal bandwidth

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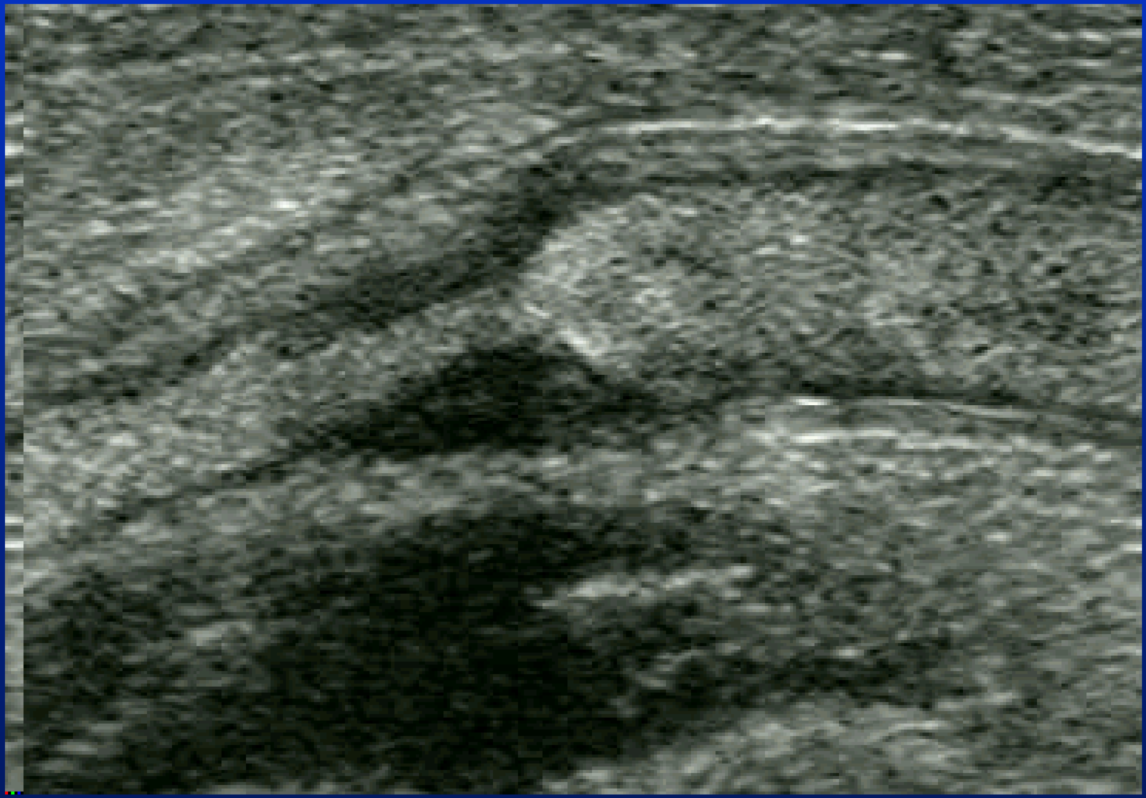
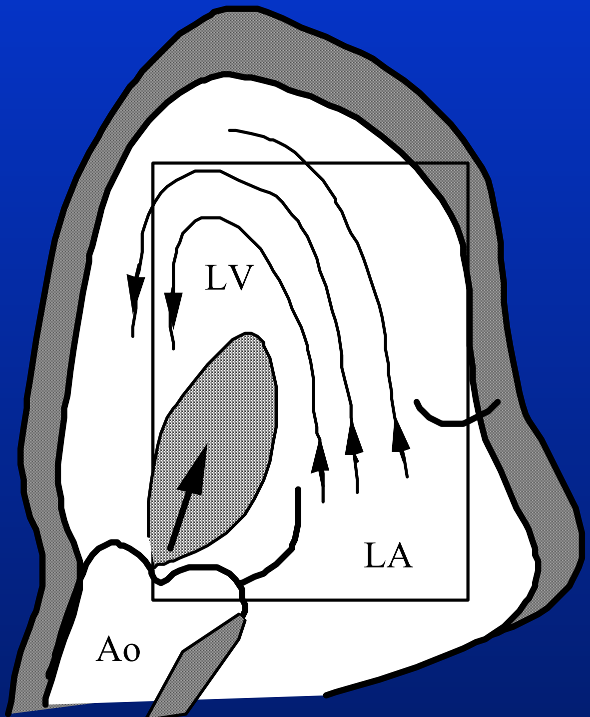
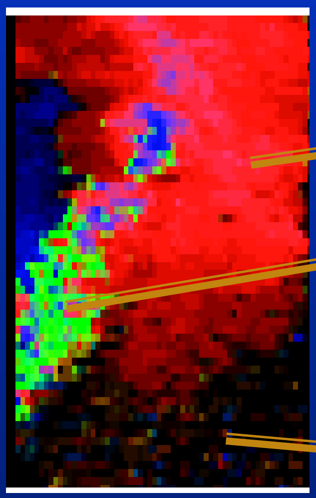
B-flow

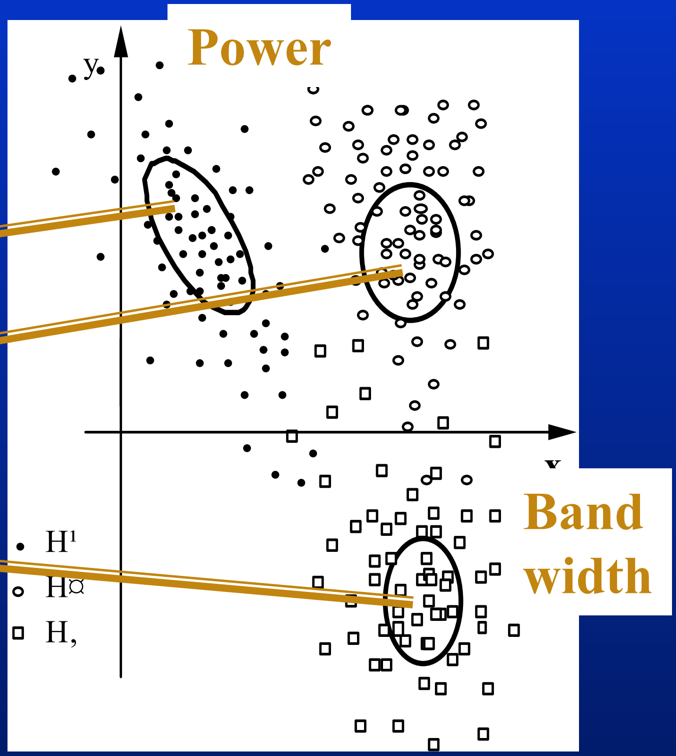


Doppler signal power added to B-mode image

Color scale for velocity and - spread







Aortic insufficiency

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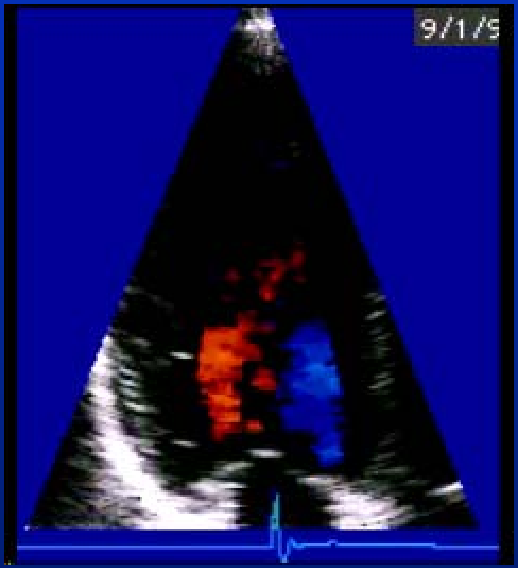
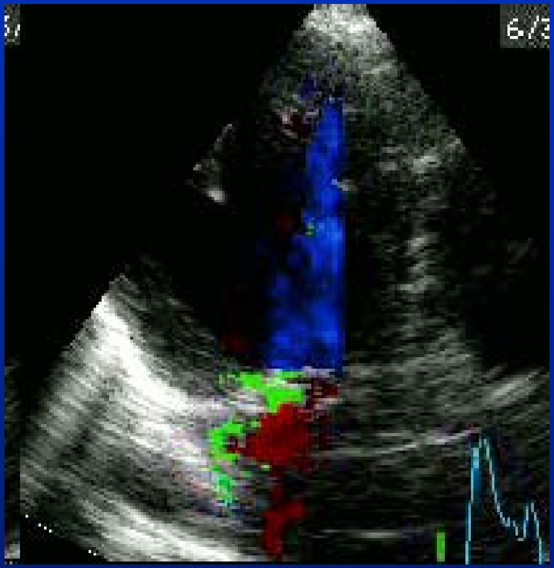
Color flow imaging
Mitral valve blood flow



Normal mitral valve



Stenotic mitral valve

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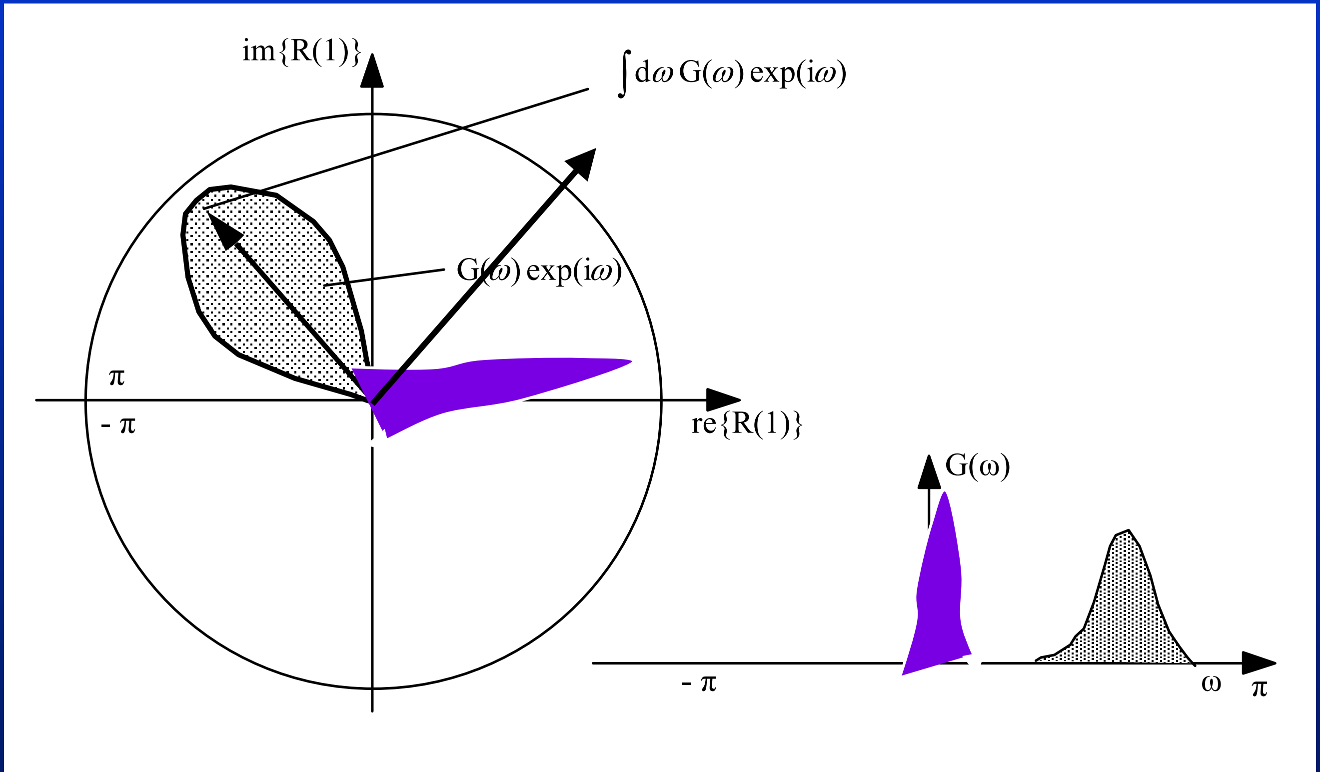
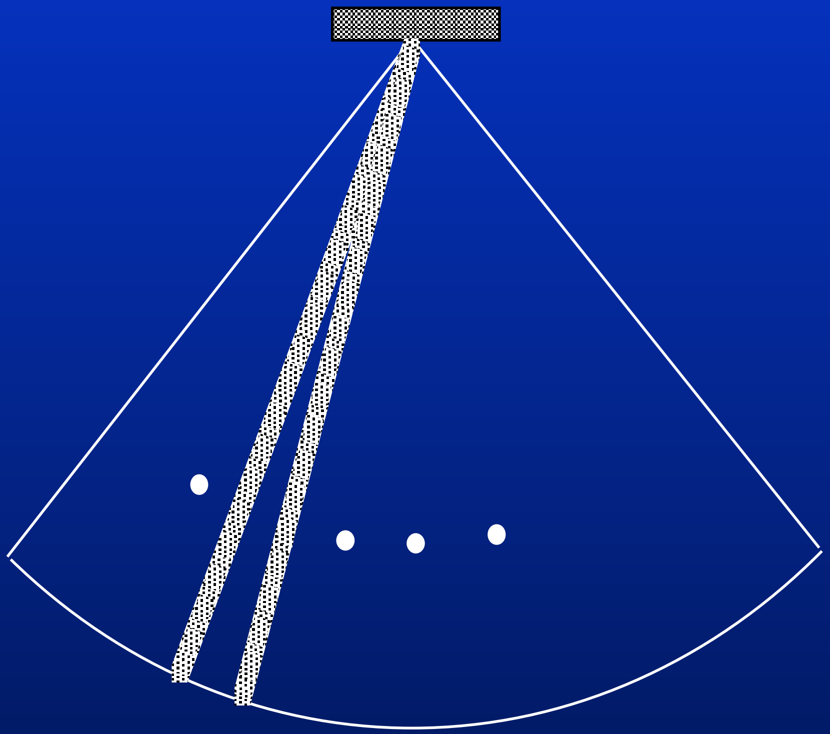
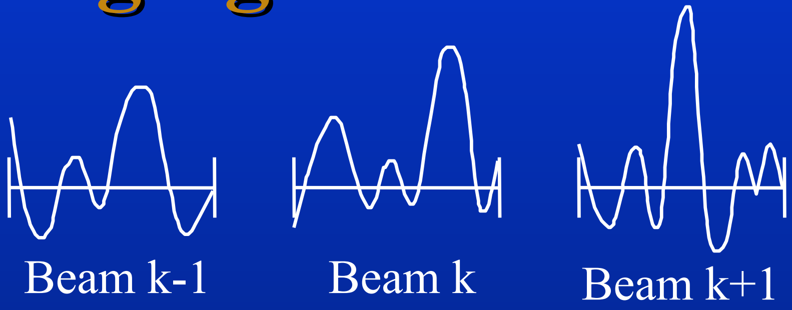
Autocorrelation method
Sensitive to clutter noise

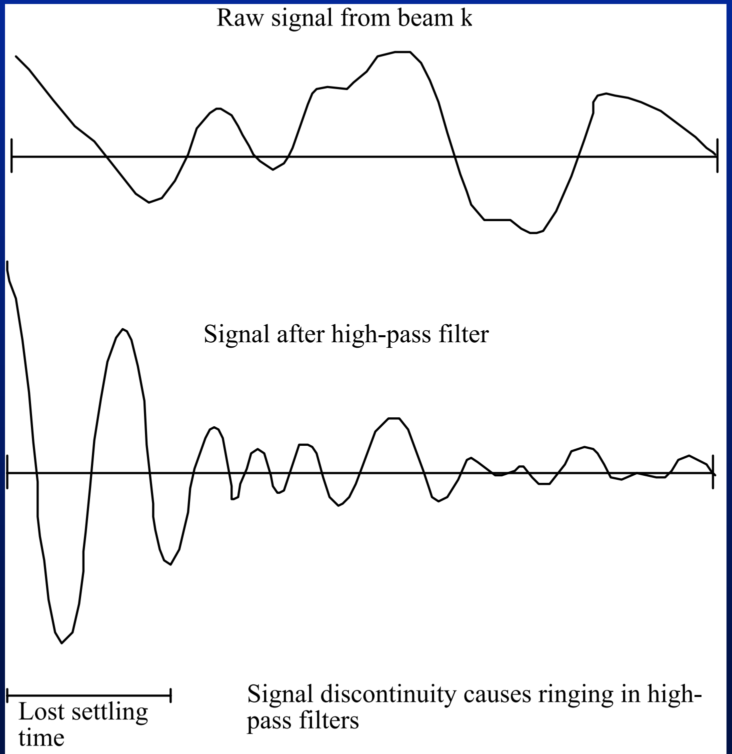


Phase angle of R(1) substantially reduced due to low frequency clutter signal
Clutter filter stopband much more critical than for spectral Doppler

How to perform clutter filter in color flow imaging?







Approaches to clutter filtering in color flow imaging

- IIR-filter with initialization techniques
- Short FIR filters
- Regression filters

General Linear Filters

- **A general linear filter is described by a matrix multiplication of the *N* - dimensional signal vector** x
  In color flow imaging N=packet size (number of pulses per beam)

$$\mathbf{y} = \mathbf{A}\mathbf{x}$$

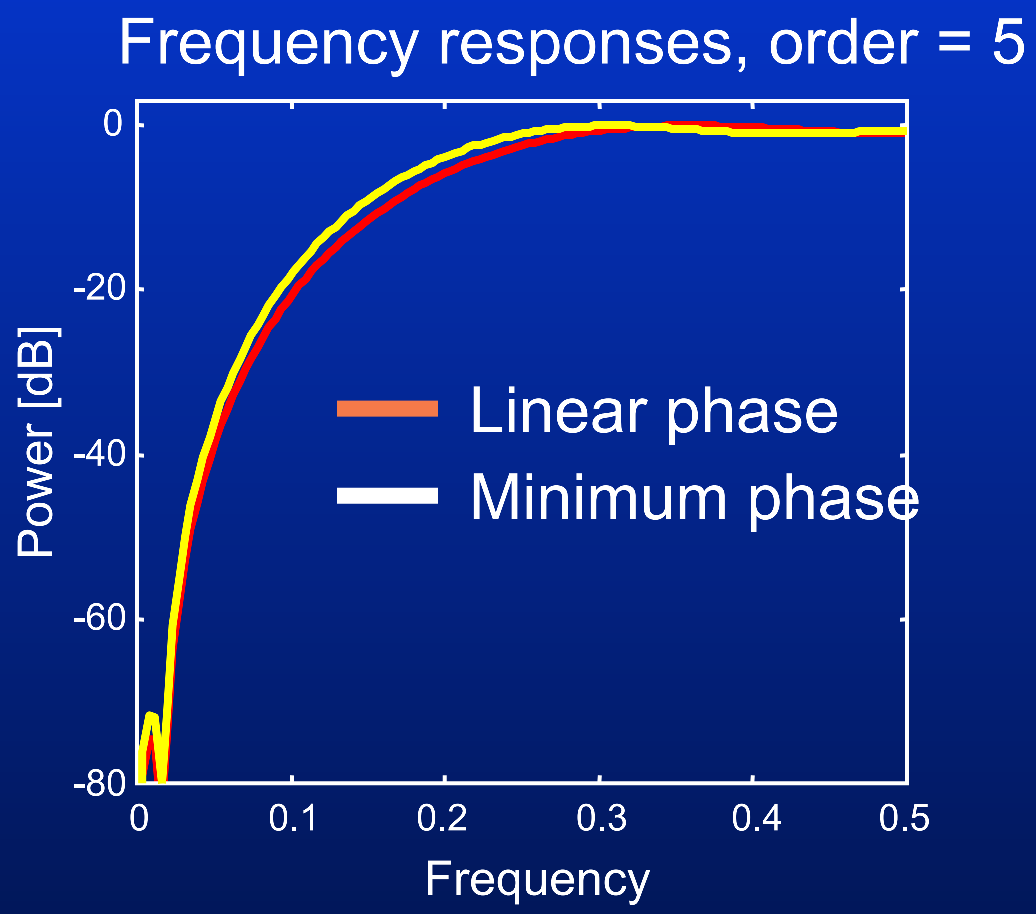
- **The matrix rows are a set of (possibly) different FIR-filters for each time instant**

- **Definition of frequency response function:**

$$H_o(\omega) = \frac{1}{N}\left\|\mathbf{A}\mathbf{e}_\omega\right\|^2 \quad \text{where} \quad e_\omega = \begin{bmatrix} 1 & e^{i\omega} \ldots e^{i(N-1)\omega} \end{bmatrix}^T$$

FIR Filters

$$H(z) = \sum_{k=0}^{M} b_k z^{-k}$$



- **Discard the first *M* output samples, where *M* is equal to the filter order**
- **Improved amplitude response when nonlinear phase is allowed**

IIR Filters

$$H(z) = \frac{\sum_{k=0}^{M} b_k z^{-k}}{\sum_{k=0}^{N} a_k z^{-k}}$$

- **Matrix formulation of IIR filter:**

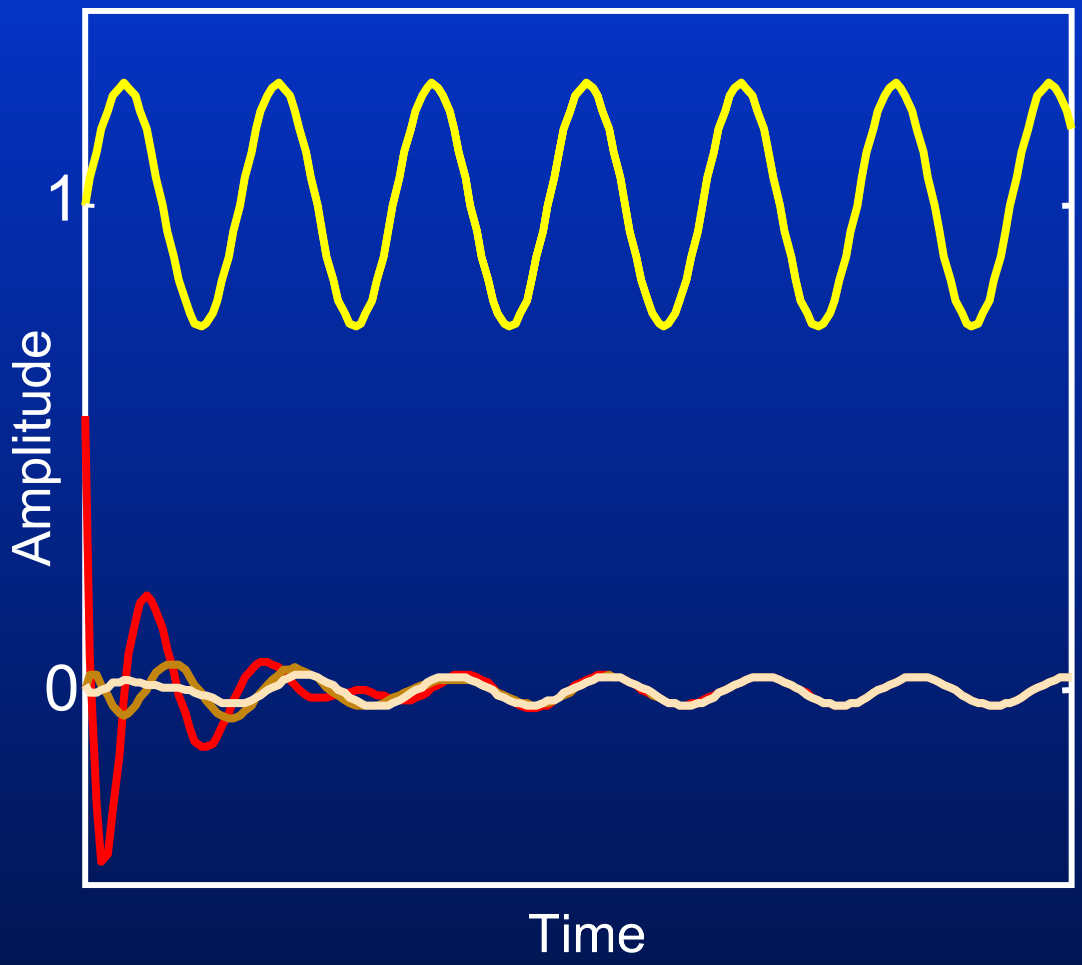
$$\mathbf{y} = \mathbf{C}\,\mathbf{v}(0) + \mathbf{D}\,\mathbf{x}$$

$\mathbf{v}(0)$ is initial filter state

- **Initialization techniques:**

  - zero: $\mathbf{v}(0) = \mathbf{0}$
  - step: $\mathbf{v}(0) = x(0)\,\mathbf{v}_{step}(\infty)$
  - projection: $\mathbf{v}(0) = -\,(\mathbf{C}^T\mathbf{C})^{-1}\,\mathbf{C}^T\,\mathbf{B}\,\mathbf{x}$

Highpass IIR Output Transient



$\mathbf{x} = 1 + 0.25 \sin \omega t$

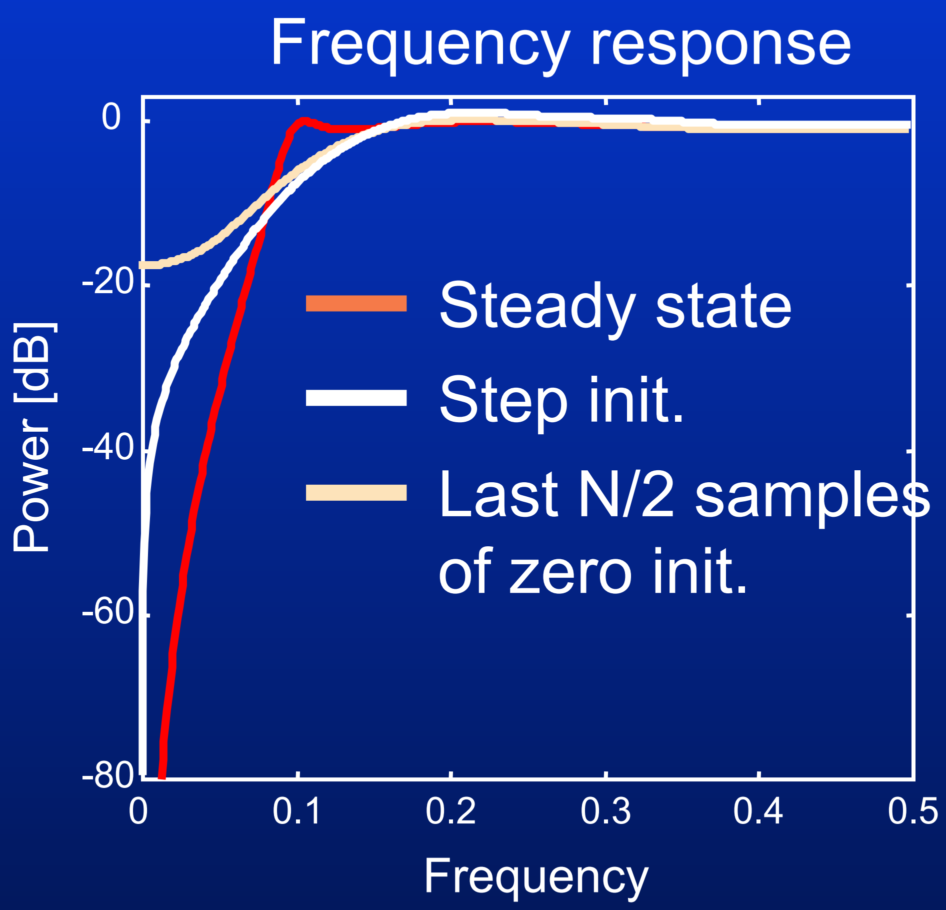
$\mathbf{y} = \mathbf{C}\,\mathbf{v}(0) + \mathbf{D}\,\mathbf{x}$

zero init.

step init.

projection init.

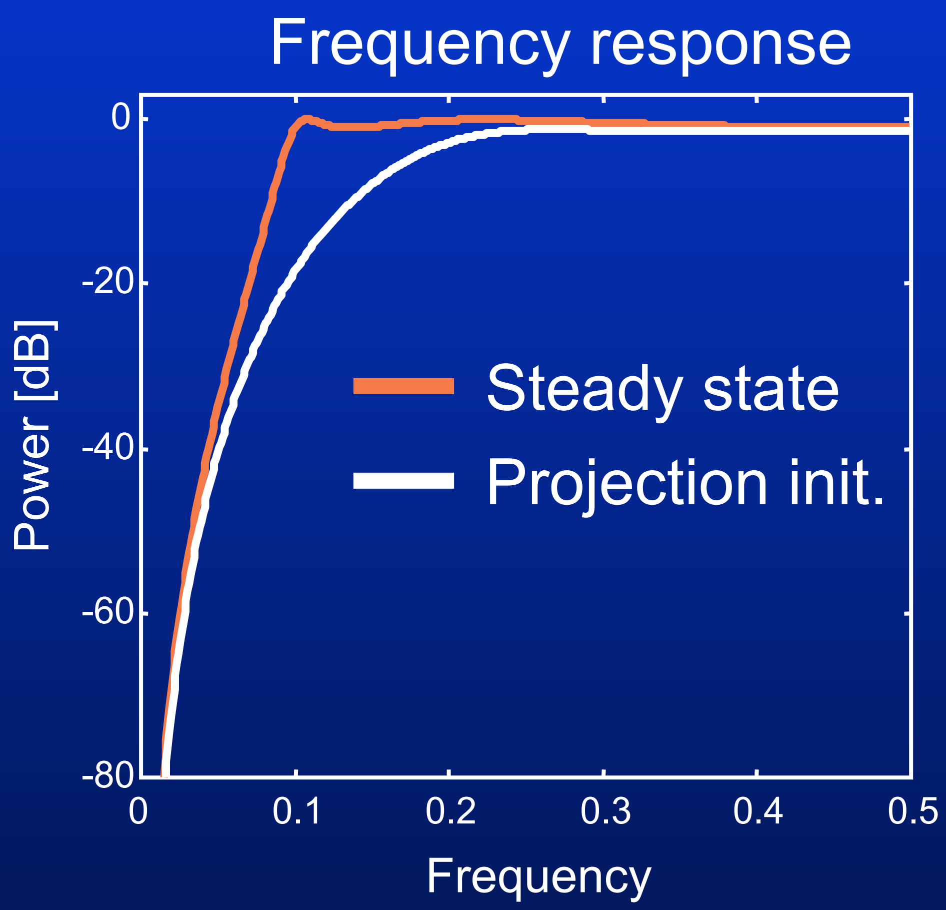
IIR Zero and Step Initialization



Chebyshev order 4, N=10

- **Very poor stop-band attenuation**
- **A more sophisticated initialization technique is needed**

IIR Projection Initialization



Chebyshev order 4, N=10

- The signal component in the transient subspace is removed

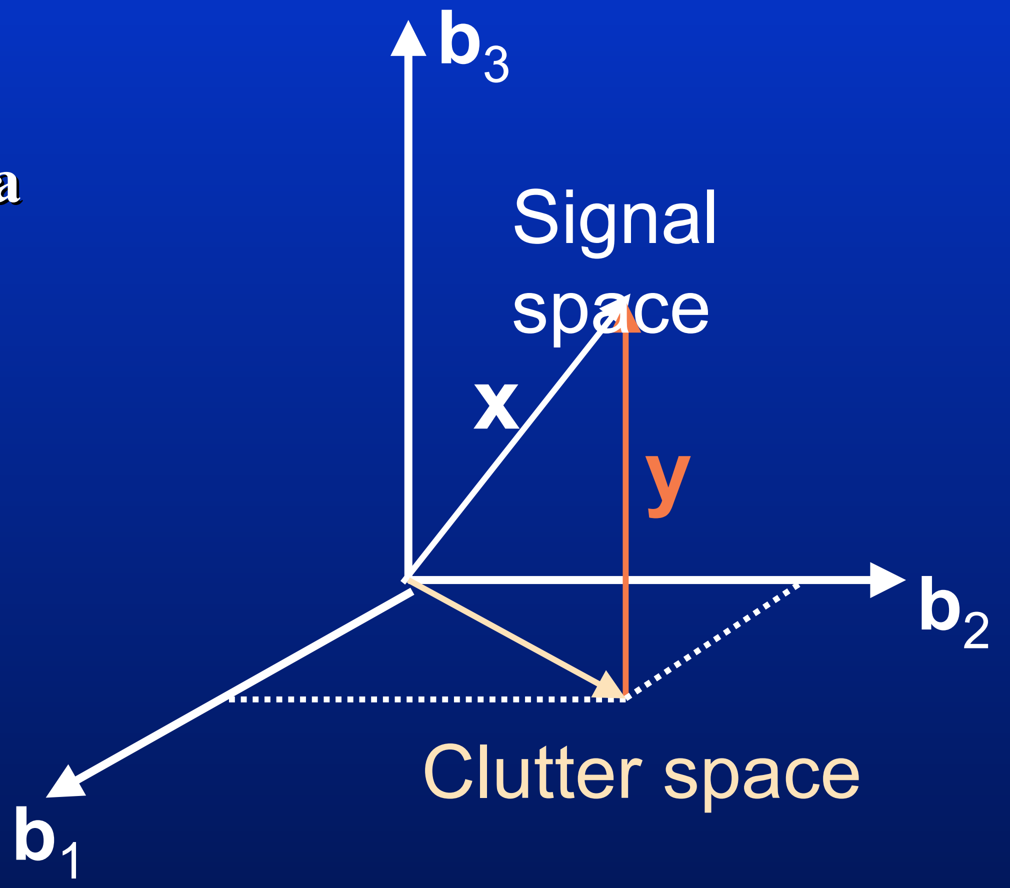
$$A = (I - P_{\text{transient}}) B$$

- Sufficient stop-band width at the cost of increased transition width

Regression Filters

- **Subtraction of the signal component contained in a *K*-dimensional clutter space:**

$$\mathbf{y} = \left(\mathbf{I} - \sum_{i=1}^{K} \mathbf{b}_i \mathbf{b}_i^H \right) \mathbf{x}$$



Fourier Regression Filters

DFT

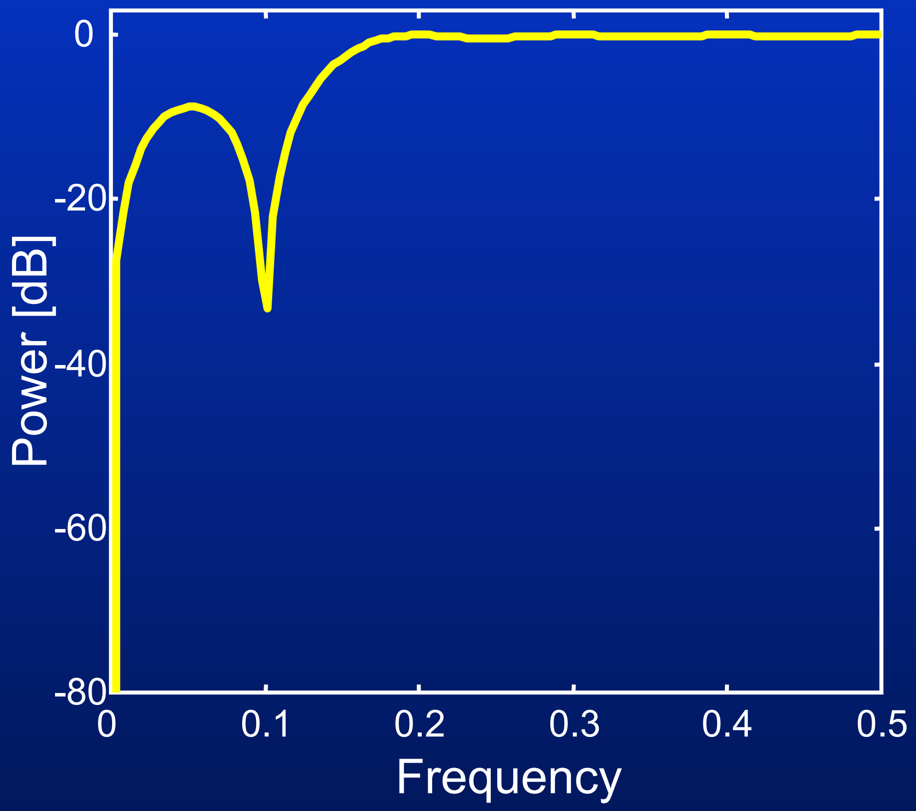
↓

Set low frequency coefficients to zero

↓

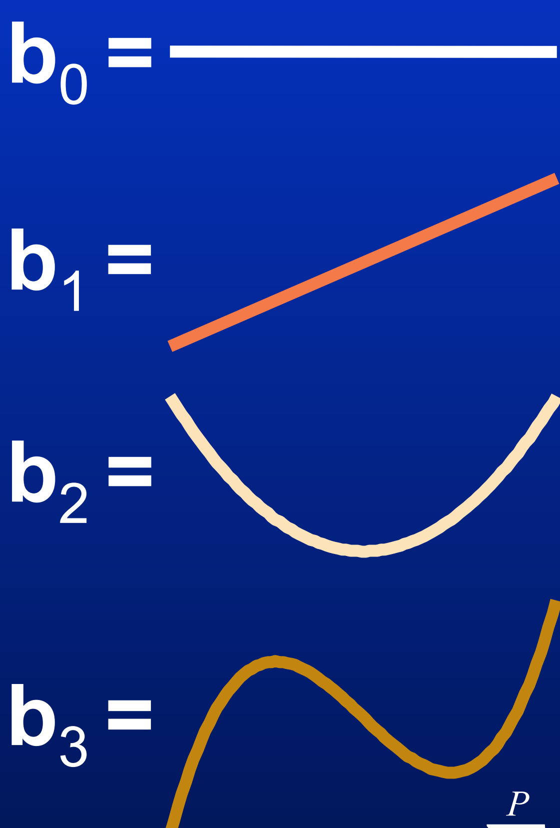
Inverse DFT

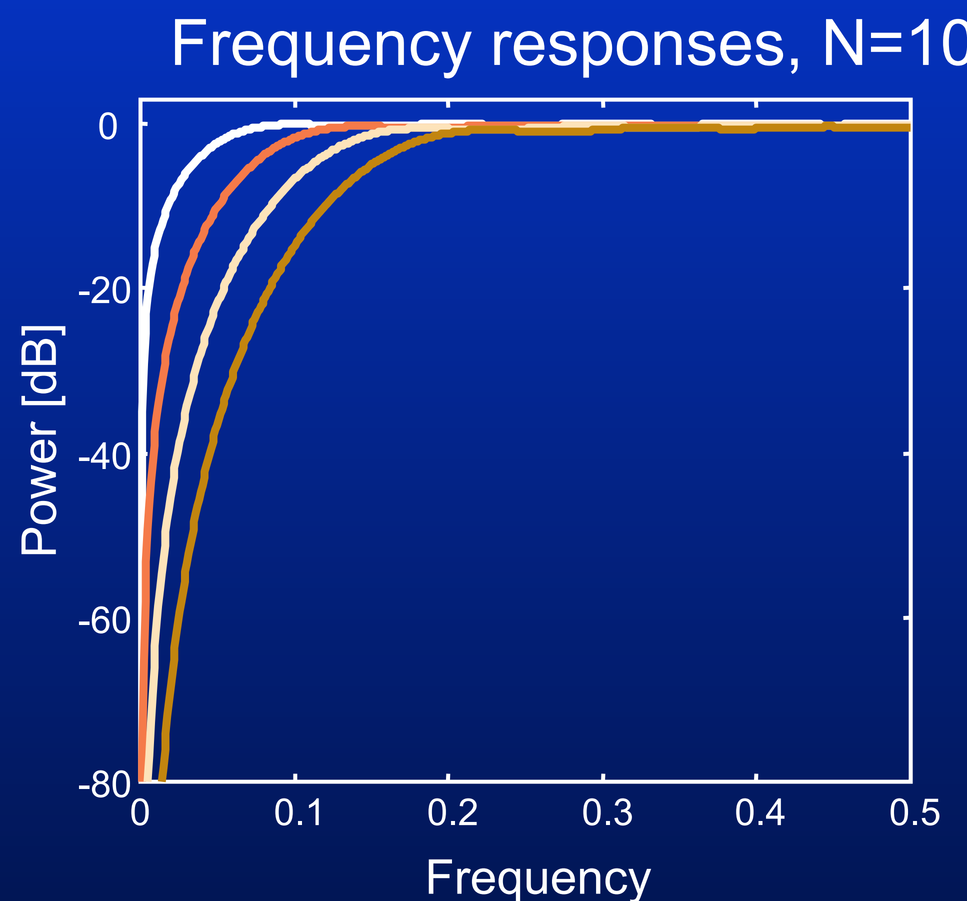
Frequency response



N=10, clutter dim.=3

Polynomial Regression Filters

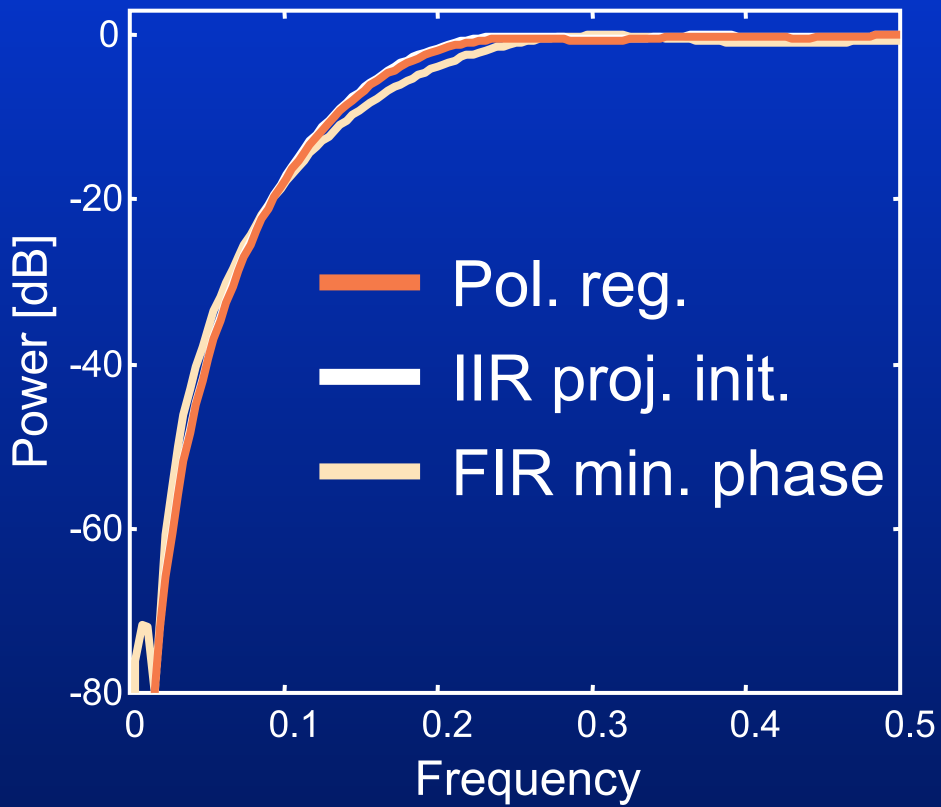




$$A = I_N - \sum_{k=0}^{P} b_k \, b_k^{\,T}$$

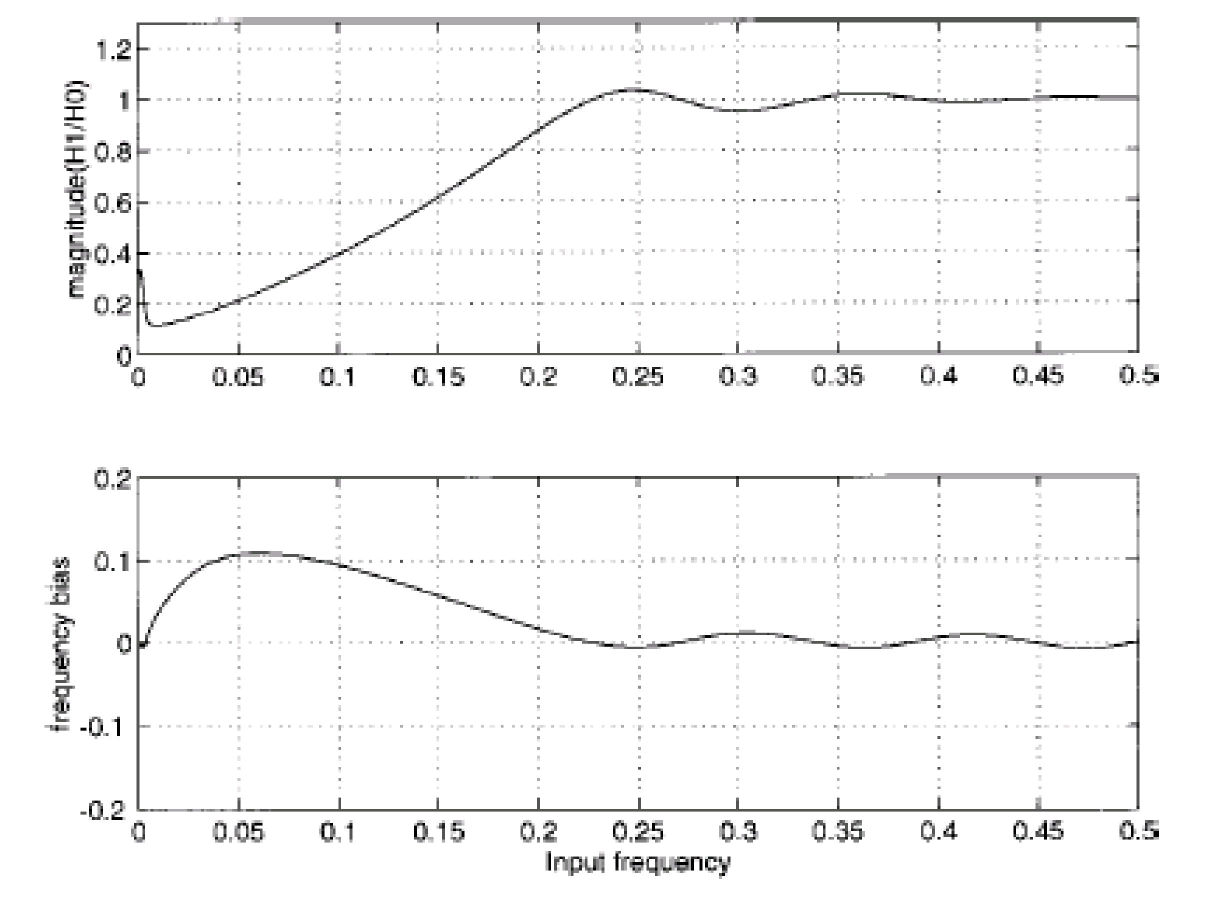
$$b_0, b_1, .., b_{N-1} \quad \textit{Legendre polynomial base}$$

Frequency Responses



Other quality measures for clutter filters than the frequency response?

Regression filter bias



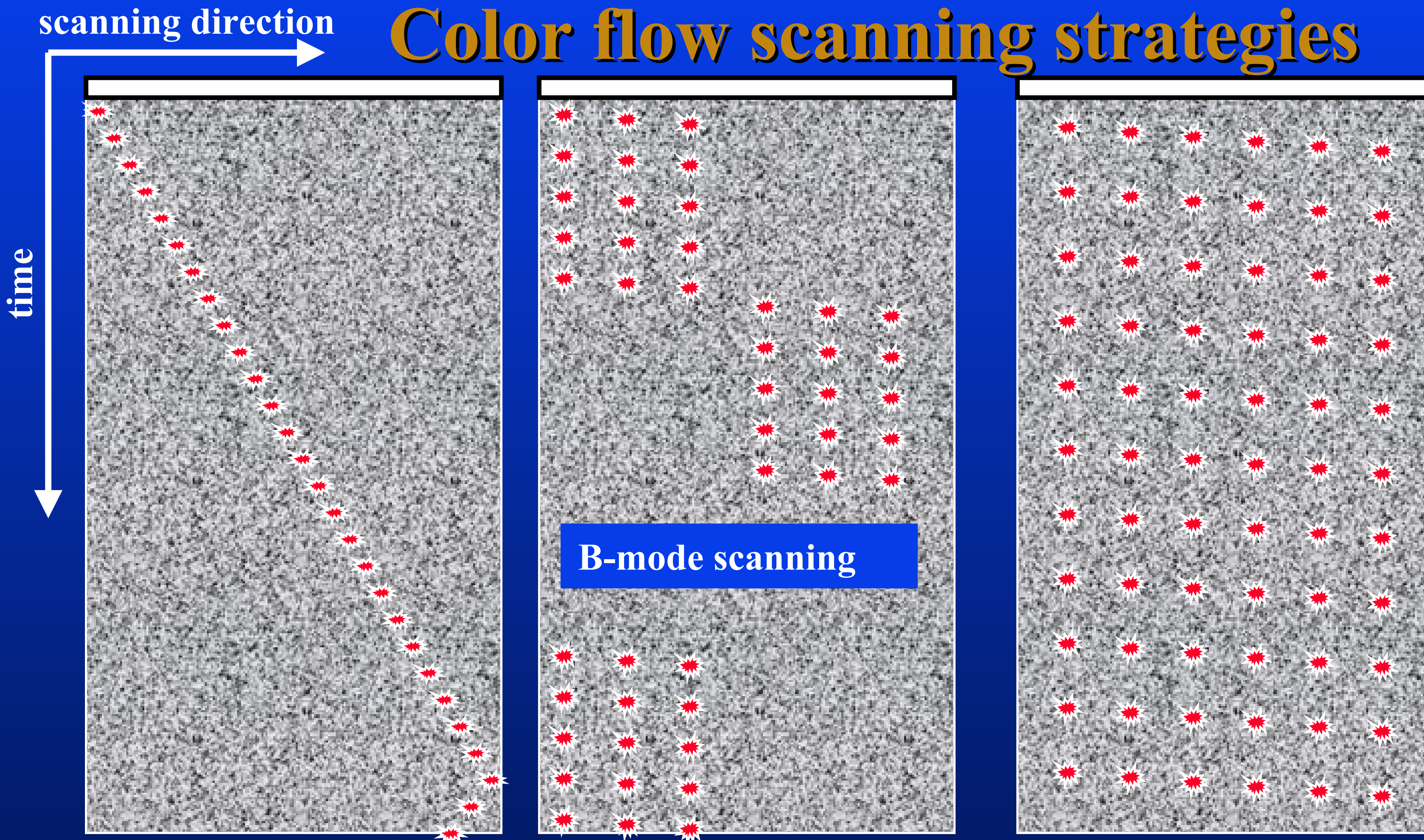
Magnitude and phase *frequency response* Polynomial regression filter *packet size* = 10, *polynom order* 3.

Severe bias in bandwidth and mean freq. estimator below cutoff frequency.

How to image low velocity flow

- Long observation time needed
- Obtained by incresed packet size or lower PRF
- Beam interleaving permits lower prf without loss in framerate

Color flow scanning strategies



Mechanical scanning	Electronic scanning Packet acquisition	Electronic scanning continuous acquisition
+ No settling time clutter filter - low frame rate	- Settling time clutter filter +flexible PRF without loss in frame rate	+ no settling time clutter filter + High frame rate - low PRF (=frame rate)

Color flow imaging with a mechanical probe

v = W*FR

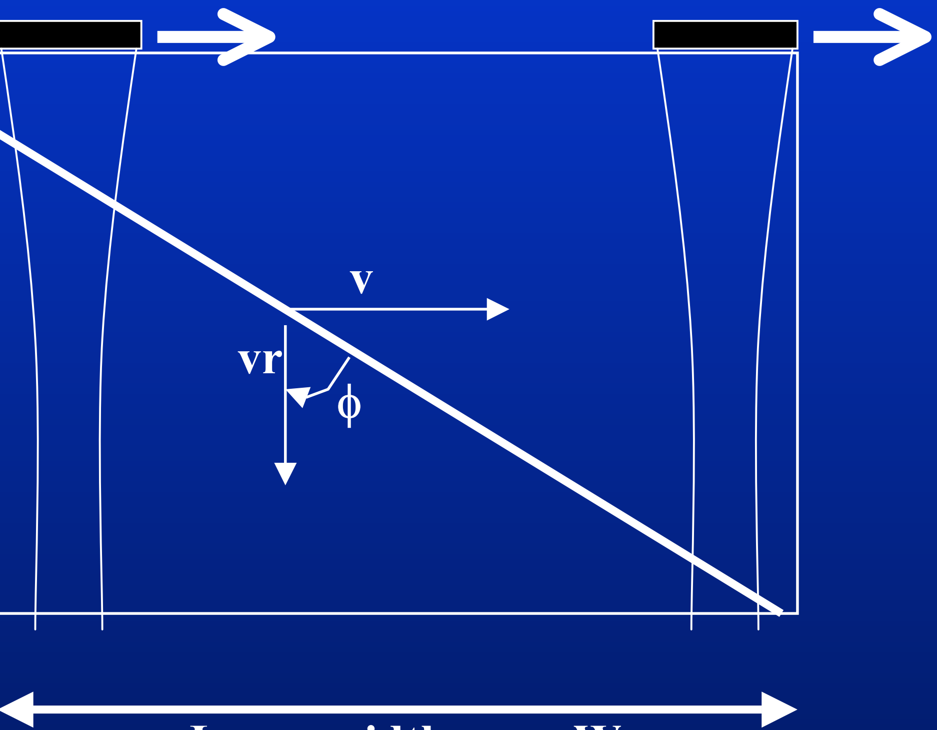


Image width	W
Frame rate	FR
Sweep velocity	v= W*FR

Virtual axial velocity: vr= v*cotan(ϕ)

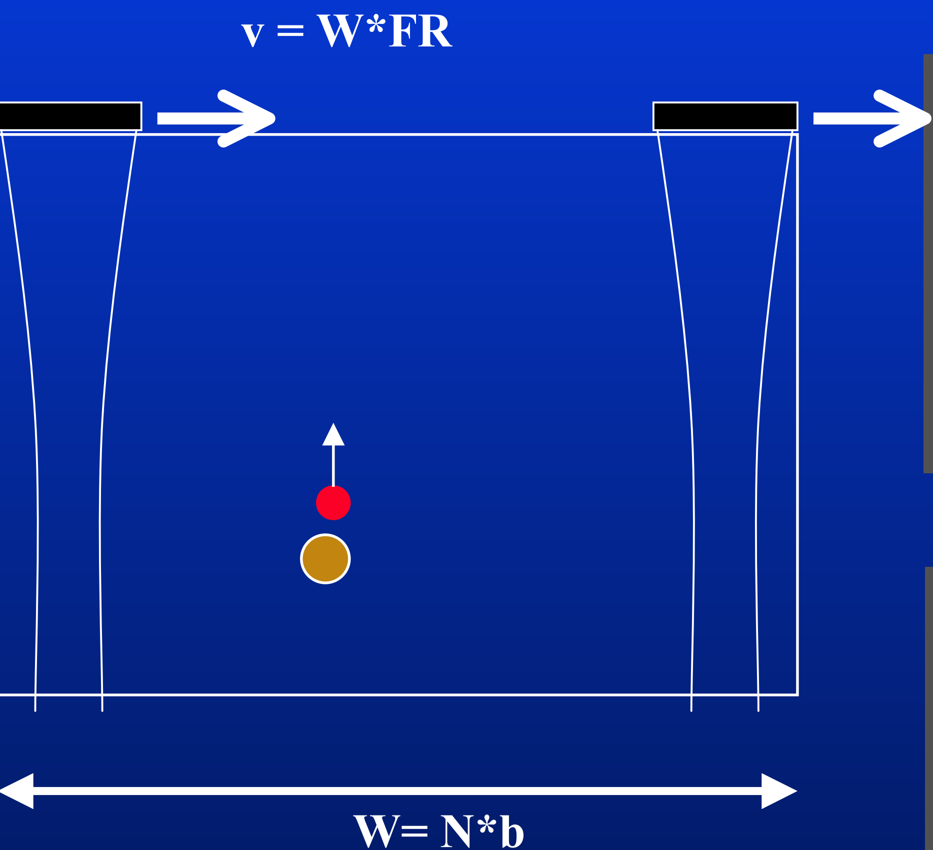
Example:

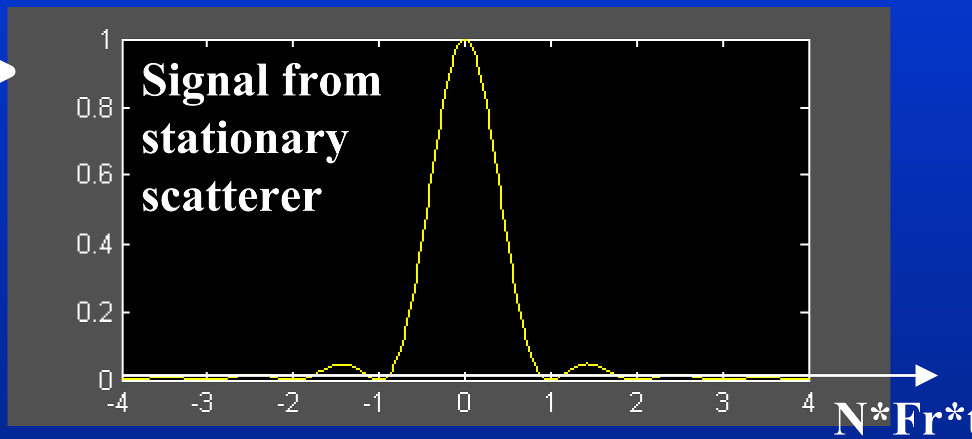
Image width	W = 5 cm
Frame rate	FR =20 fr/sec
Angle with beam	ϕ = 45 deg.
Sweep velocity	v= 1 m/s

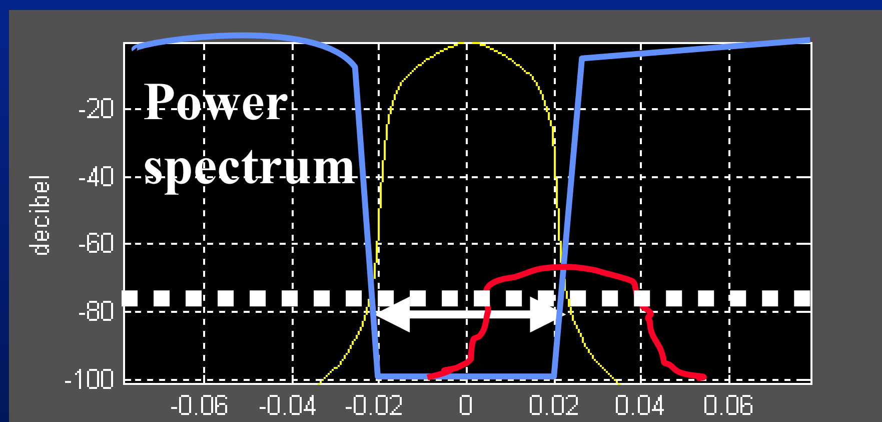
Virtual axial velocity: **vr= 1 m/s**

vr > max normal blood flow velocities!

Color flow imaging with a mechanical probe







Beamwidth (Rayleigh criterion): b
Effective number of beams: N =W/b
Frame Rate: FR

Clutter signal bandwidth: 2*N*FR

Frequency components < fc removed

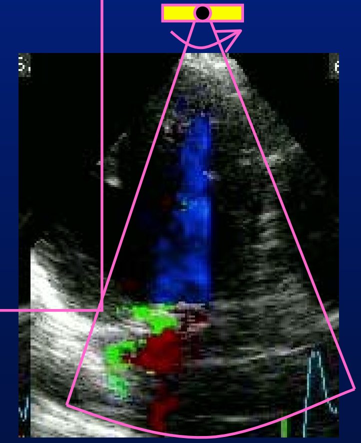
Clutter filter cutoff frequency: fc > N*FR

Minimum detectable Doppler shift

Clutter filter cutoff frequency: fc > N*FR
(transit time effect mechanical scan)

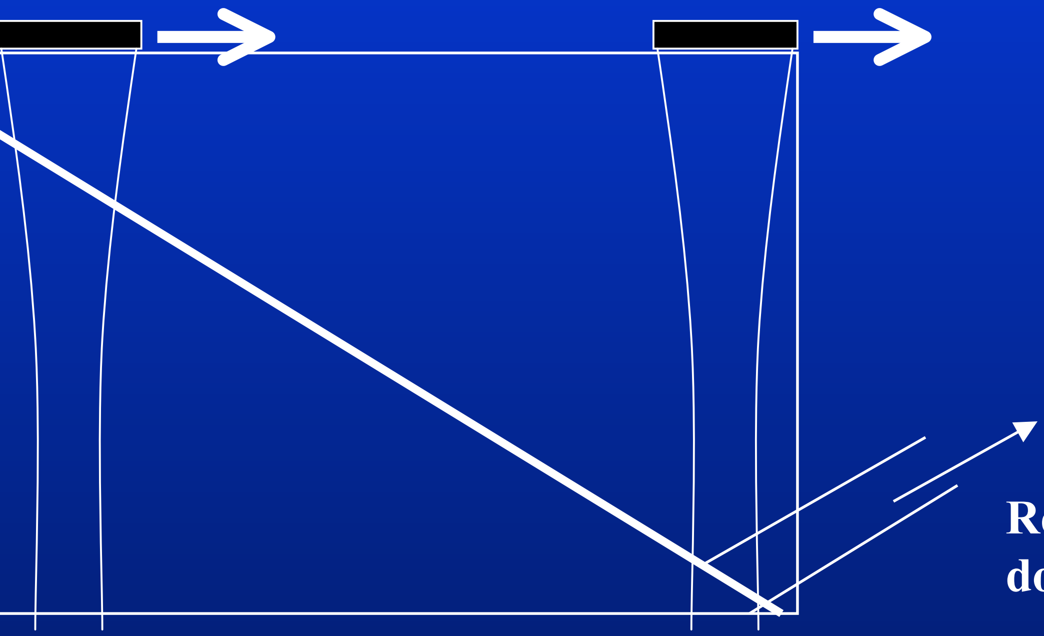
Frame rate	FR =1 Hz	FR = 10 Hz	FR=20 Hz
Width (# beams)			
N=30	30 Hz	300 Hz	600 Hz
N=70	70 Hz	700 Hz	1400 Hz

Cardiac flow imaging:
fo= 2 MHz, 15 mm aperture, beamwidth 3 mm
30 beams covers the left ventricle
fc = 600 Hz ~ 0.21 m/sec. lower velocity limit



Color flow imaging with a mechanical probe

v = W*FR



Reflected wave
does not hit the transducer

Max Dopplershift 600 Hz
~ 0.21 m/sec

Atlanta, GA april 1986

Vingmed, introduced *CFM*
The first commercial colorflow imaging scanner with mechanical probe

Horten, Norway september 2001

GE-Vingmed closed down production line for *CFM*

after 15 years of continuous production

Minimum detectable Doppler shift

Clutter filter cutoff frequency: fc > N*FR

Frame rate	FR =1 Hz	FR = 10 Hz	FR=20 Hz
Width (# beams)			
N=30	30 Hz	300 Hz	600 Hz
N=70	70 Hz	700 Hz	1400 Hz

Periferal vessel imaging with fo= 10 MHz

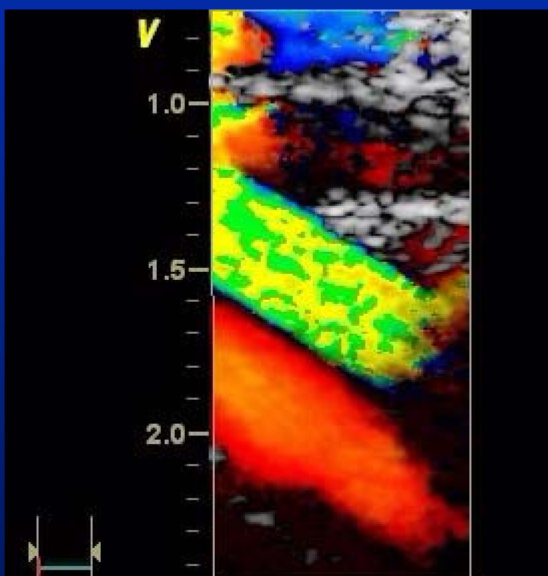
Mechanical scanning: fc = 1400 Hz ~ *108 mm/sec.*

Electronic scanning: fc = 30 Hz ~ *2.3 mm/sec.*

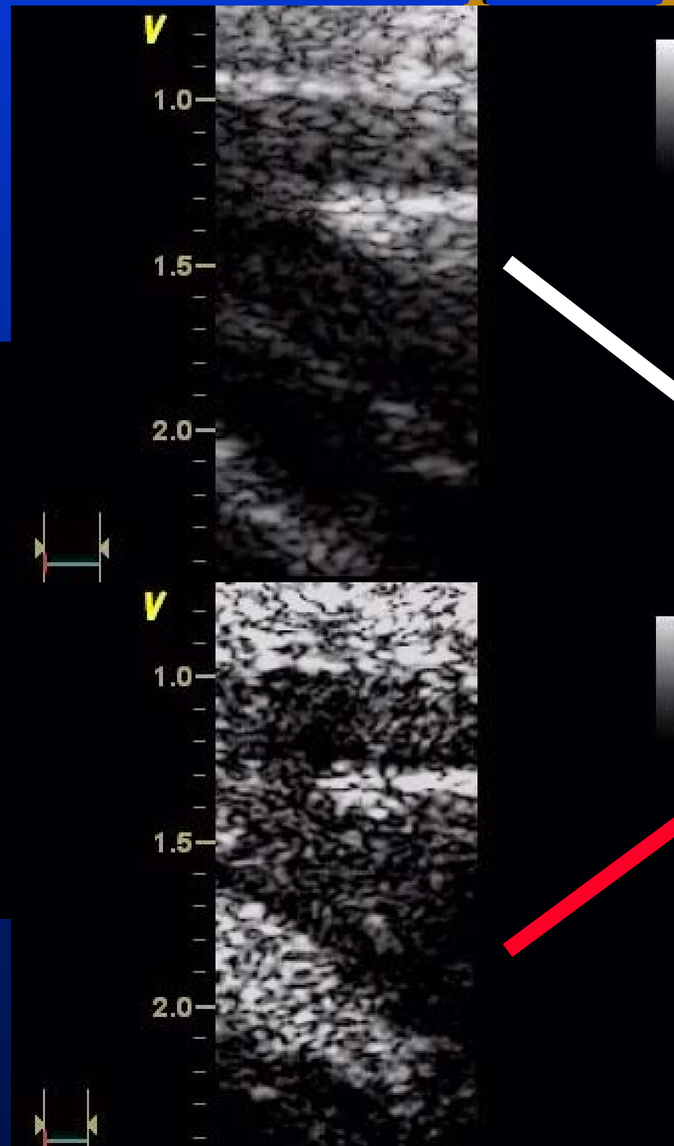
Packet acquisition (P=10): Frame rate = 35 frames/sec

Continuous acquisition: Frame rate = 350 frames/sec

Combining tissue and flow
Continuous sweep acquisition



Brachial artery



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