Resonant Bars: Time dispersion and efficiency detection for impulsive signals of known shape using the “ROG Delta Filter”

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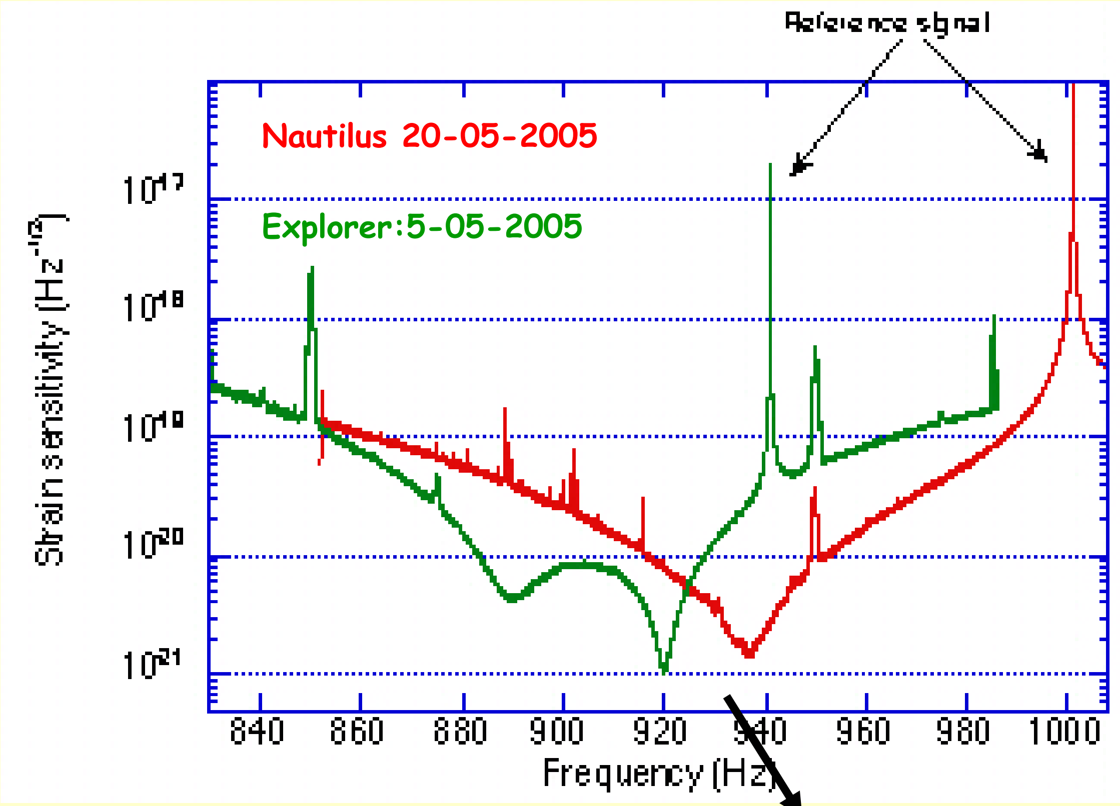
Status of the EXPLORER- NAUTILUS resonant bars



Sqrt(T/MQ)

EXPLORER 2005:

$$\sqrt{S_n(f)} \approx 10^{-21} / \sqrt{Hz}$$

BW ~ 50 Hz at $10^{-20} / \sqrt{Hz}$

T=3 K

Teff ~ 2mK

NAUTILUS 2005:

$$\sqrt{S_n(f)} \approx 1.5 * 10^{-21} / \sqrt{Hz}$$

BW ~ 40 Hz at $10^{-20} / \sqrt{Hz}$

T=3.3K

Teff ~ 2mK

Investigating the Data Analysis Issues for Improved Bandwidth (BW)

- Presently the resonant bars Explorer and Nautilus are working with broader BW.
- It is worth investigating different kind of signals in addition to the delta signals as done in the past.
- It is necessary to reassess the assumption of delta-like signals for matched filtering as the filtered output crucially depends on the shape of the waveform.
- In this study we discuss this problem with an example of GW signals: quasi-normal-modes of proto-NS during the cooling phase after the supernova core collapses: Damped sinusoid evolving in frequency and damping time.

Investigating the Data Analysis Issues for Improved Bandwidth (BW)

- **Topic of this talk:**

Validate ROG delta filters :

a). Loss in SNR using ROG delta filters compared to SNR for Matched filter (in case of known signal)

b). Accuracy in the signal arrival time measured by ROG delta filter compared to that obtained with the Matched filter.

Important while searching coincidences between resonant bars

c) Amplitude signal estimation using the ROG delta filter (Ad) compared to that obtained with the matched filter (Am).

- signal parameters: [?] where :
- → we can use the Delta matched filter
- we have to use a "bank of filters"

Investigating the Data Analysis Issues for Improved Bandwidth (BW)

First Step (discussed in this presentation):

In this preliminary work we consider damped sinusoid signals of known shape with constant frequency Fo and damping time τ .

This study is performed by

analytical approach

&

Simulations: injection of signals of known shape at the input of adaptive delta/signals matched filters

We have used Explorer data “Dec 2004”:

Resonant frequencies at the minus/plus mode=Fm=904.7Hz/Fp=927.45Hz.

Second Step: (Future Work)

Study for signals of unknown shape

Quasi-normal Modes of a newly born hot NS : Signal

[V. Ferrari *et al* , MNRAS 338 (2003) 389]

Scenario: Stellar Core Collapse $\rightarrow$ Neutrino Diffusion & Thermalisation $\rightarrow$ Cooling & Contraction $\rightarrow$ Energy Dissipation *via* Neutrino emission

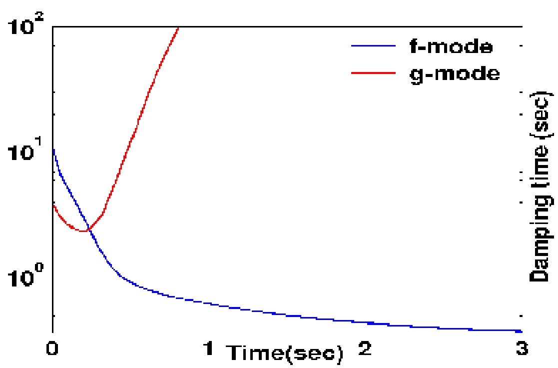
Various QNM of a star are excited in above physical processes $\Longrightarrow$ GW Emission

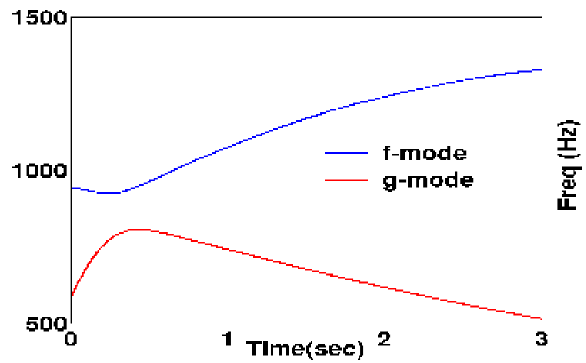
Signal: Damped Sinusoid with varying damping time (τ) and frequency (f)

(Variation depends on the equation of state)

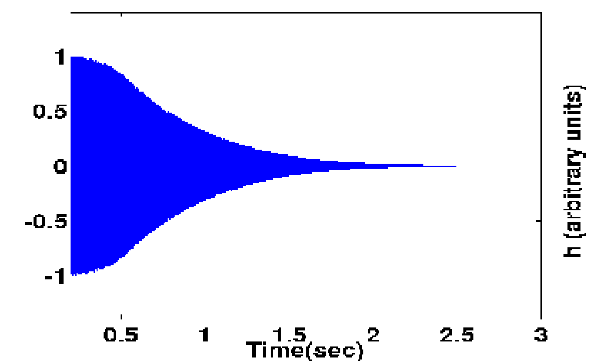
$$h(t) = h_0 \exp^{-(t-t_0)/\tau(t)} \sin[2\pi f(t)(t-t_0)]$$

Example:





$h(t)$ of f-mode



f-mode : Fundamental Mode, Frequency in kHz region

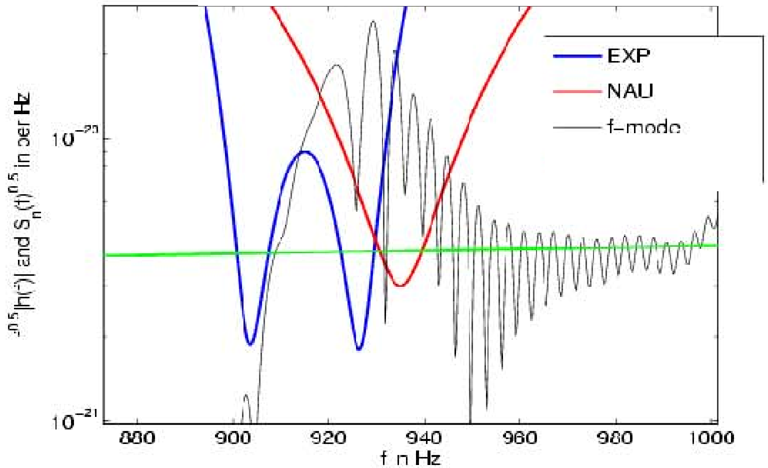
g-mode : Due to entropy and composition gradients in proto-NS

Typically energy: Core collapse $\Delta E \sim 10^{-6} - 10^{-8} M_{sun} c^2$ QNM: $\Delta E \sim 10^{-9} M_{sun} c^2$.

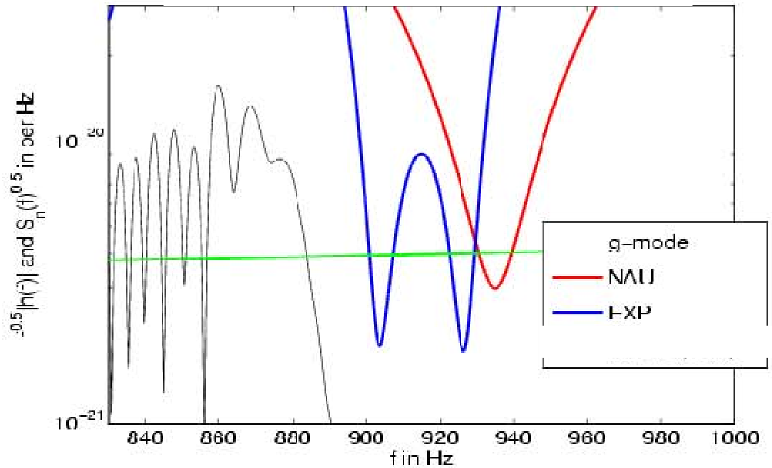
QNM of a newly born hot NS: Detectability

Matched Filter SNR: $SNR^2 = 4\int_0^\infty \frac{|h(f)|^2}{S_n} df$

Evolving f-mode with A=10^-20



Evolving g-mode with A=10^-20



☞ To obtain SNR=5 for galactic source (r = 10 kpc), minimum energy ΔE required in QNM (in $M_{sun}c^2$)

	f-mode	g-mode
Explorer	10^{-4}	1

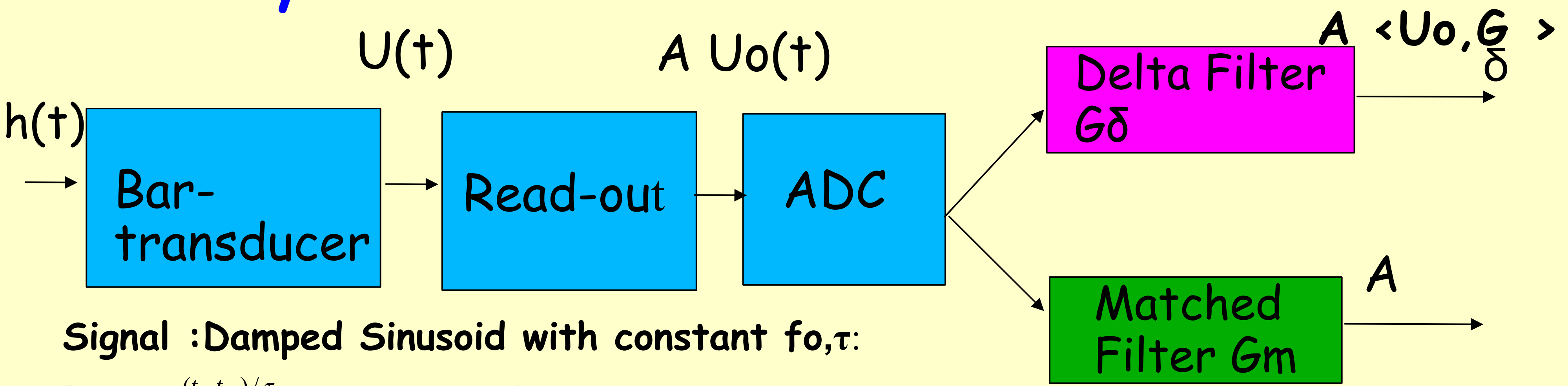
Typical energy: SN Core collapse $\Delta E \sim 10^{-6} - 10^{-8} M_{sun}c^2$ QNM: $\Delta E \sim 10^{-9} M_{sun}c^2$

Recent simulations [Shibata&Uryu,2002 Simulation] have shown that a merger of two NS with equal mass and low compactness can give rise to short lived supra massive NS.

Typical energy during merger $\Delta E \approx 10^{-2} M_{sun} c^2$

The QNM in such a merger may have more energy than those during the cooling phase after the core collapse $\Delta E \approx 10^{-4} M_{sun} c^2$

Layout-ROG Detector + Filters



Signal :Damped Sinusoid with constant fo,τ:

$$h(t) = e^{-(t-t_o)/\tau}\sin(\omega_o(t-t_o)) * \theta(t-t_o)$$

Amplitude, A ~ A(τ,Fo,ho,S)
S=System parameters

Force :

$$F(t) = m_x \frac{L}{2}\frac{\partial^2 h(t)}{\partial^2 t}$$

L is the effective lenght $L = l/4\pi^2$

mx is the reduced mass $m_x = M/2$

SNRd (delta matched filter)=A<Uo,Gδ>/σd
SNRm (matched filter)=A/ σm
σd, σm :std dev of the filtered noise

Response of Bar-Transducer to h(t) :

$$U(j\omega) = W_{ux}(j\omega) * F(j\omega) = -\omega^2 m_x \frac{L}{2} * W_{ux}(j\omega) * H(j\omega)$$

↑ System transfer function

Response of the bar-transducer to the damped sinusoid (summary)

$$u(t)=A_+(t,\tau,F_o,S)*\sin(\omega_+t+\phi_+)-A_-(t,\tau,F_o,S)*\sin(\omega_-t+\phi_-)-A_o(t,\tau,F_o)*\sin(\omega_o t+\phi_o)$$

τ ↓

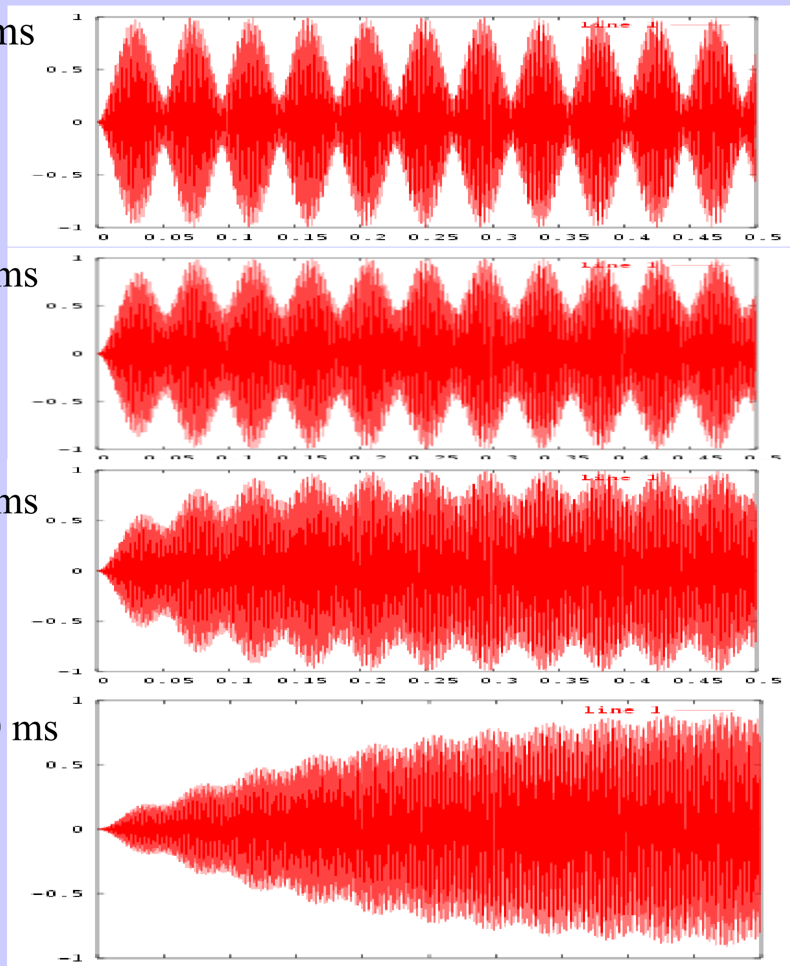
Case I:Fo=Fm, τ :[10 ms - 200 ms]

10 ms

20 ms

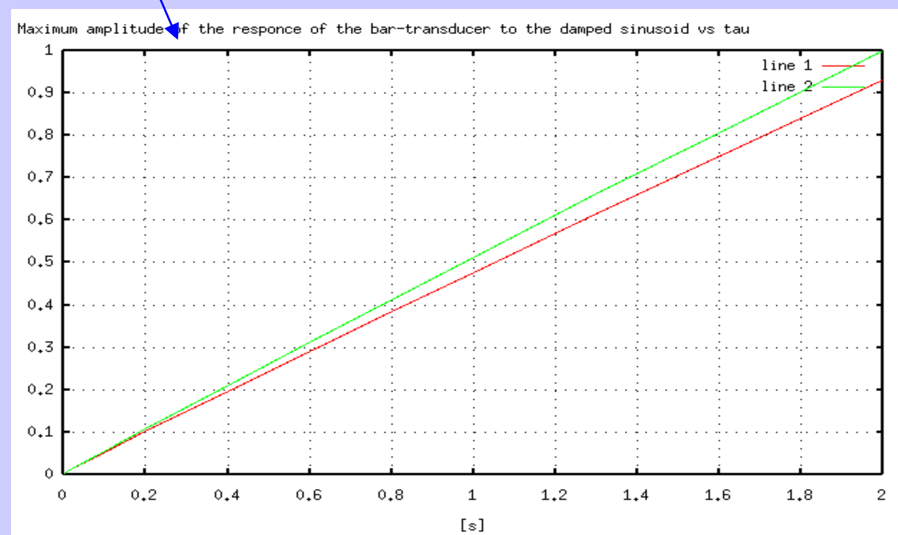
50 ms

200 ms



Maximum amplitude A=u(To) vs τ

To increases with τ



For Fo=Fm :

For $\tau \geq$ 50 ms

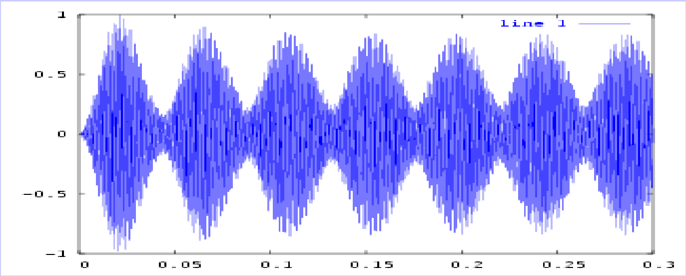
A+<<A-

A+ and Ao $\propto \tau$

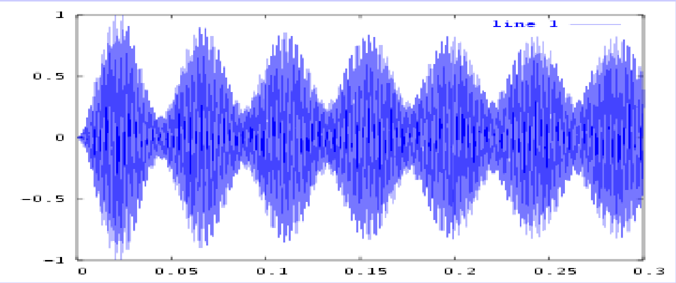
Response of the bar-transducer to the damped sinusoid (summary)

Case III :Fm < Fo < Fp , let τ=50 ms

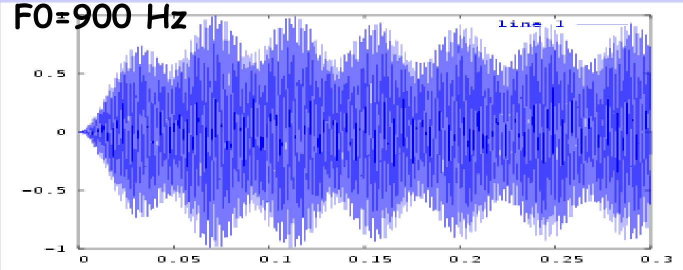
F0=880Hz



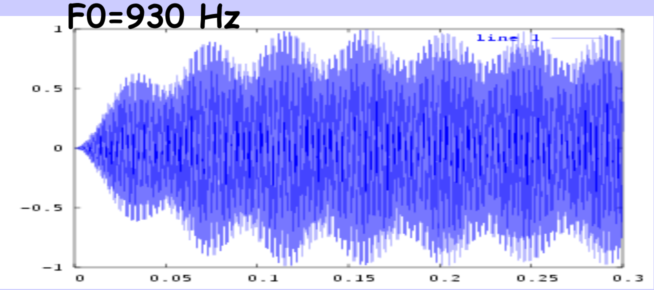
F0=950 Hz



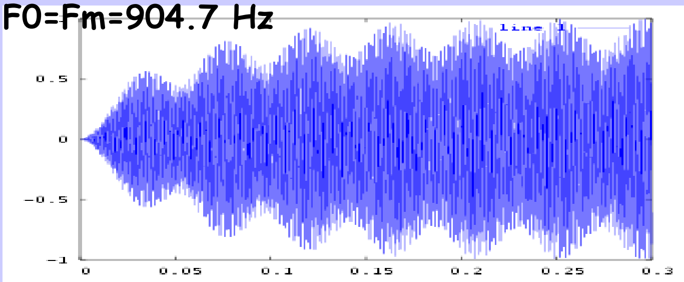
F0=900 Hz



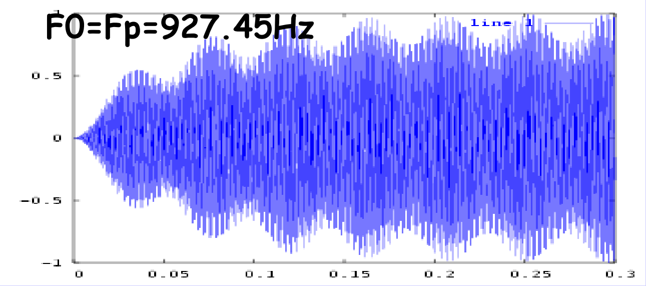
F0=930 Hz



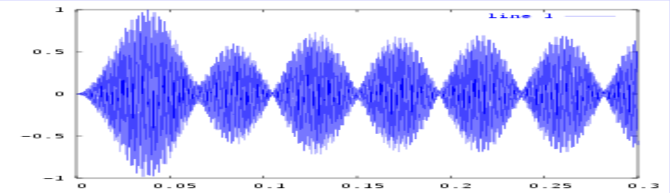
F0=Fm=904.7 Hz



F0=Fp=927.45Hz



F0=915 Hz



MATCHED FILTER Gm

Filtered signal g(t)

- Example: Fo=Fm, τ :[few ms till 1 sec]

τ[ms]

10 ms

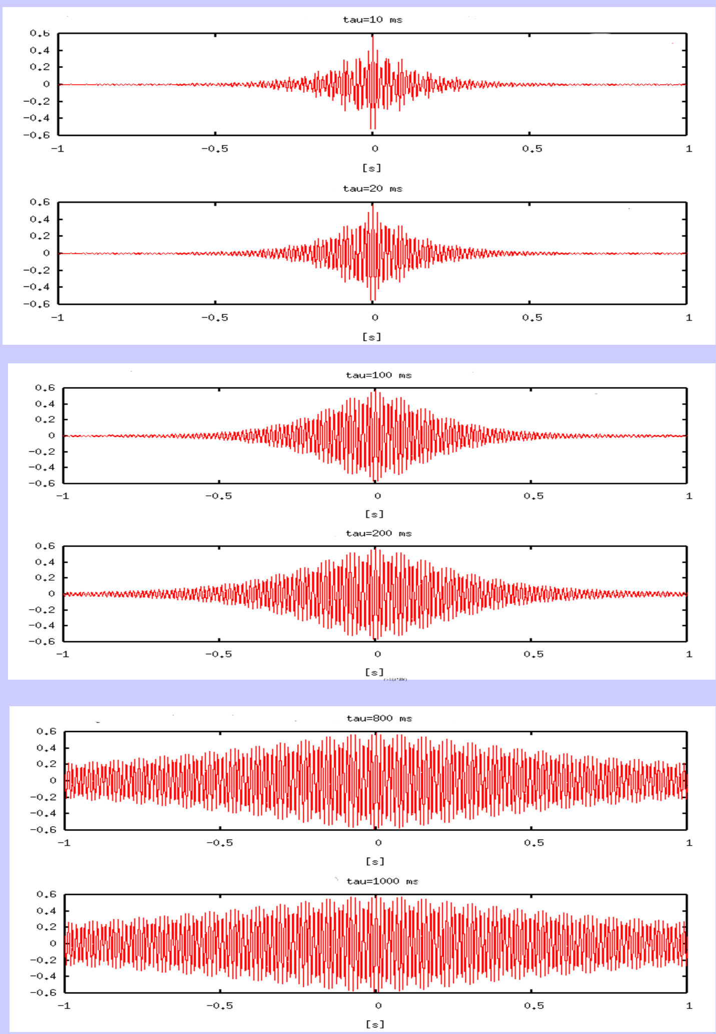
20 ms

100 ms

200 ms

0.8 s

1 s



The decay time of g(t), (τ_g) depends on BW and τ.

$\tau_{BW} = 1/(\pi * BW)$ ~140 ms

For $\tau < 0.1 * \tau_{BW}$, τ_g ~ 1/BW.

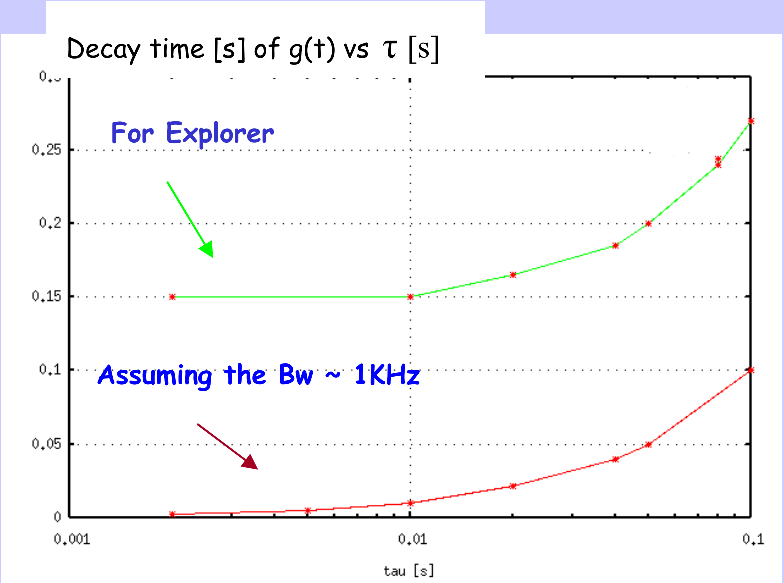
For $\tau > 1/(\pi * BW)$,τ_g increases with τ

! (Independent of detectors' bandwidth)

Max(g(t)=g(To)) is not wel-peaked.

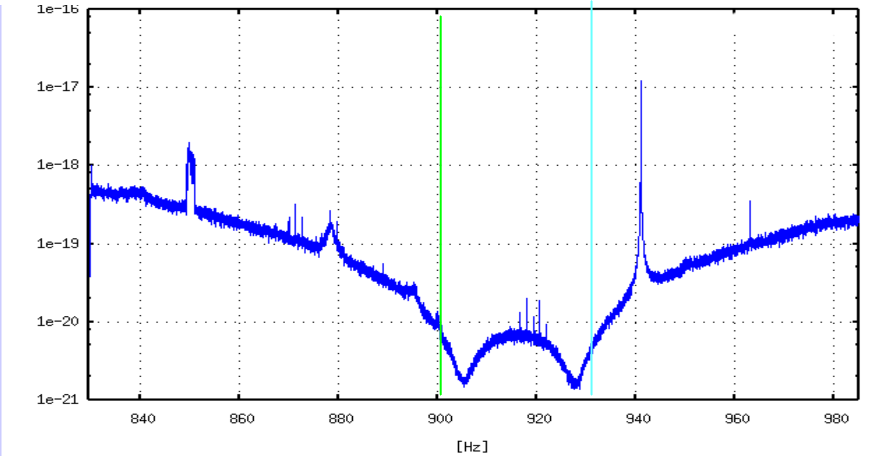
With noise, the error in To can be large !

τ_g[s]

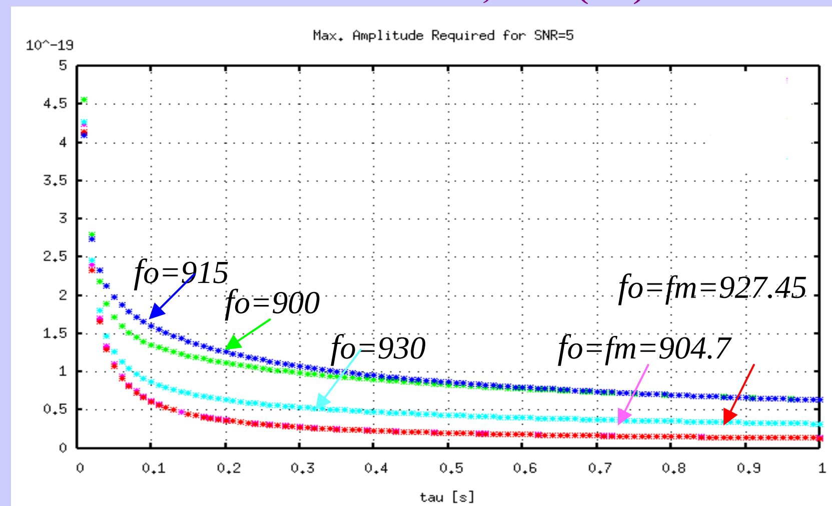


MATCHED FILTER SNR

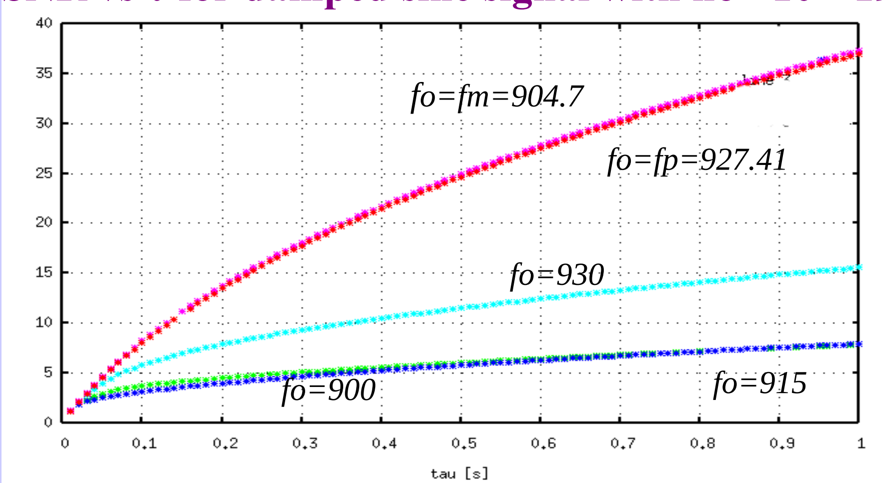
Explorer:Dec 2004 (Data used for simulations)



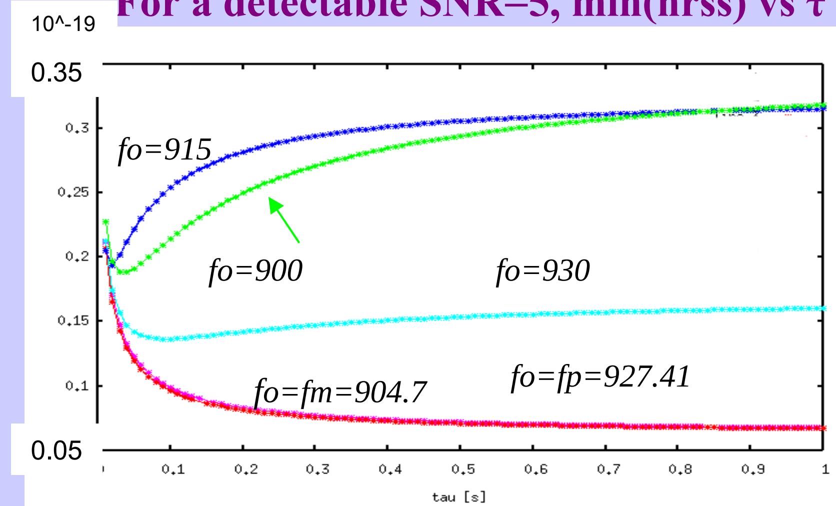
For a detectable SNR=5, min(ho) vs τ



SNR vs τ for damped sine signal with ho =10^-19

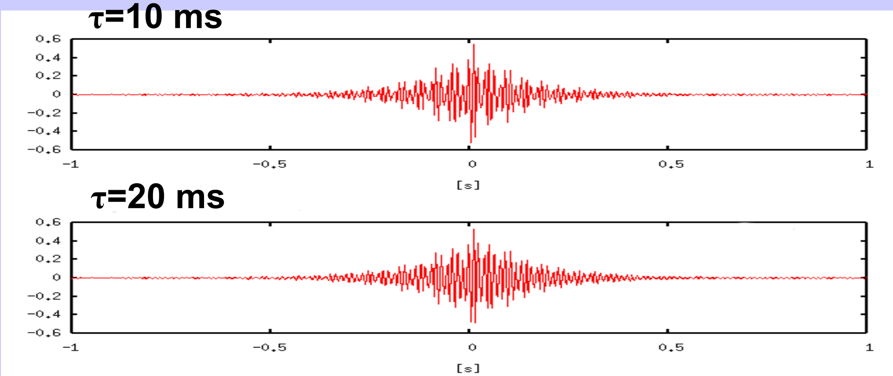


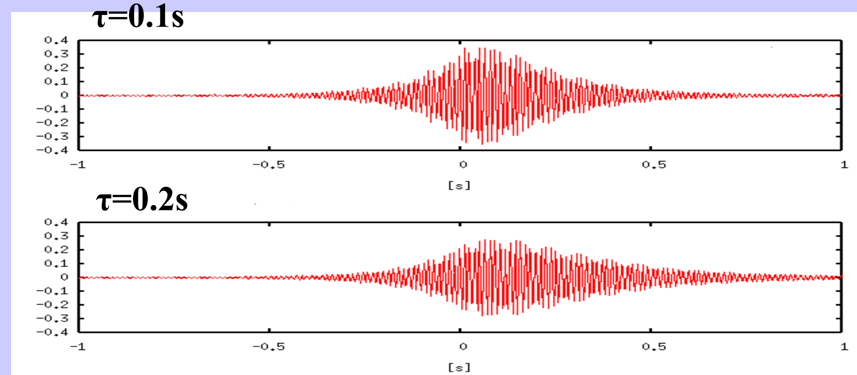
For a detectable SNR=5, min(hrss) vs τ

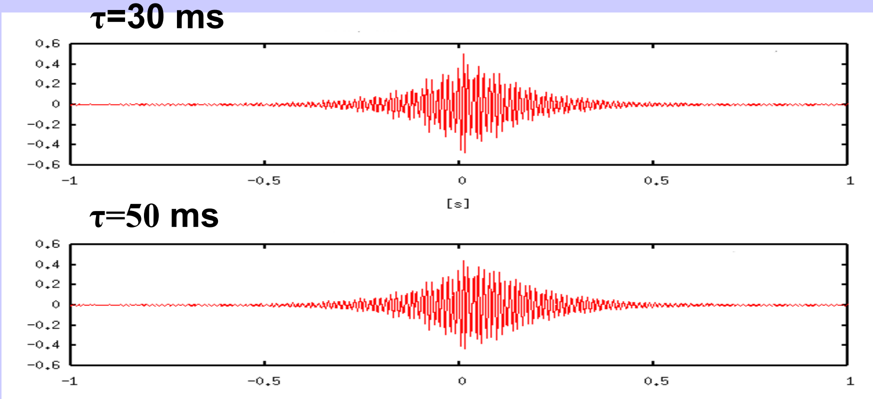


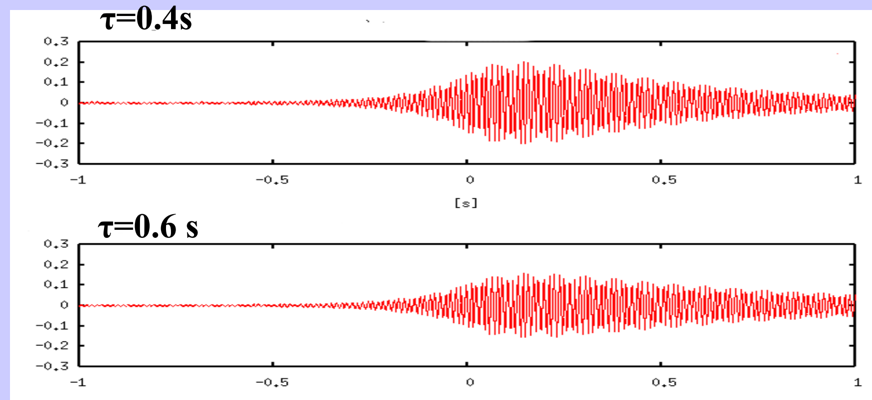
Damped sinusoid filtered with Delta Filter

Case $f_o=f_m$, τ [10 ms-0.6 s]



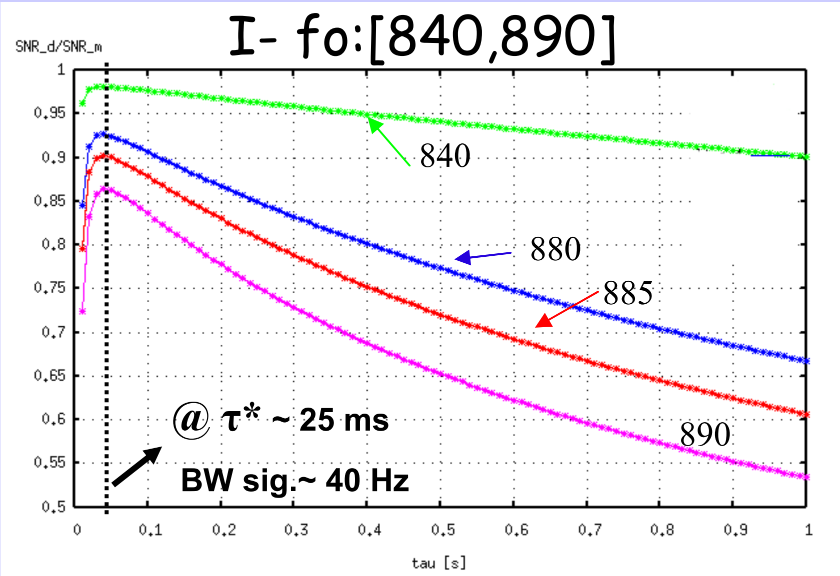




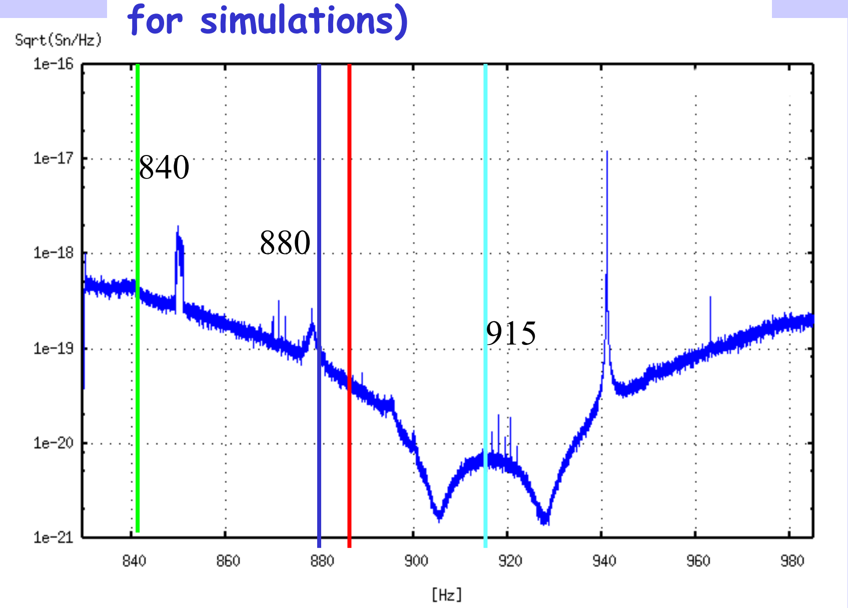


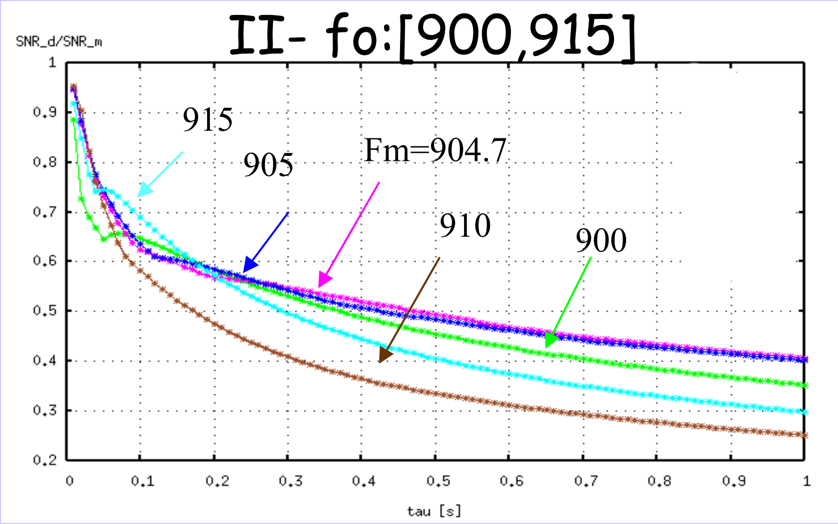
Delta Filter: SNR COMPARISON

SNR-Delta Filter to SNR-Matched Filter



Explorer:Dec 2004 (Data used for simulations)





I- ***Fo far from the resonant frequencies***, for τ <τ* the loss in the SNR decreases with τ because the frequency band of the signal falls in the more sensitive band of the detector till τ=τ* -> important to apply the matched filter for τ<τ*.

For τ >τ* the loss in the SNR increases with τ : the signal stays in the detector for more time =>important to apply the matched filter

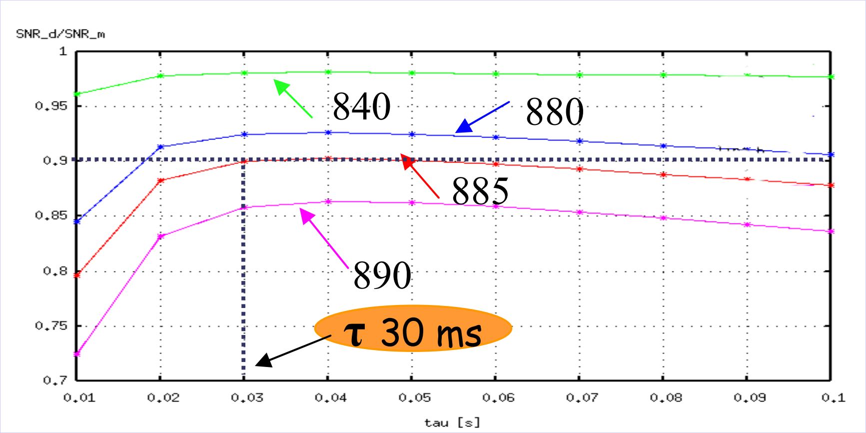
II- ***Fo near the resonant frequencies***

The loss in the SNR rapidly increases with τ

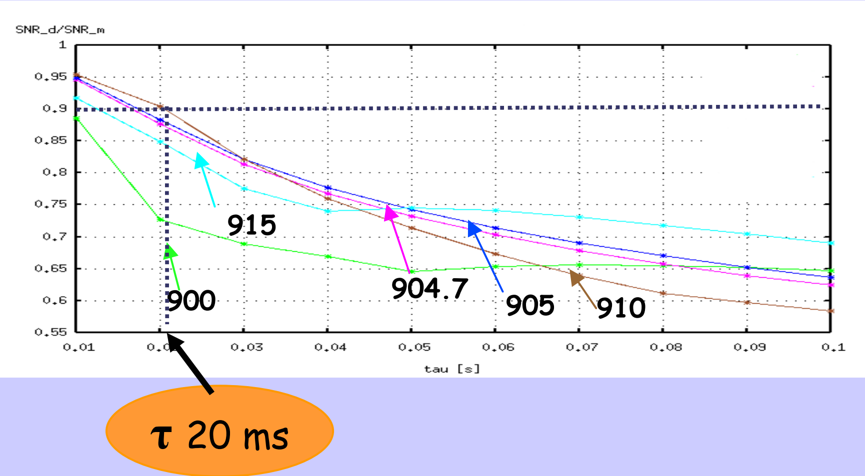
Delta Filter: SNR COMPARISON

SNR-Delta Filter to SNR-Matched Filter

Fo:[840,890] Hz < Fm = 904.7 Hz



Fo:[900,915] Hz around Fm=904.7 Hz



Accepted loss in SNR with Delta filter ~ 10%

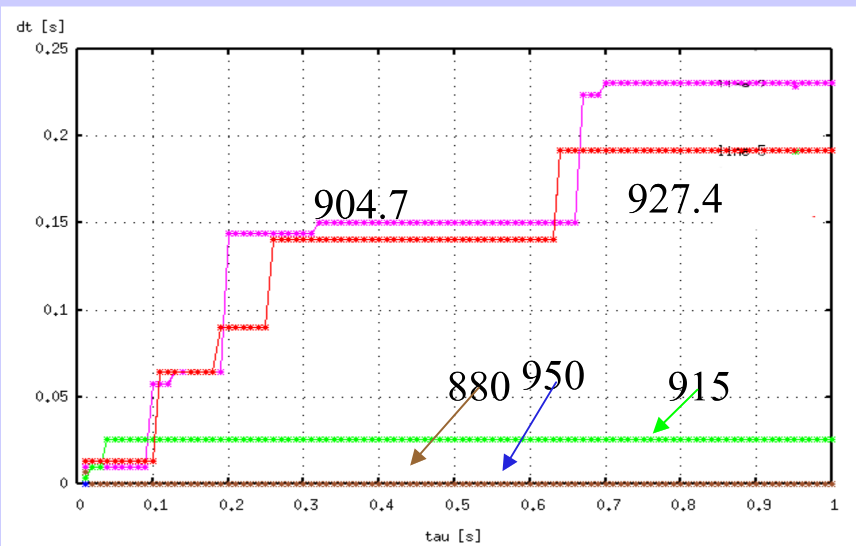
1. Fo< Fm (Fo > Fp) and away from the freq -band
   SNR_D ~ SNR_M,

2. For [900, 930], Max(τ) to be searched

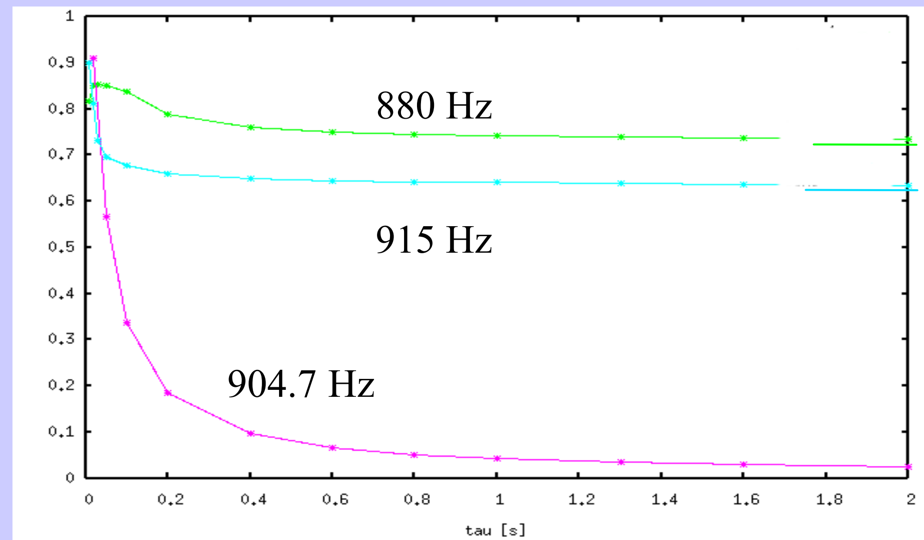
Fo	Max(τ)	Q
Fm=904.7	18ms	~51
910	20ms	~57
915	12ms	~35

DELTA FILTER : Time Dispersion and Amplitude Estimation

Time dispersion :Δt Vs τ



Ad/Am: Vs τ



1. ***Time dispersion*** :

- For Fo near the two resonant frequencies **Δt** increases with τ.

Constant after τ >1sec is misleading

Important while fixing the coincidence window

- For Fs away from the freq-band, Δt ->0 msec

2. ***The error in the amplitude estimation is***

- For Fo near the two resonant frequencies the error increases faster with τ
- For Fs away from the freq-band. The error is ~ 20%

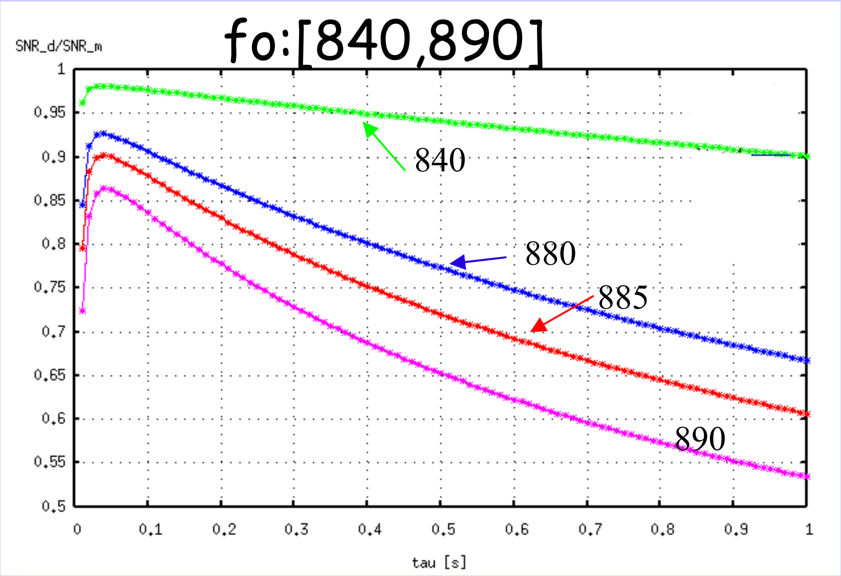
Conclusions on the use of the Delta Filter

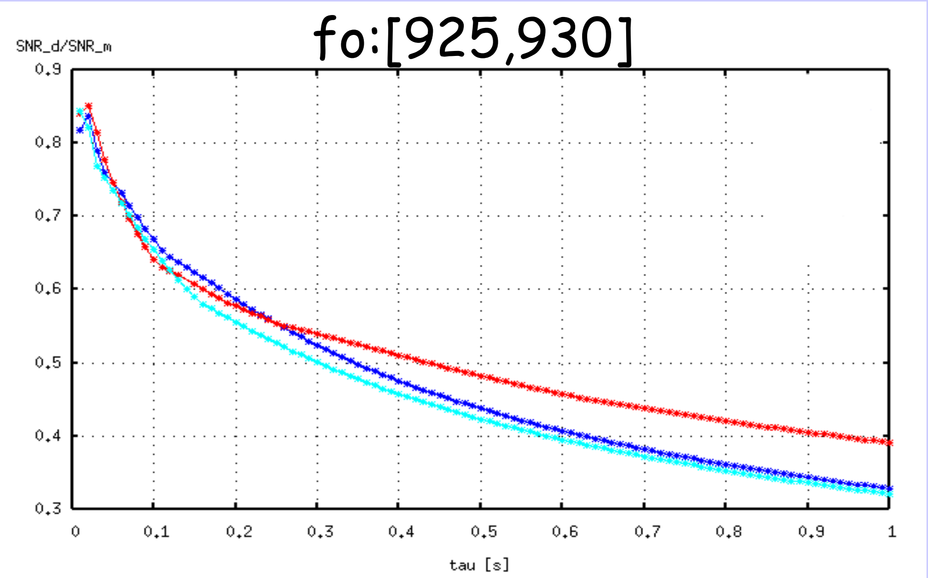
Signal parameters	Dt	Error in the amplitude estimation	Loss in SNR
Fo<880 Hz Fo>935Hz **T** <100ms	0	15%	10%
	Delta filter is ok		
Fo near Fm,Fp **T** <20 ms	Increases with **T** < Few ms	Increases with **T** <30%	Increases with **T** <10%
	Delta filter is ok		

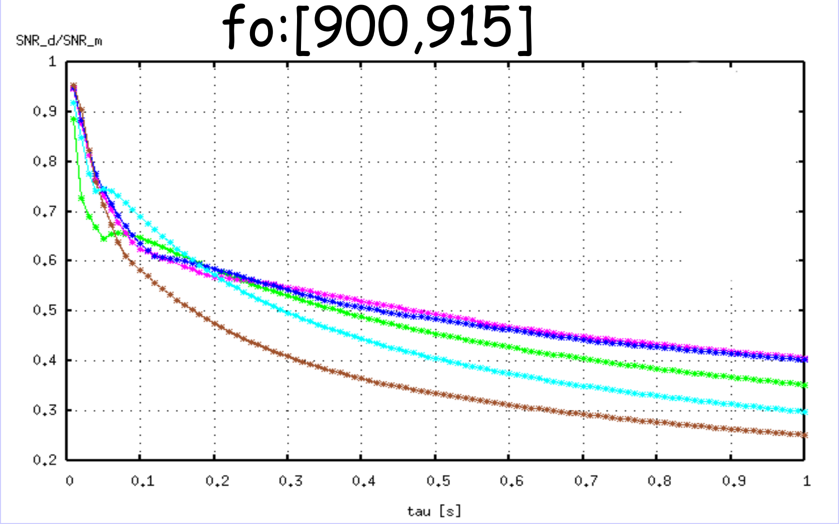
Bank of Matched filters should be used for the other cases !

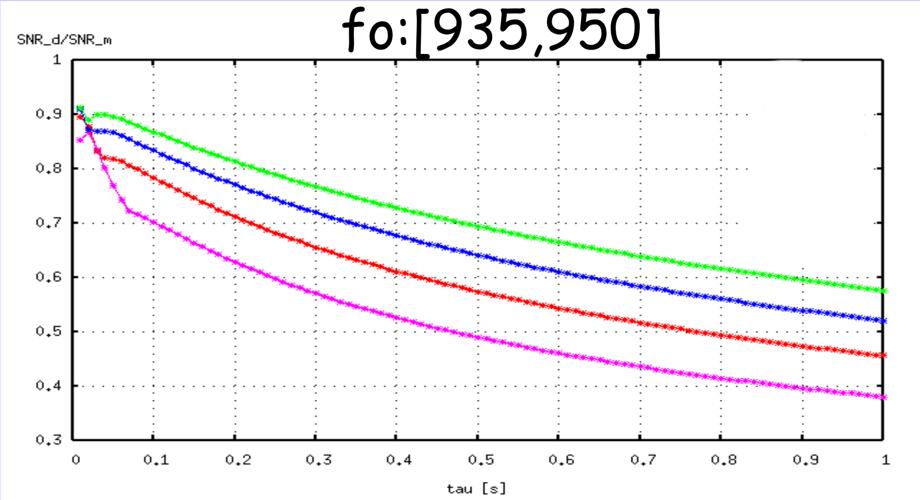
Delta Filter: SNR COMPARISON

SNR-Delta Filter to SNR-Matched Filter

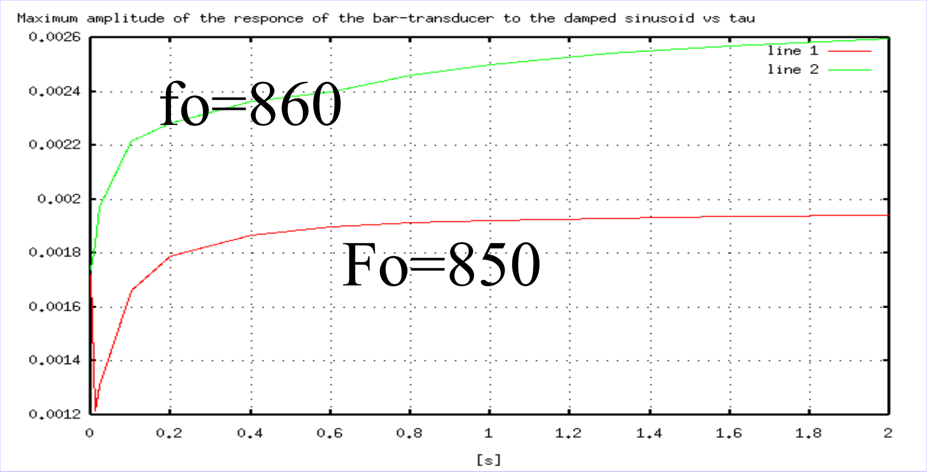


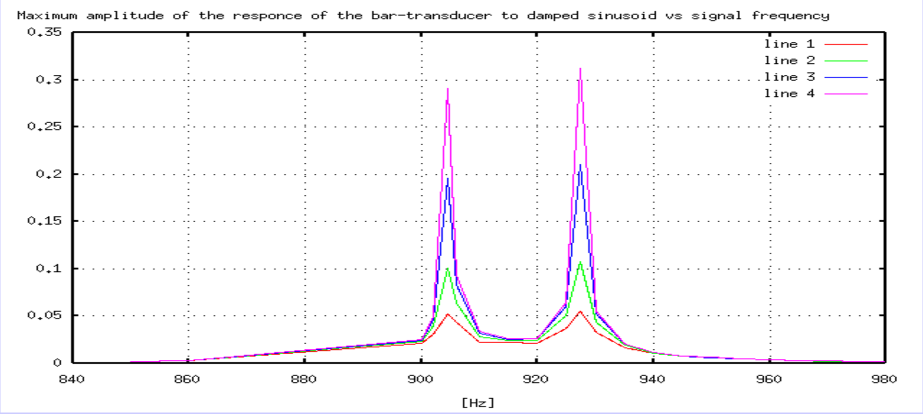






Response of the bar-transducer ...

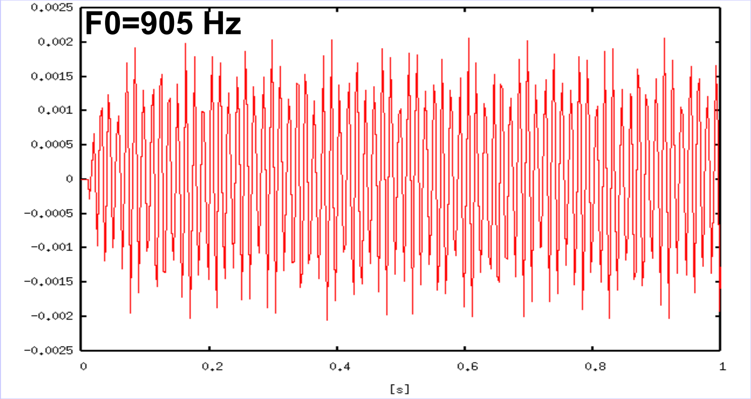


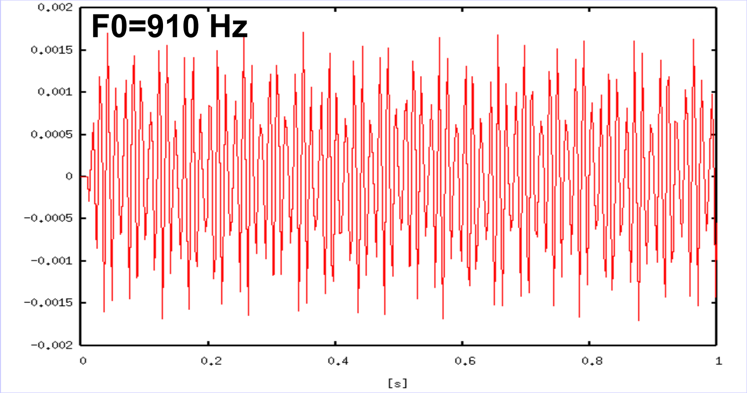


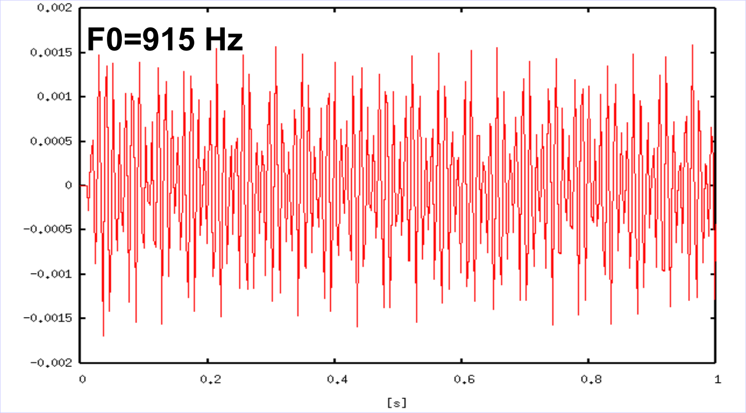
Tau = 0.1,0.2,0.4,0.6 ms

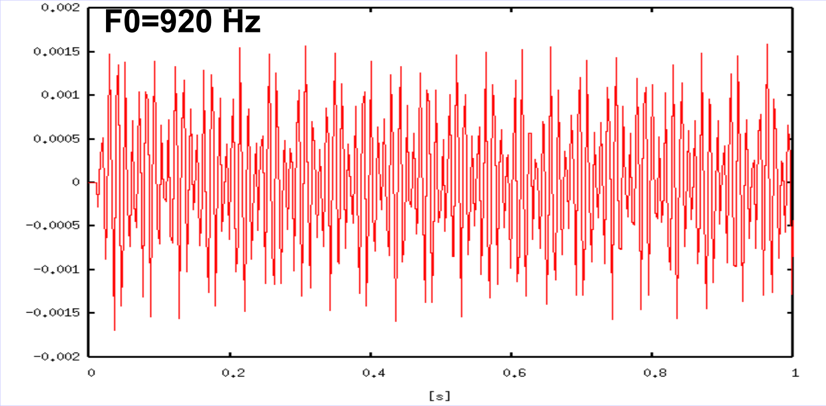
Response of the bar-transducer to the damped sinusoide

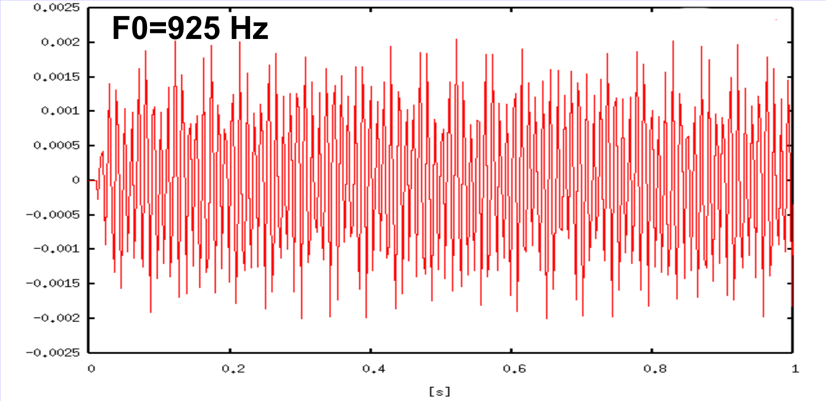
Case III :Fm < Fo < Fp , let τ=30 ms







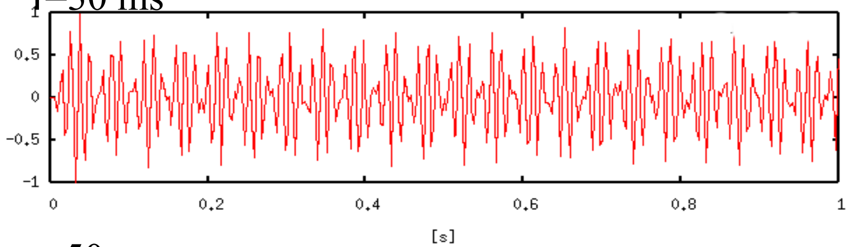




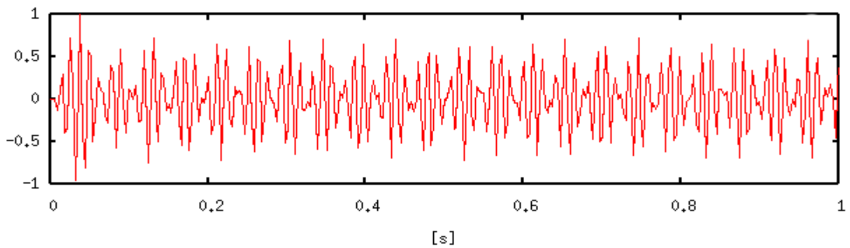
Response of the bar-transducer to the damped sinusoide (summary)

Case II :Fm < Fo < Fp , τ increasing from 30 ms till 1 s

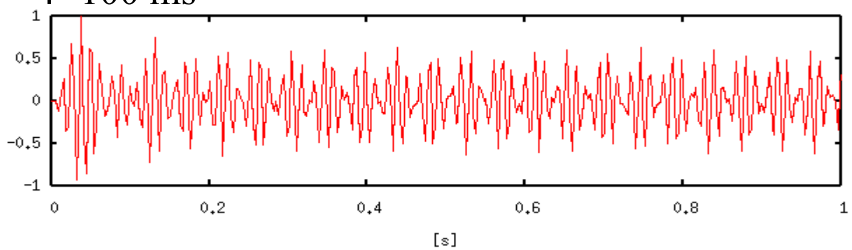
τ=30 ms



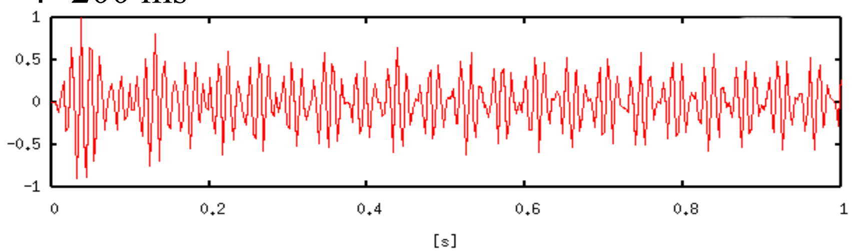
τ=50 ms



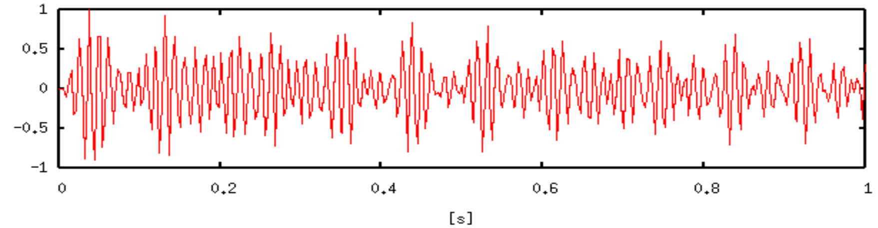
τ=100 ms



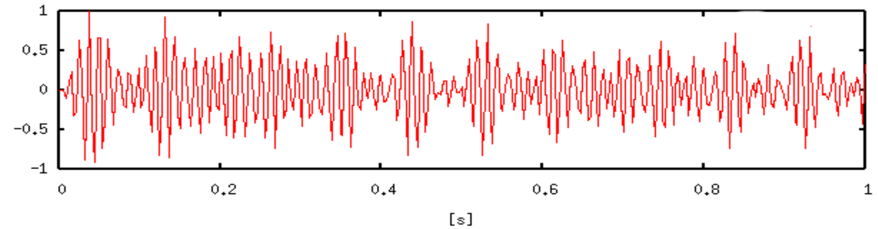
τ=200 ms



τ=800 ms



τ=1 s



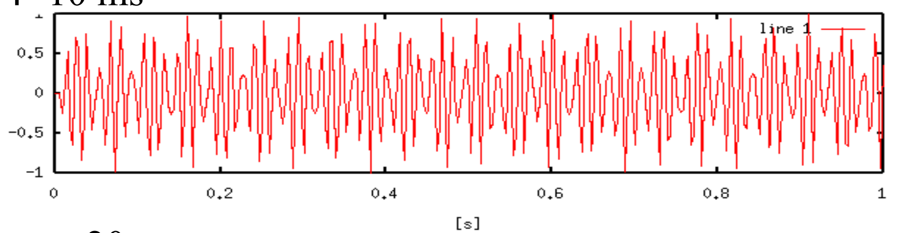
The maximum amplitude **A**=u(**to**) is a function of τ

to is constant in this particular case: Fo=(Fm+Fp)/2

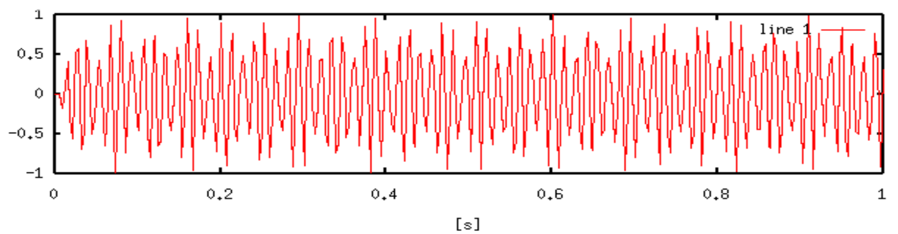
Response of the bar-transducer to the damped sinusoide

Case I:Fo=Fm, τ increasing from 10 ms till 1 s

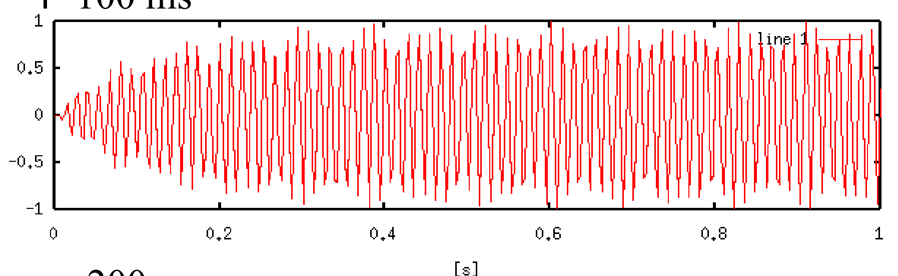
τ=10 ms



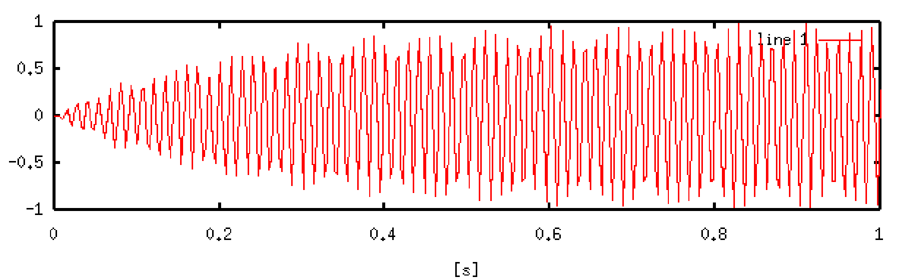
τ= 20 ms



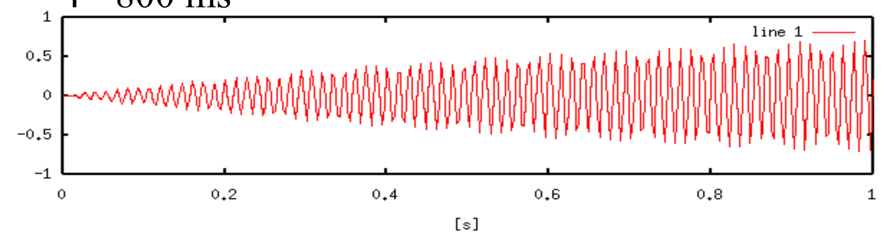
τ=100 ms



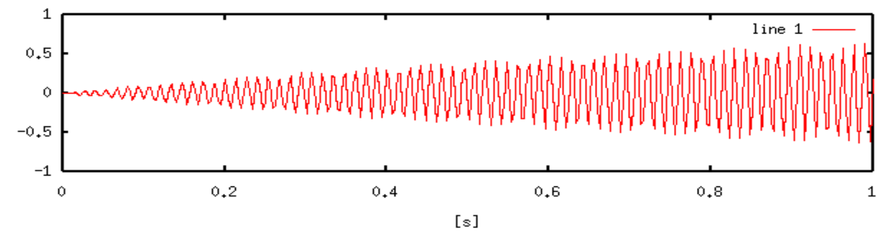
τ= 200 ms



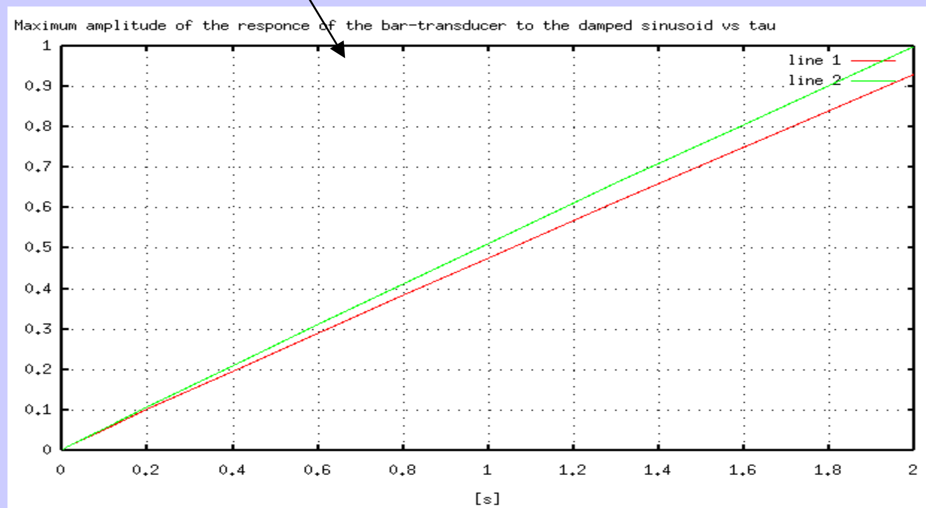
τ= 800 ms



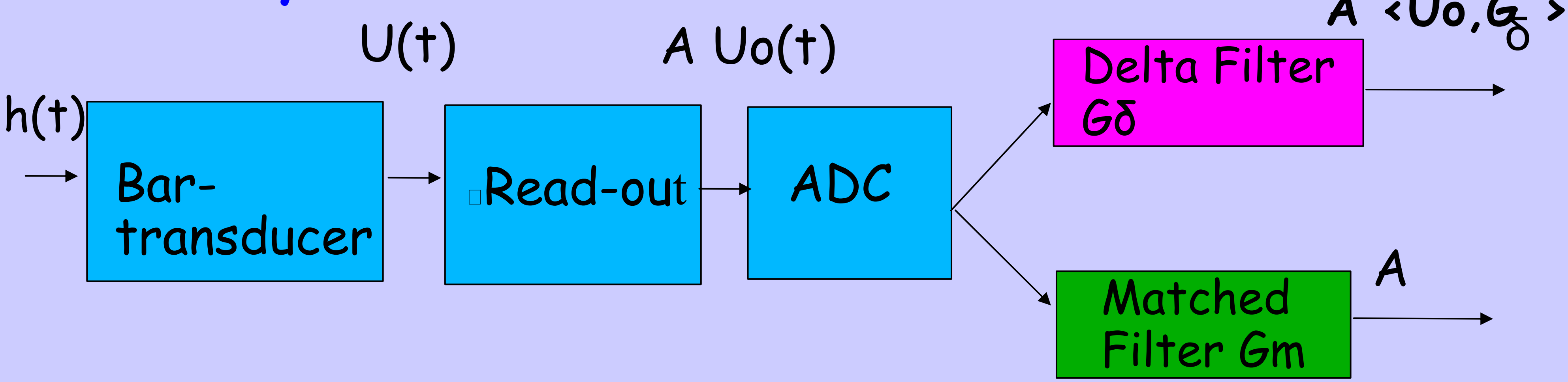
τ=1 s



The maximum amplitude **A**=u(**to**) is a linear function of τ.



Layout-ROG Detector + Filters



Amplitude, A ~ A(tau,Fo,ho,S)

S=System parameters

ROG Delta Filter: $G\delta = N_d W^*ux(f)/(S(f)*M_d)$

SNR=A<Uo,Gδ>/Nd

Matched filter: $Gm = N_m Uo^*(f)/(S(f))$

SNR=A/Nm

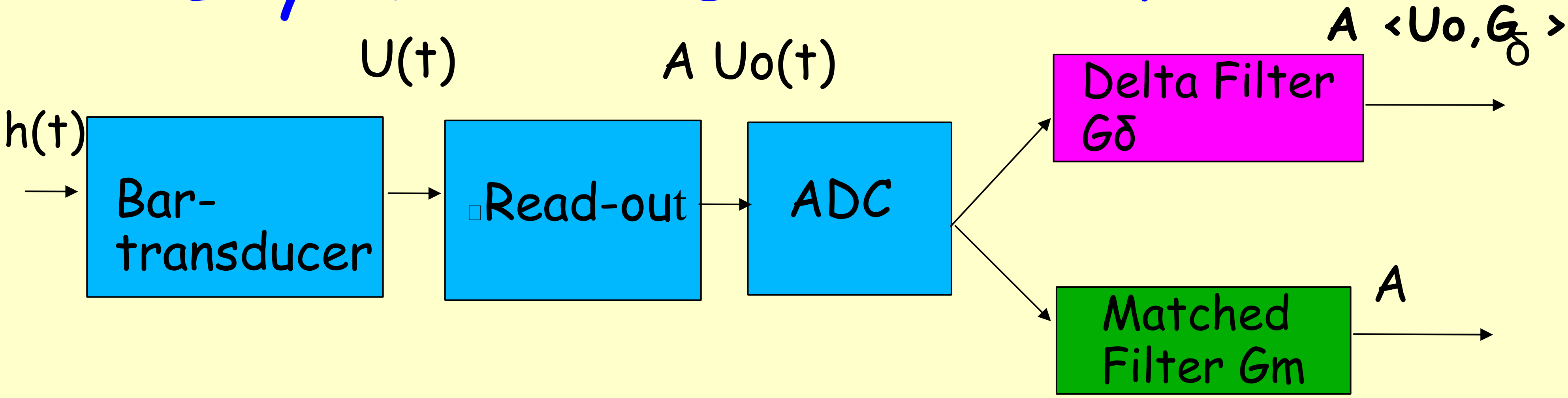
S(f) :Noise power spectra at the output

Nm,Nd :std dev of the filtered noise

$$N^2_m = [\frac{1}{2\pi}\int \frac{|U_o(j\omega)|^2}{S(\omega)} d\omega]^{-1}$$

$$N_d^2 = [\frac{1}{2\pi}\int \frac{|W_{ux}(j\omega)|^2}{S(\omega)(M_d)^2} d\omega]^{-1}$$

Layout-ROG Detector + Filters



Amplitude, A ~ A(tau,Fo,ho,S)

S=System parameters

ROG Delta Filter: $G_\delta = N_d W^* ux(f)/(S(f)^* M_d)$

SNR=A<Uo,Gδ>/Nd

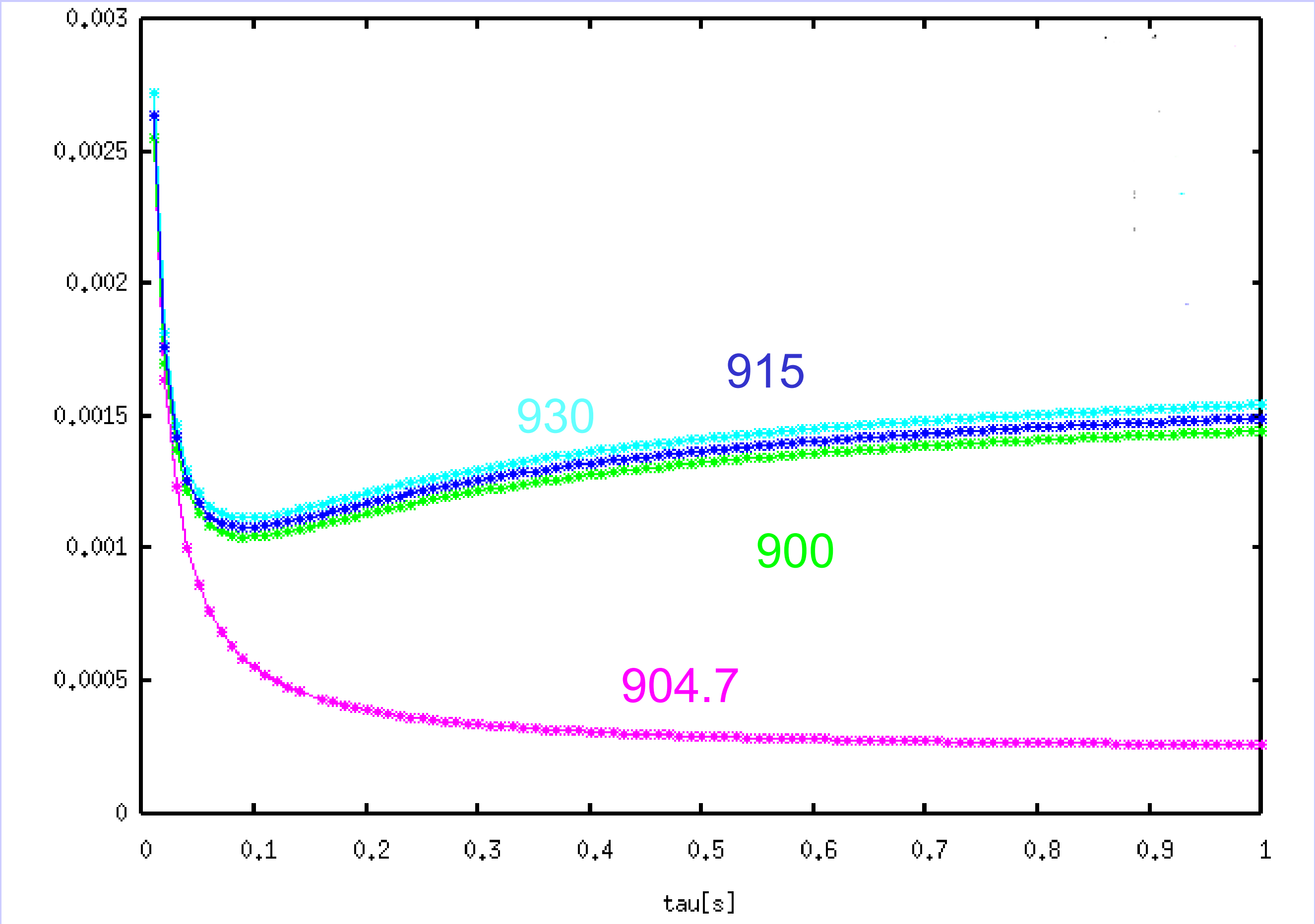
Matched filter: $G_m = N_m U_o^*(f)/(S(f))$

SNR=A/Nm

S(f) :Noise power spectra at the output

Nm,Nd :std dev of the filtered noise

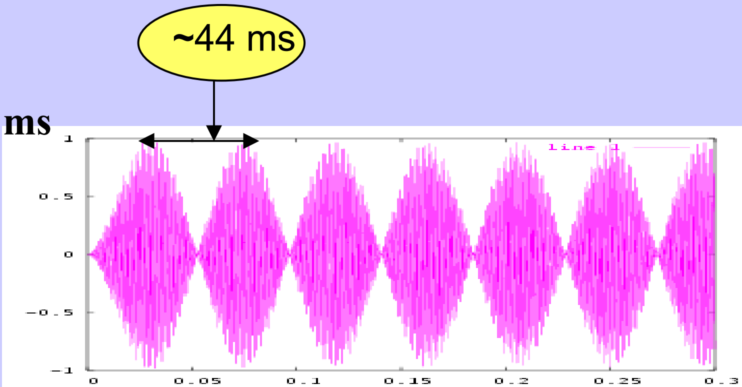
Minimum energy (Mc^2) to be emitted in QNM to obtain SNR=5



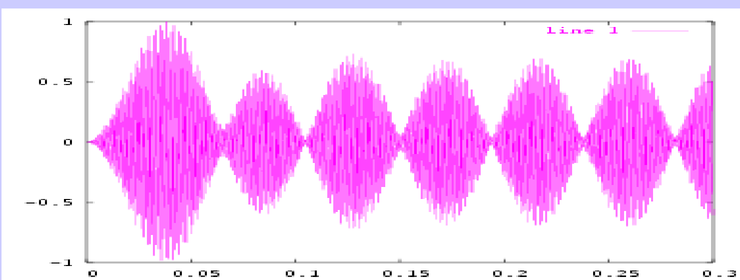
Response of the bar-transducer to the damped sinusoid (summary)

Case II : Fo = (Fp +Fm)/2 = 915, τ : [10 ms till 200ms]

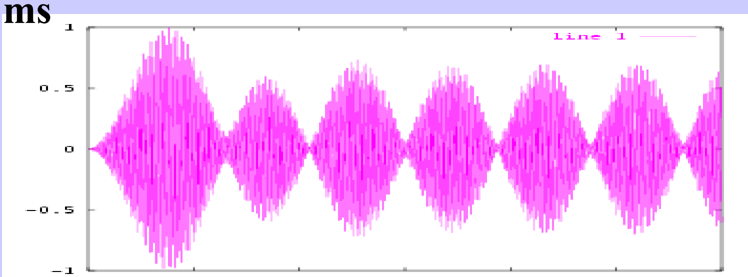
τ=10 ms



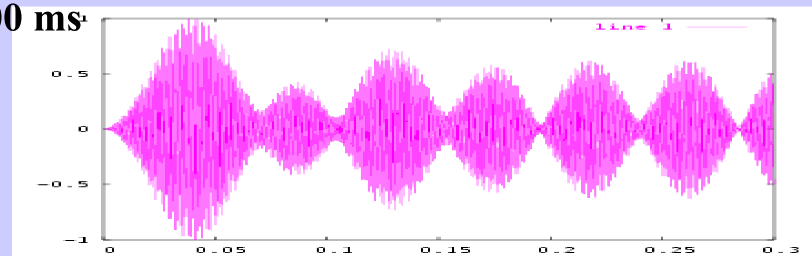
τ=20 ms



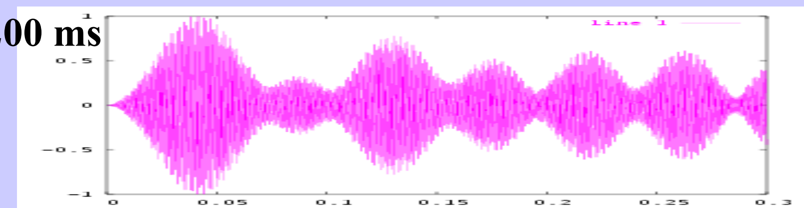
τ=50 ms



τ=100 ms



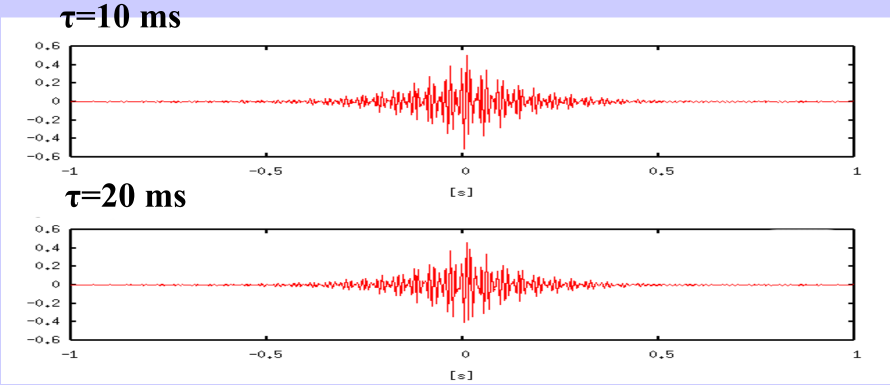
τ=200 ms

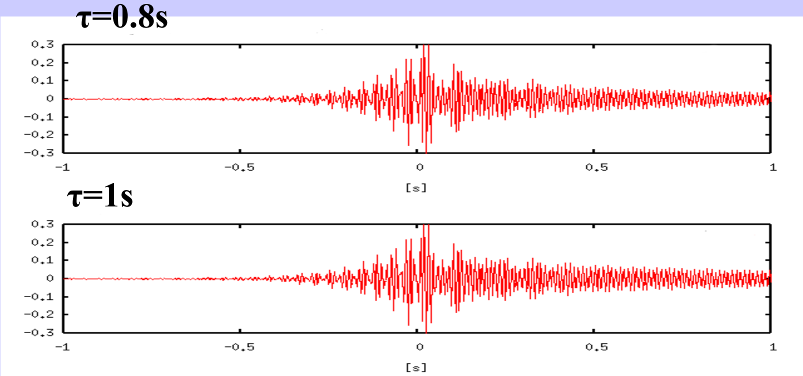


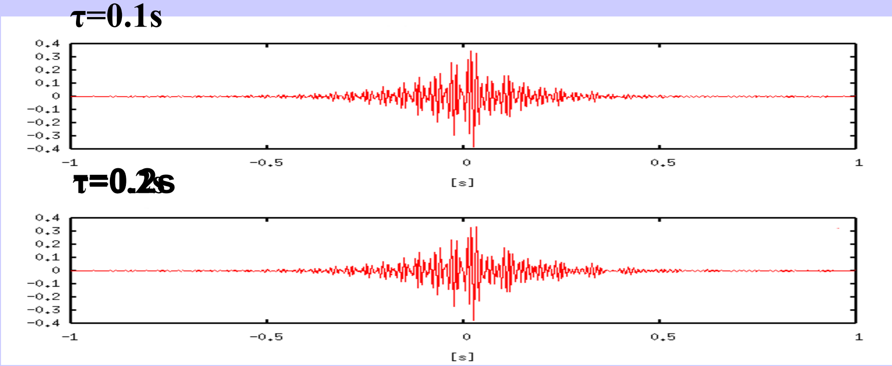
1. Maximum amplitude A=u(To) increases with τ
2. To is constant.
   Depends on the modulation freq of
   the envelope i.e. (Fp – Fm) ~ 22.7Hz

Damped sinusoid filtered with Delta Filter

CASE $f_o=(f_m+f_p)/2$, τ [10 ms- 1s]







The temporal position of Max(A <Uo,G >) independent of τ.

Because the time To corre. to max(u(t)) is independent of τ