

# INTERAKCE LAMBOVÝCH VLN SE SIMULOVANÝM DEFEKTEM

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Příspěvek vznikl na základě podpory projektu GA ČR č. 101/09/1630  
*Numerické řešení stacionárních a nestacionárních problémů dispersního šíření  
vln v mechanických systémech na různých úrovních*  
a záměru ÚT AV ČR, v.v.i., AV0Z20760514.

## Motivace

Standardní ultrazvukové metody

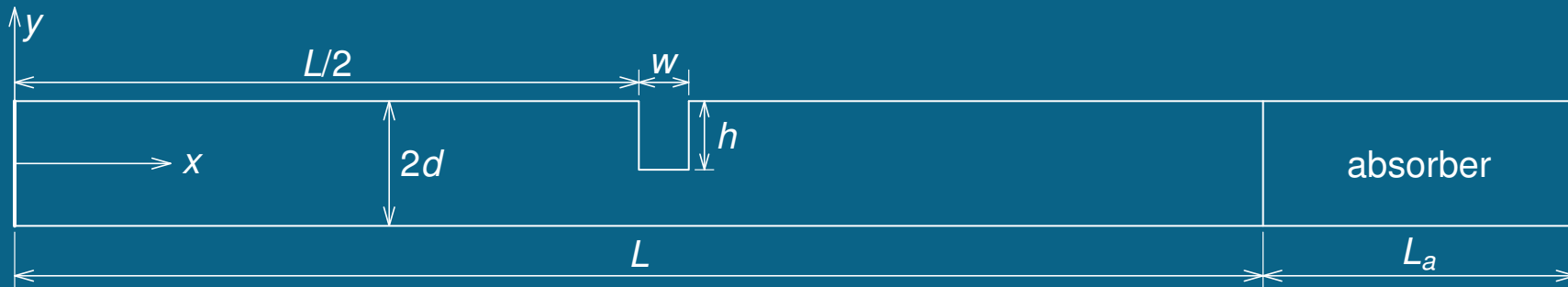


*guided waves* metody

Schopnost *guided waves* metod:

- testovat celou strukturu v jediném měření,
- testovat i nepřístupné oblasti konstrukce,
- nasazení v SHM (*Structural Health Monitoring*) systémech.

## Geometrie úlohy



### Ocelová deska

délka:  $L = 120$  mm,  
 tloušťka:  $2d = 4$  mm,  
 Youngův modul:  $E = 205$  GPa,  
 Poissonovo číslo:  $\nu = 0,30$ ,  
 hustota:  $\rho = 7800$  kg/m<sup>3</sup>.

### Vrub

hloubka:  $h = 0,5 - 2$  mm,  
 šířka:  $w = 0,5 - 2$  mm,  
 umístění:  
 na horním okraji desky,  
 $L/2 = 60$  mm od místa buzení.

## Časový průběh budícího pulzu

$$y(t) = \frac{1}{2} (1 - \cos(\omega_0 t / N_c)) \sin(\omega_0 t) \quad \text{pro} \quad t \in \langle 0, N_c / f_0 \rangle,$$

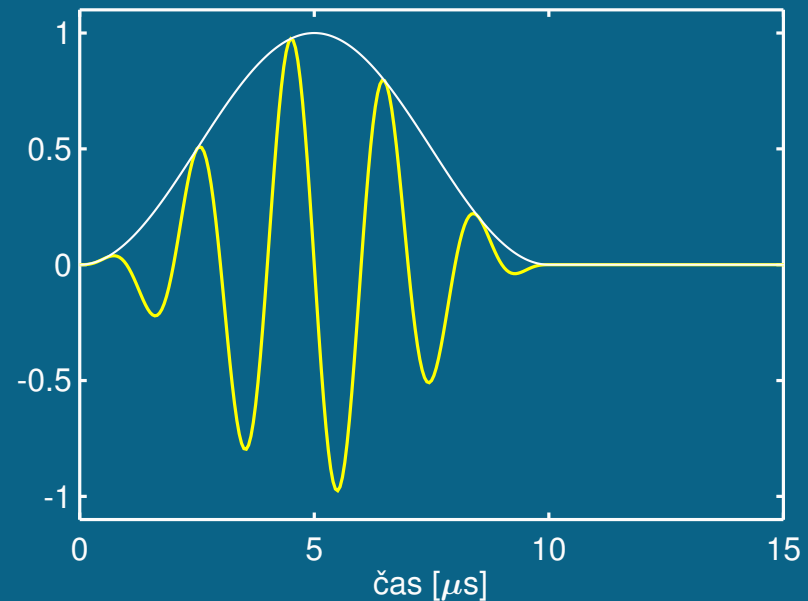
kde

$f_0$  ... nosná frekvence (0.5 MHz),

$\omega_0$  ... nosná úhlová frekvence,

$N_c$  ... počet cyklů (5),

$t$  ... čas.



## COMSOL Multiphysics

- strukturální mechanika, rovinná deformace
- Lagrangeovy – kvadratické prvky

### Časová analýza

- buzení předepsané tabulkou ze souboru
- čas od 0 do  $100 \mu s$  s krokem  $0,01 \mu s$
- relativní tolerance:  $10^{-5}$ , absolutní tolerance:  $10^{-10}$
- čtvercová síť – velikost prvku  $0,5 \times 0,5 \text{ mm}$

### Frekvenční analýza

- buzení předepsané tabulkou ze souboru
- frekvence předepsané tabulkou ze souboru
- čtvercová síť – velikost prvku  $0,5 \times 0,5 \text{ mm}$

## Disperzní vztahy pro tlustou desku

Symetrické módy:

$$\frac{\tan \beta d}{\tan \alpha d} = - \frac{4\alpha\beta k^2}{(k^2 - \beta^2)^2}$$

Antisymetrické módy:

$$\frac{\tan \beta d}{\tan \alpha d} = - \frac{(k^2 - \beta^2)^2}{4\alpha\beta k^2}$$

kde

$$\alpha^2 = \omega^2 / c_1^2 - k^2,$$

$$\beta^2 = \omega^2 / c_2^2 - k^2,$$

$k$  ... vlnové číslo,

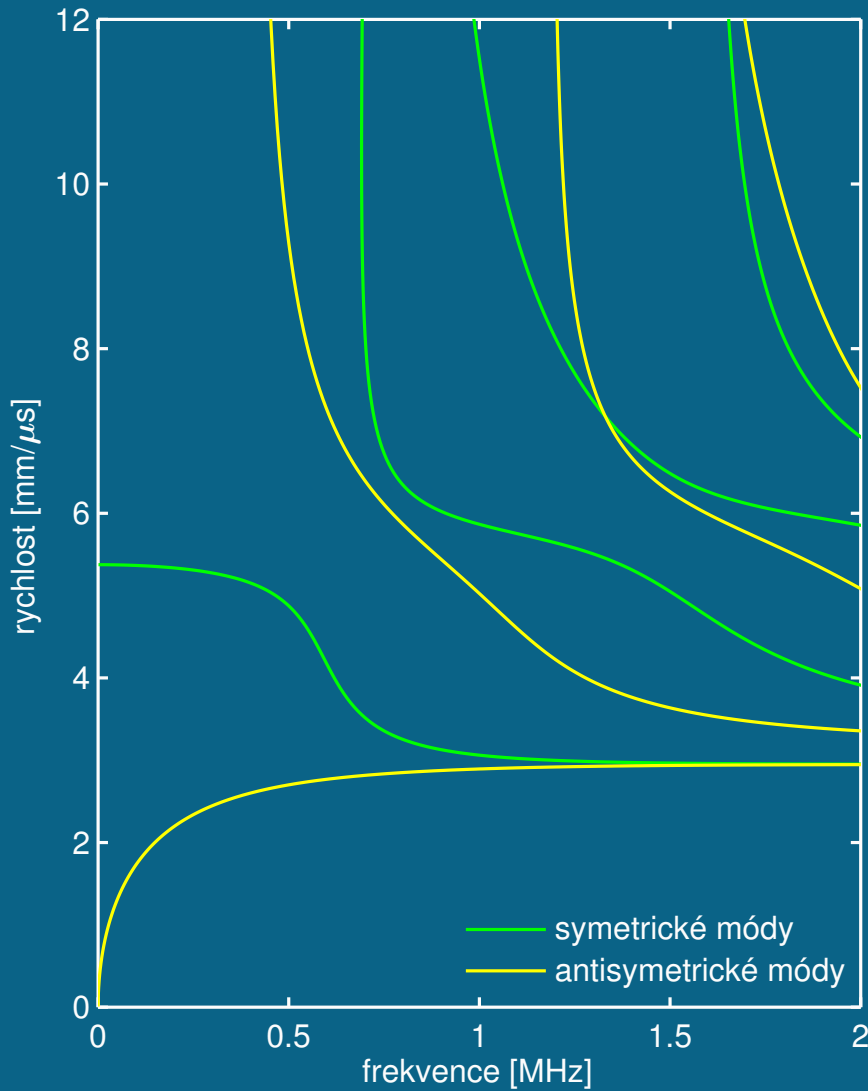
$\omega$  ... úhlová frekvence,

$c_1, c_2$  ... fázové rychlosti,

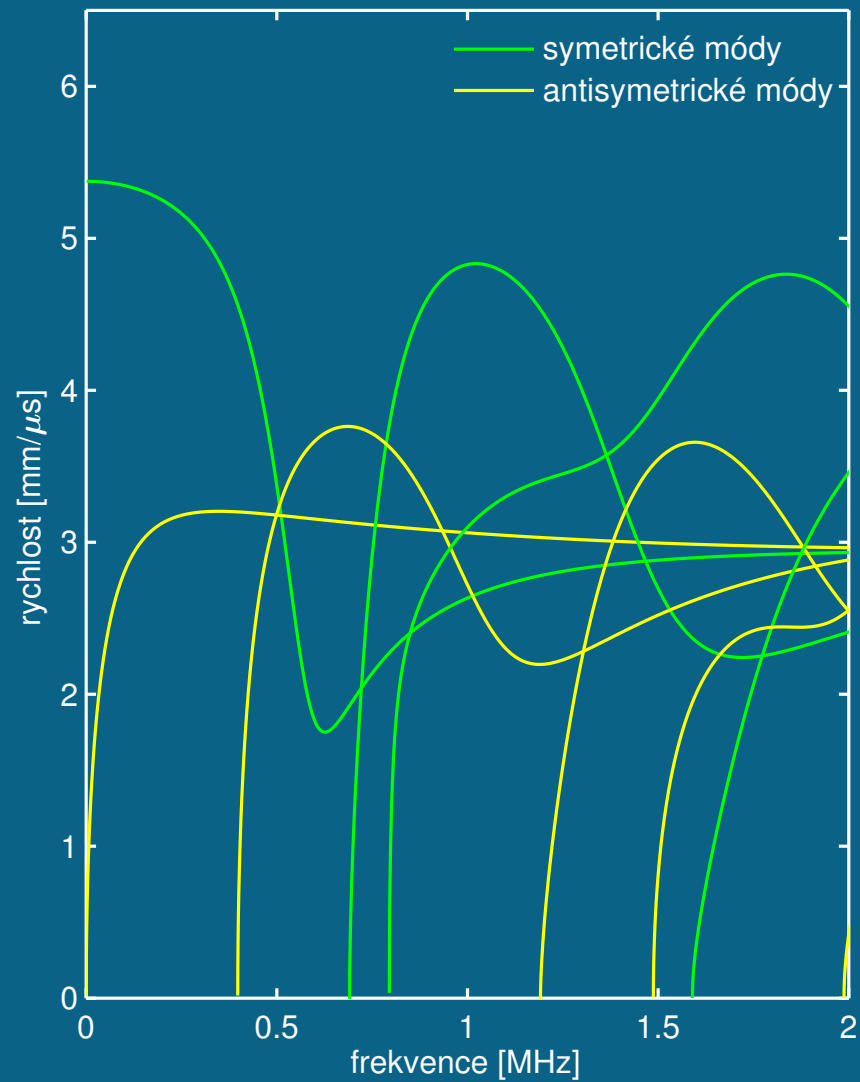
$d$  ... polotloušťka desky.

# Disperzní křivky

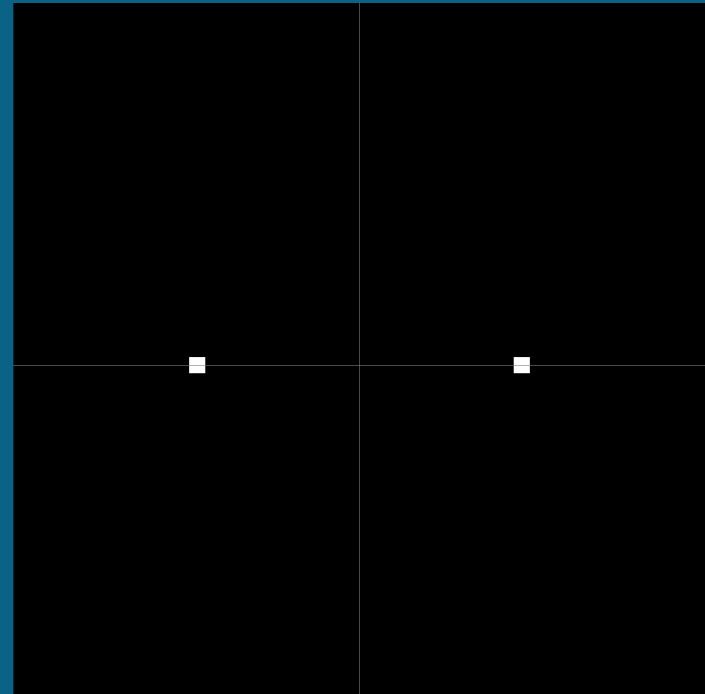
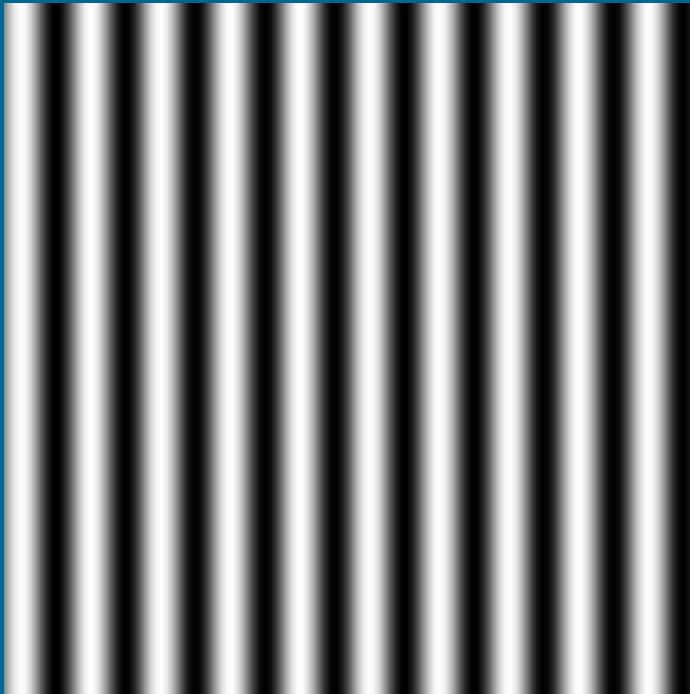
fázové rychlosti



grupové rychlosti

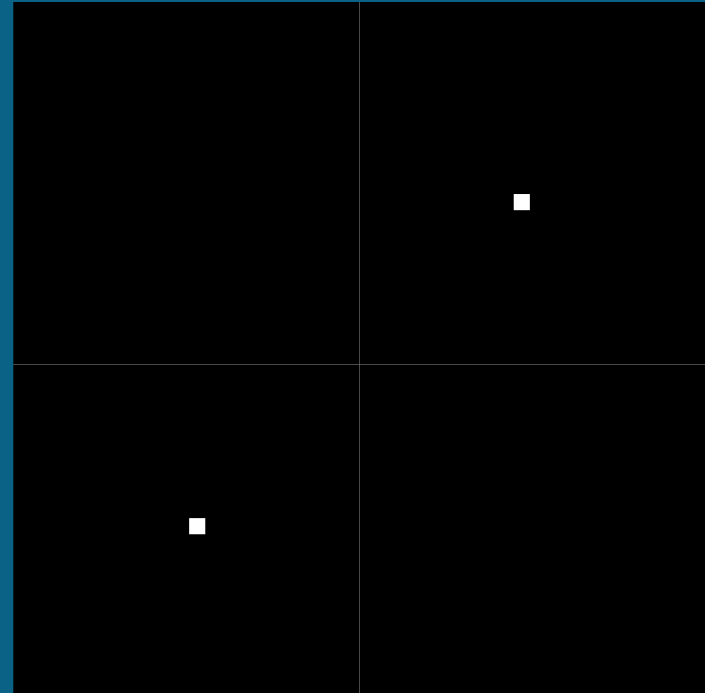


## Fourierova transformace ve 2D

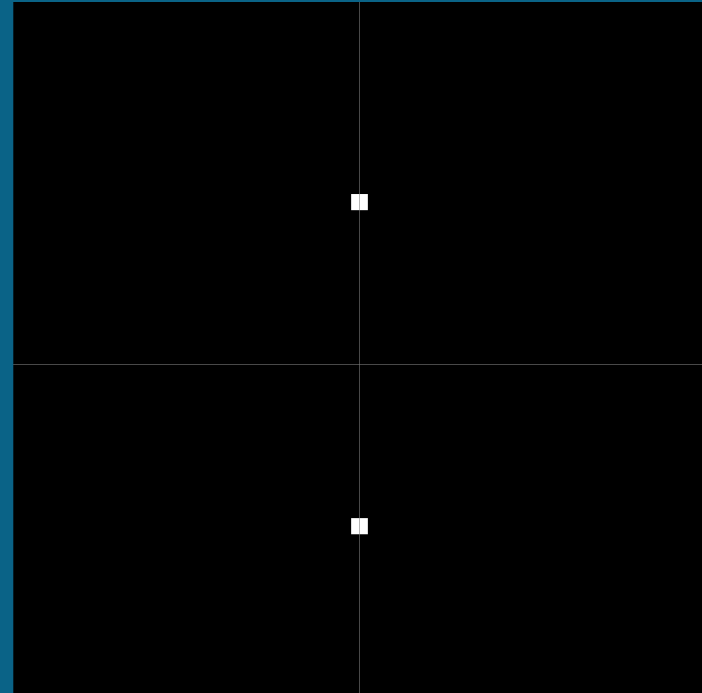




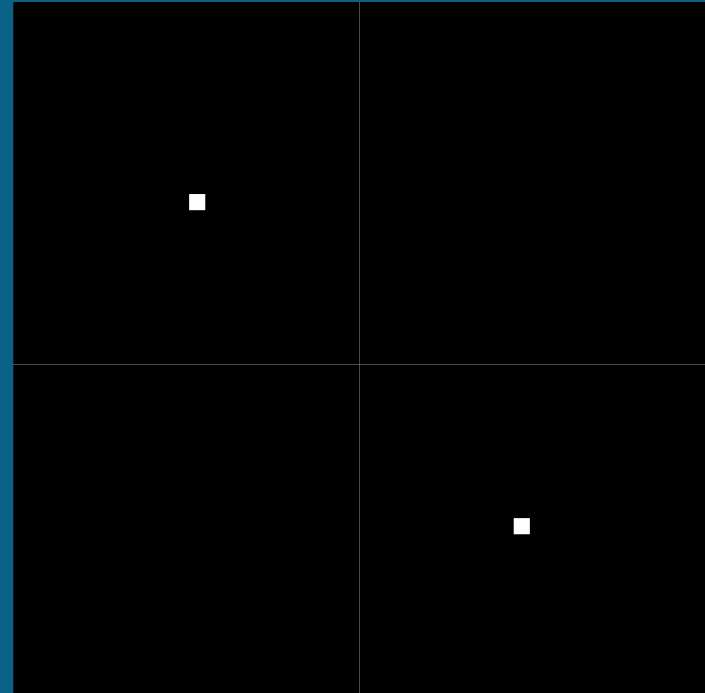
## Fourierova transformace ve 2D



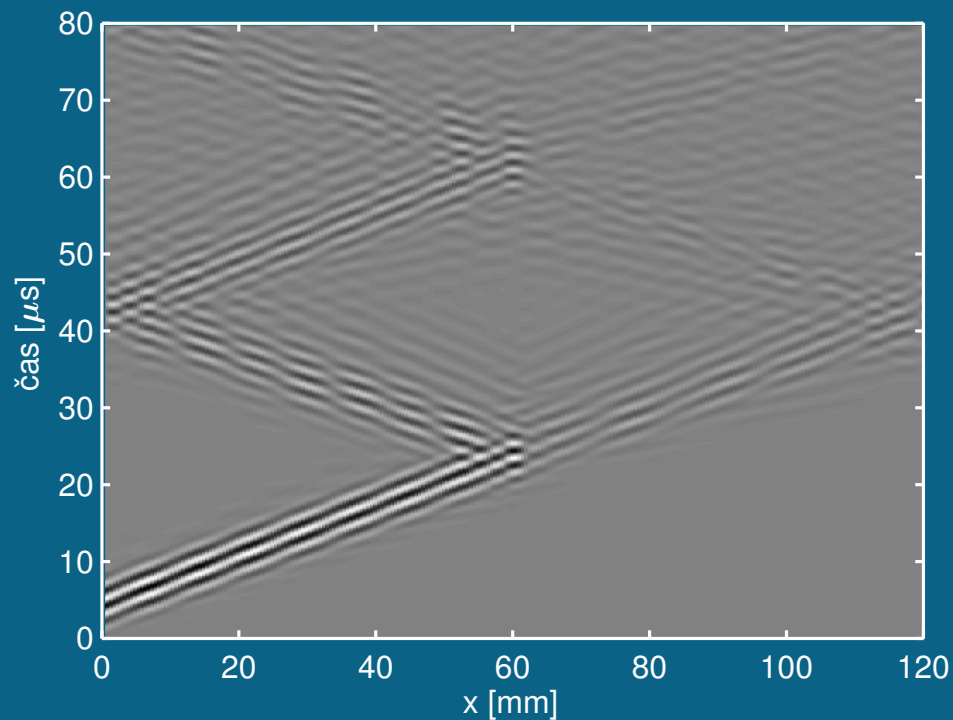
## Fourierova transformace ve 2D



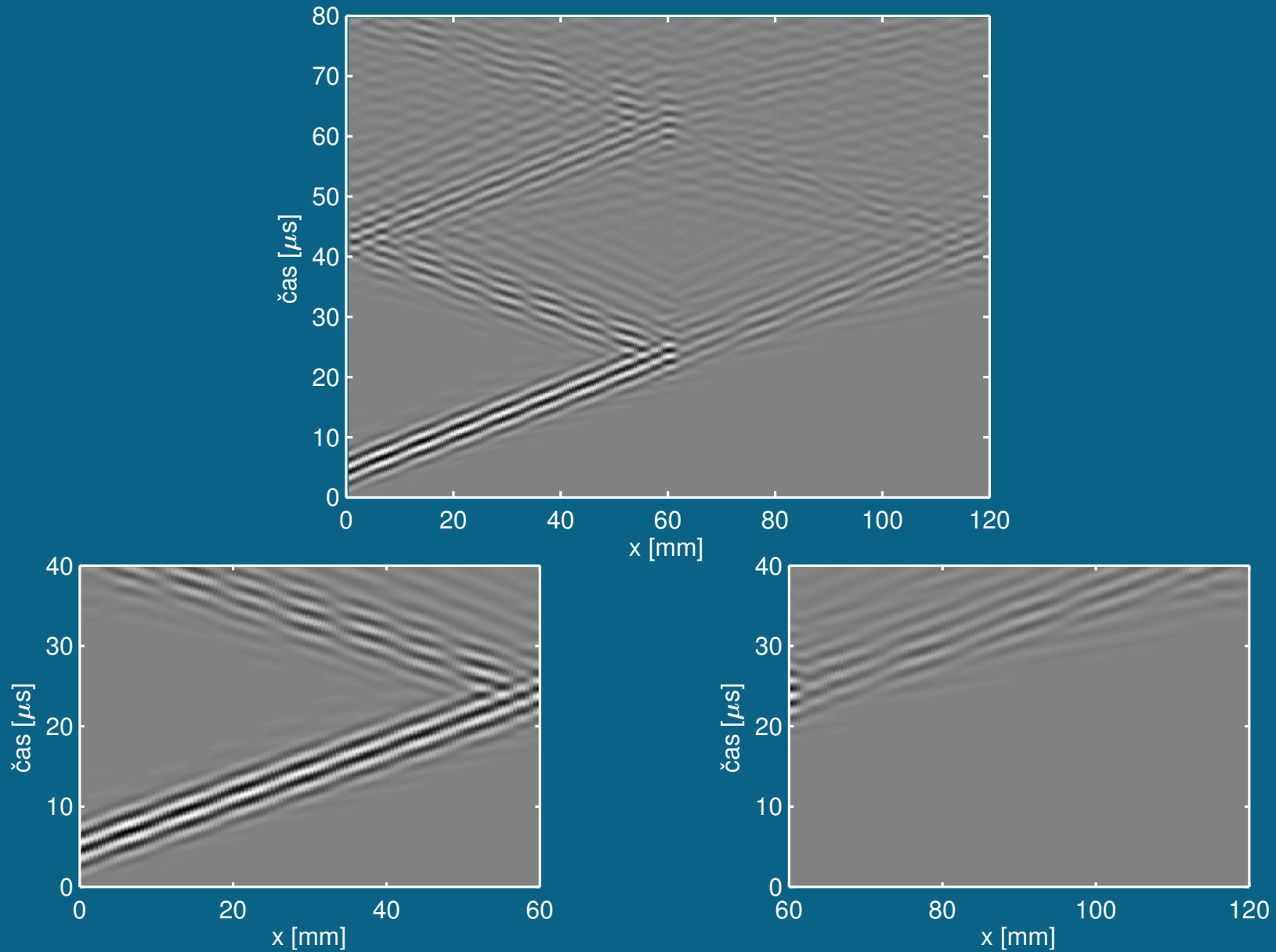
## Fourierova transformace ve 2D



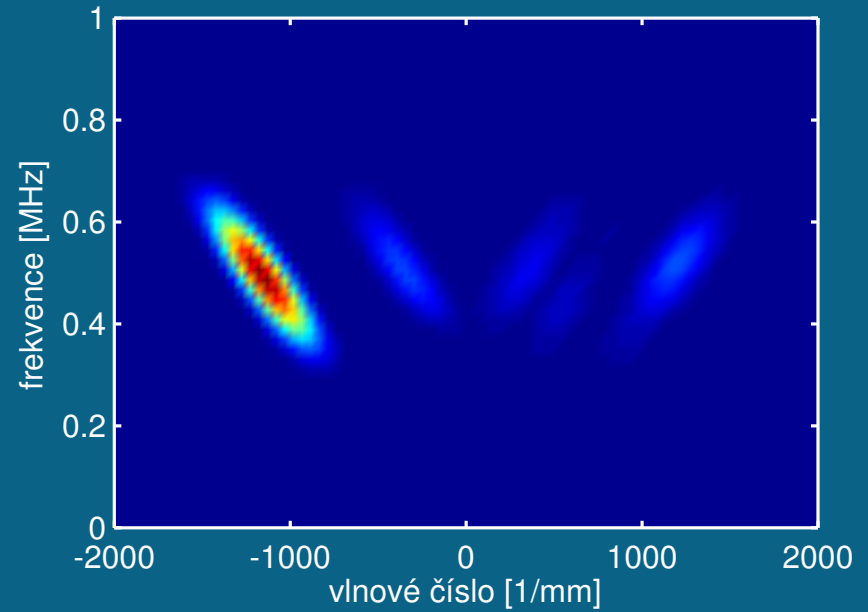
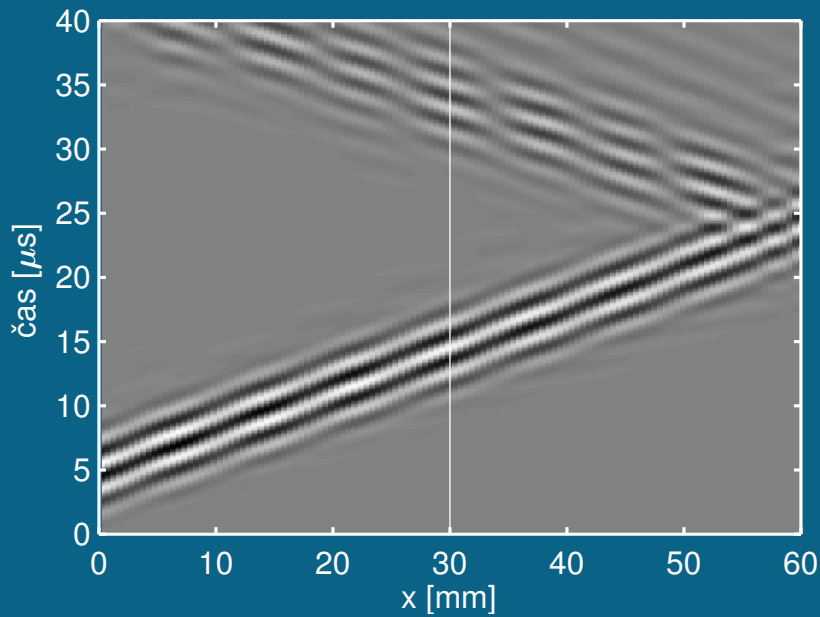
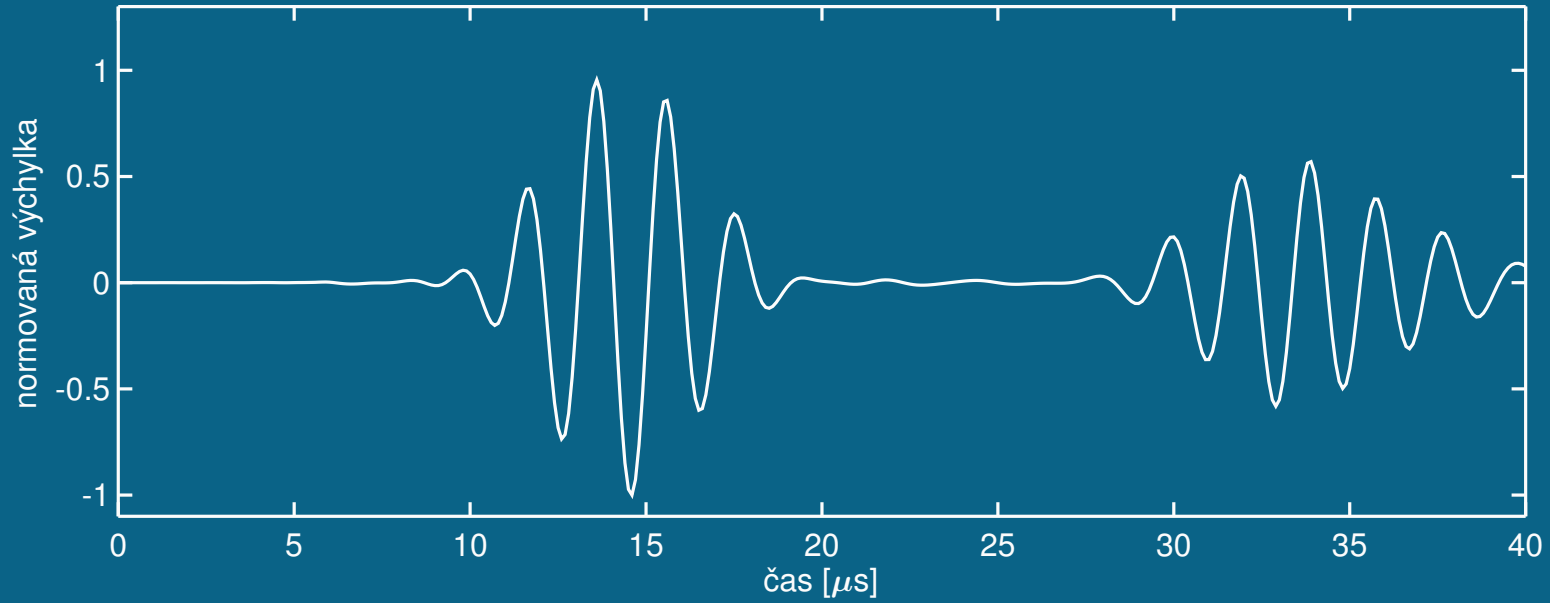
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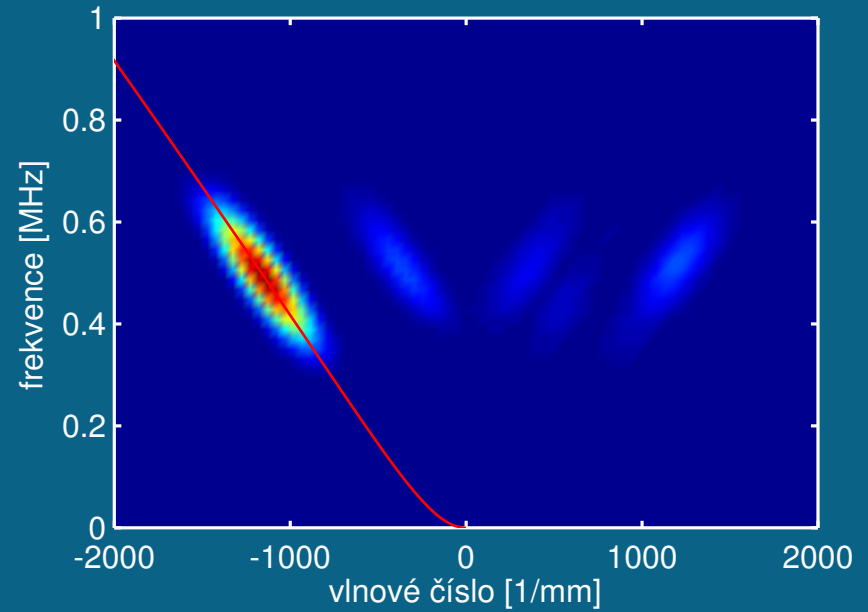
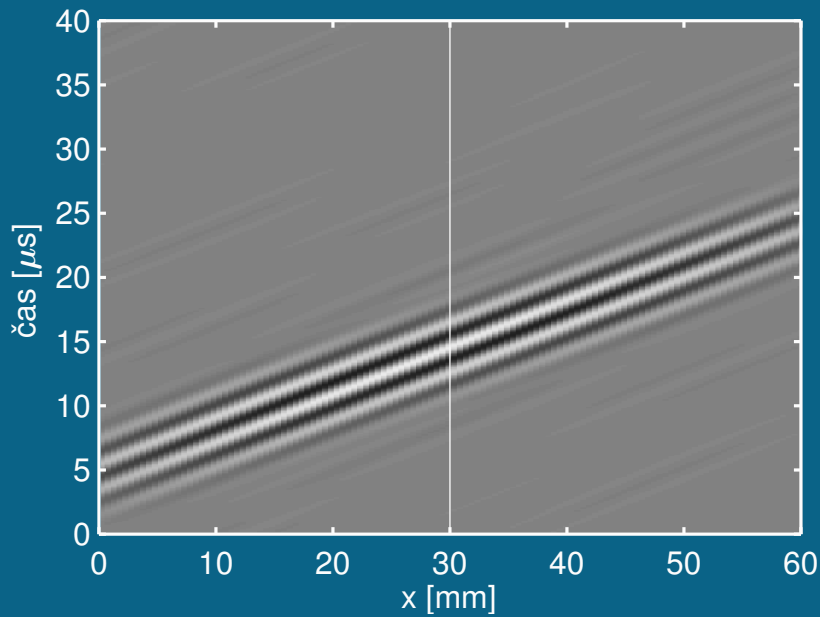
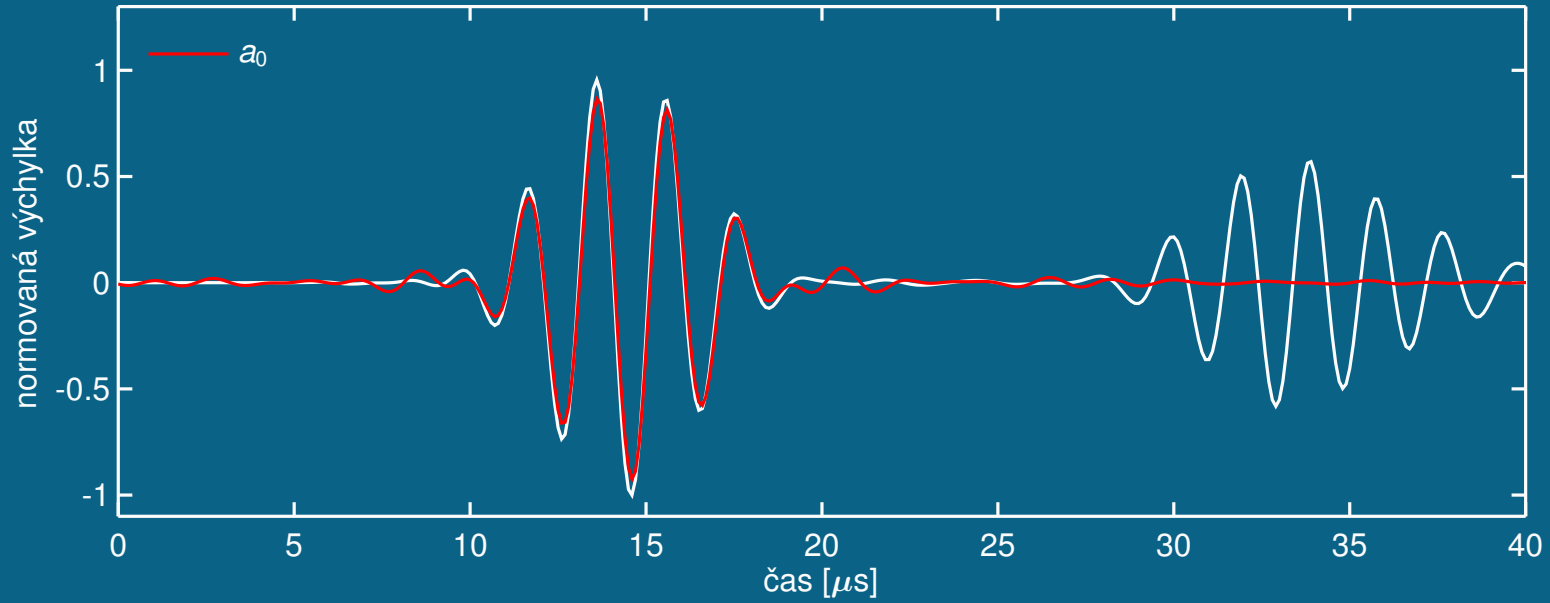
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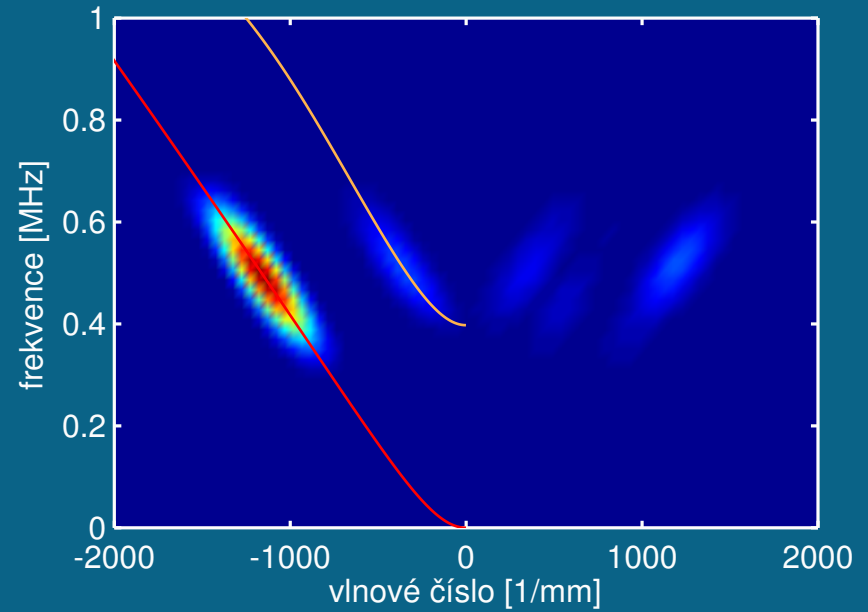
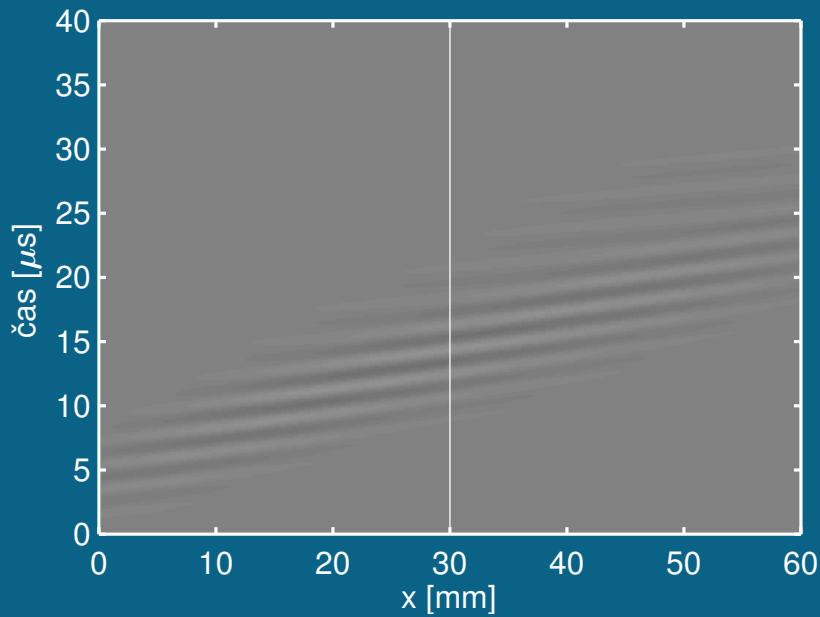
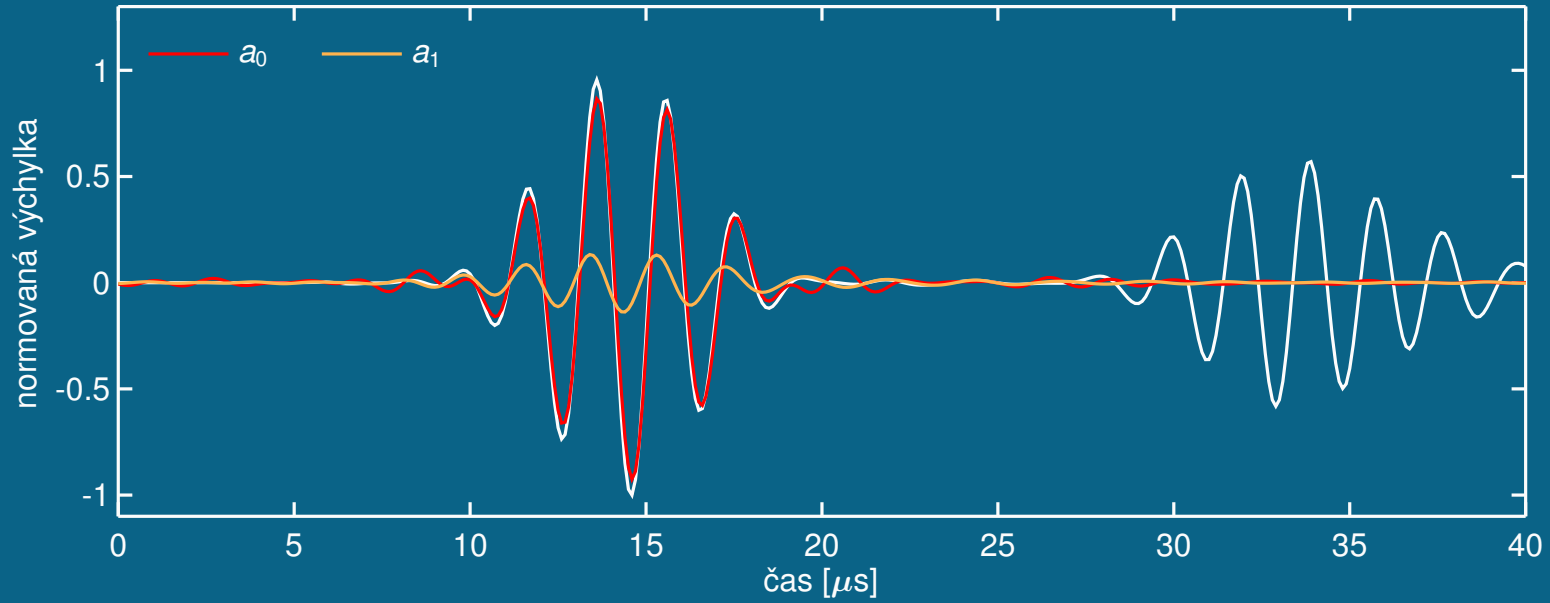
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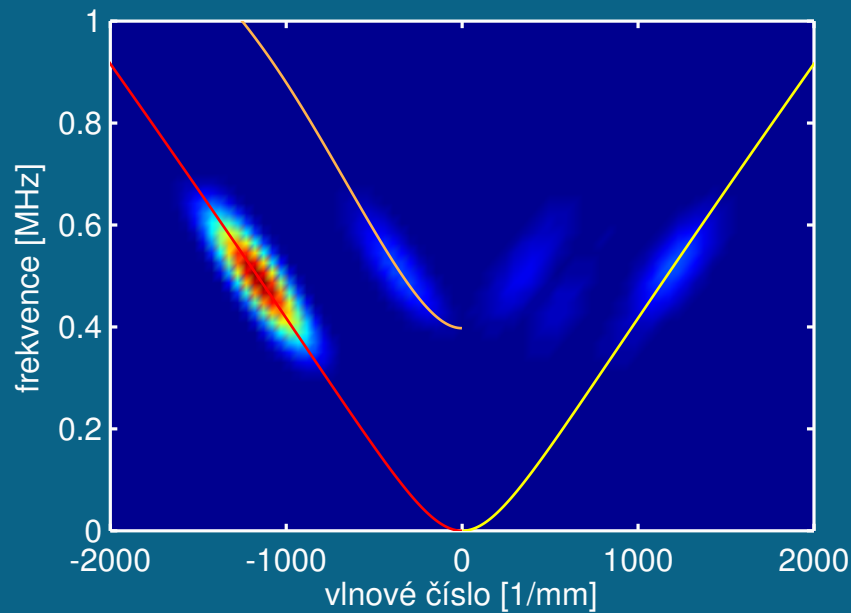
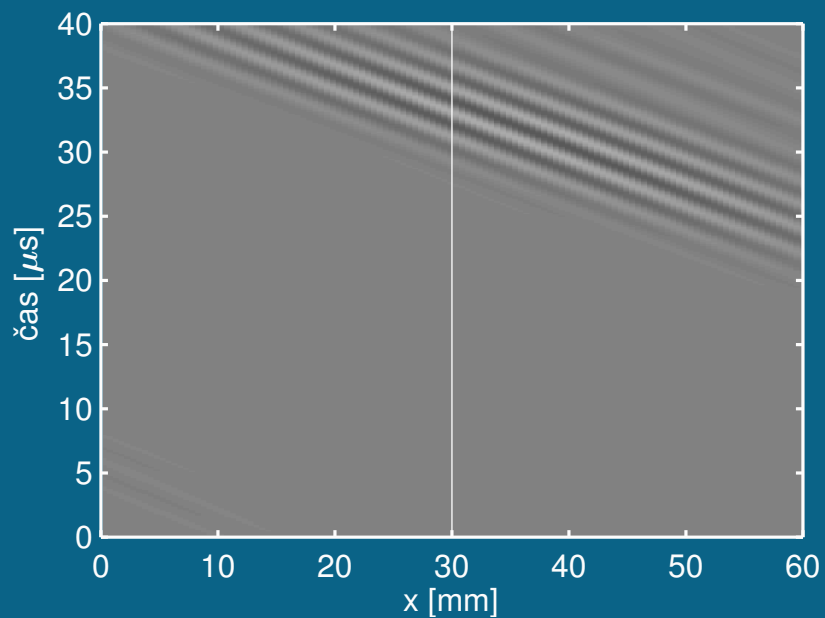
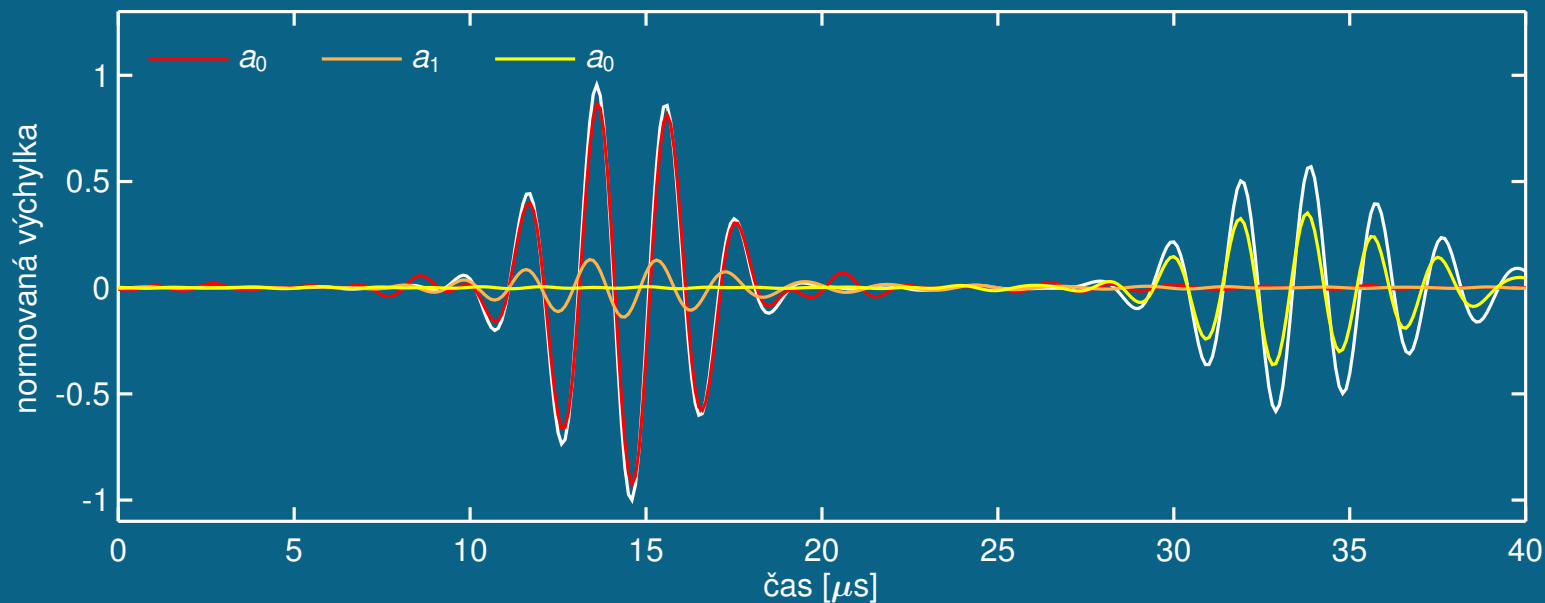


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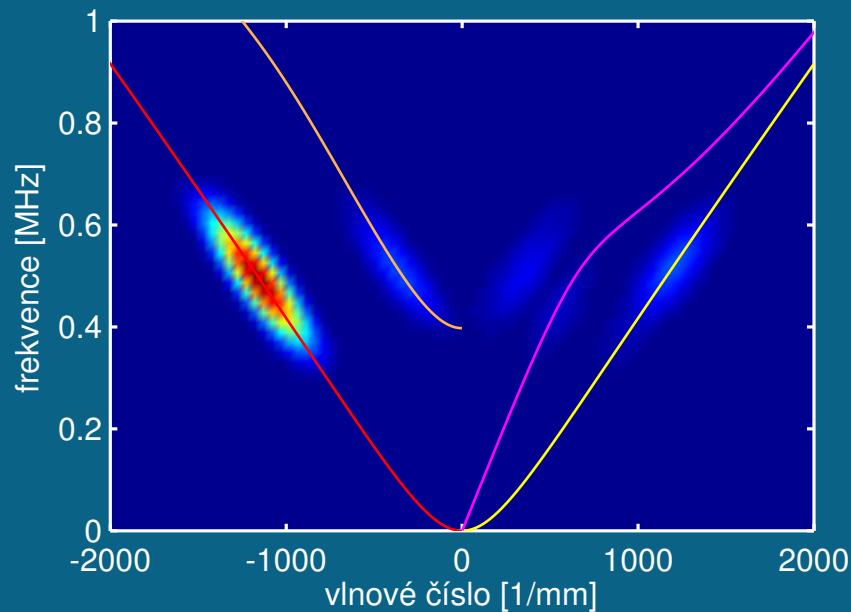
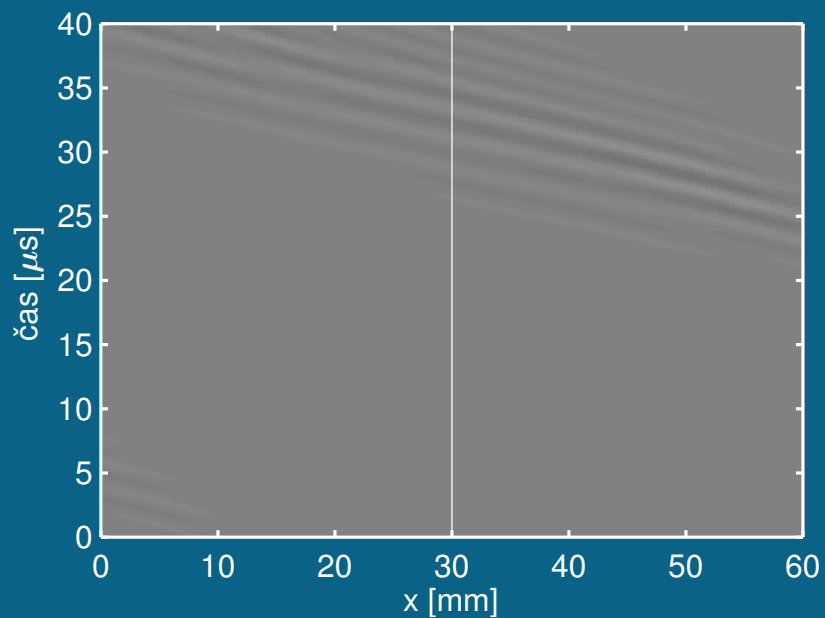
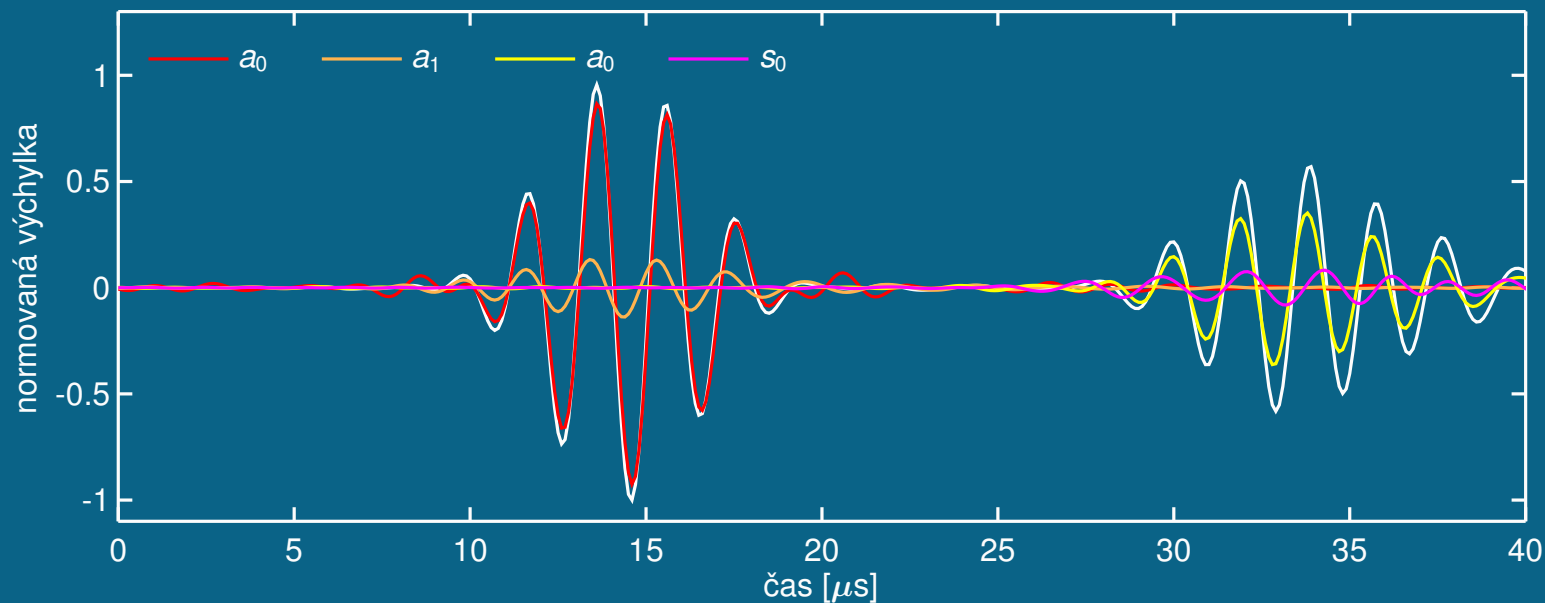




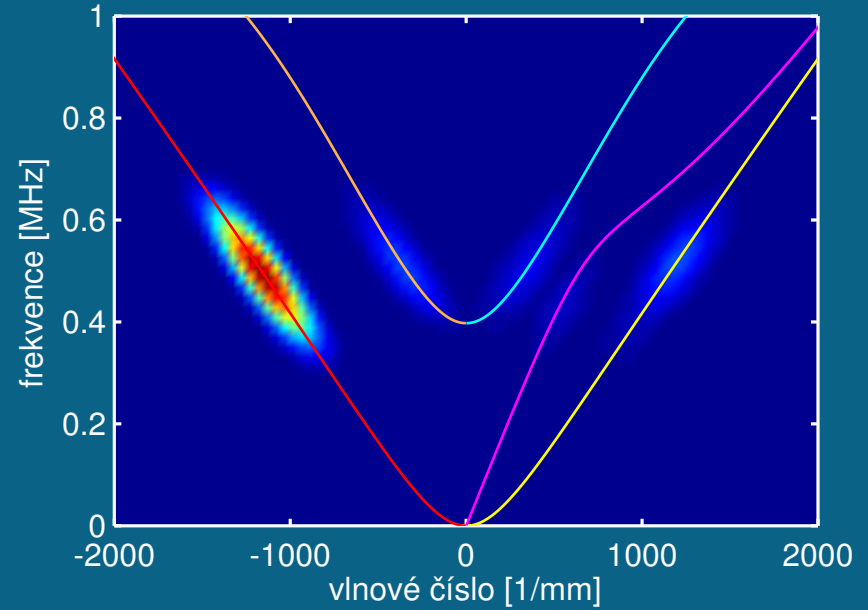
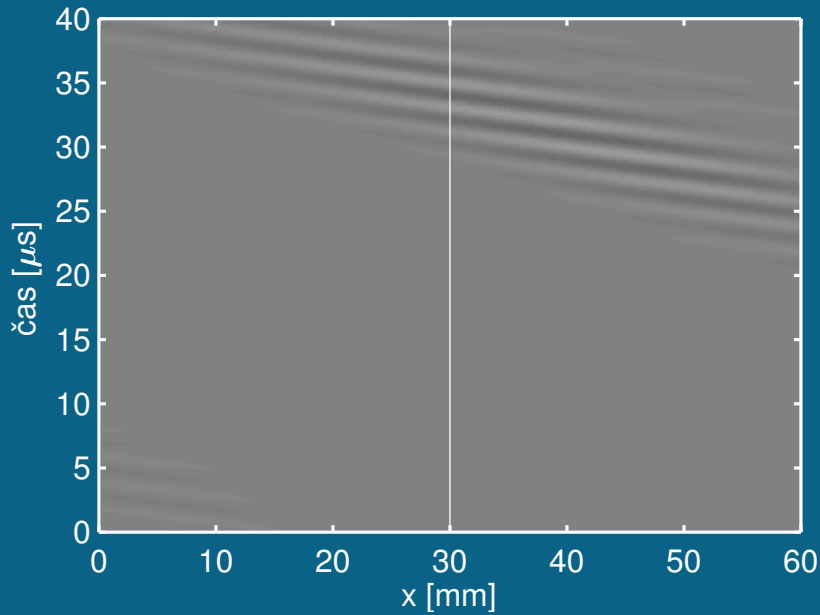
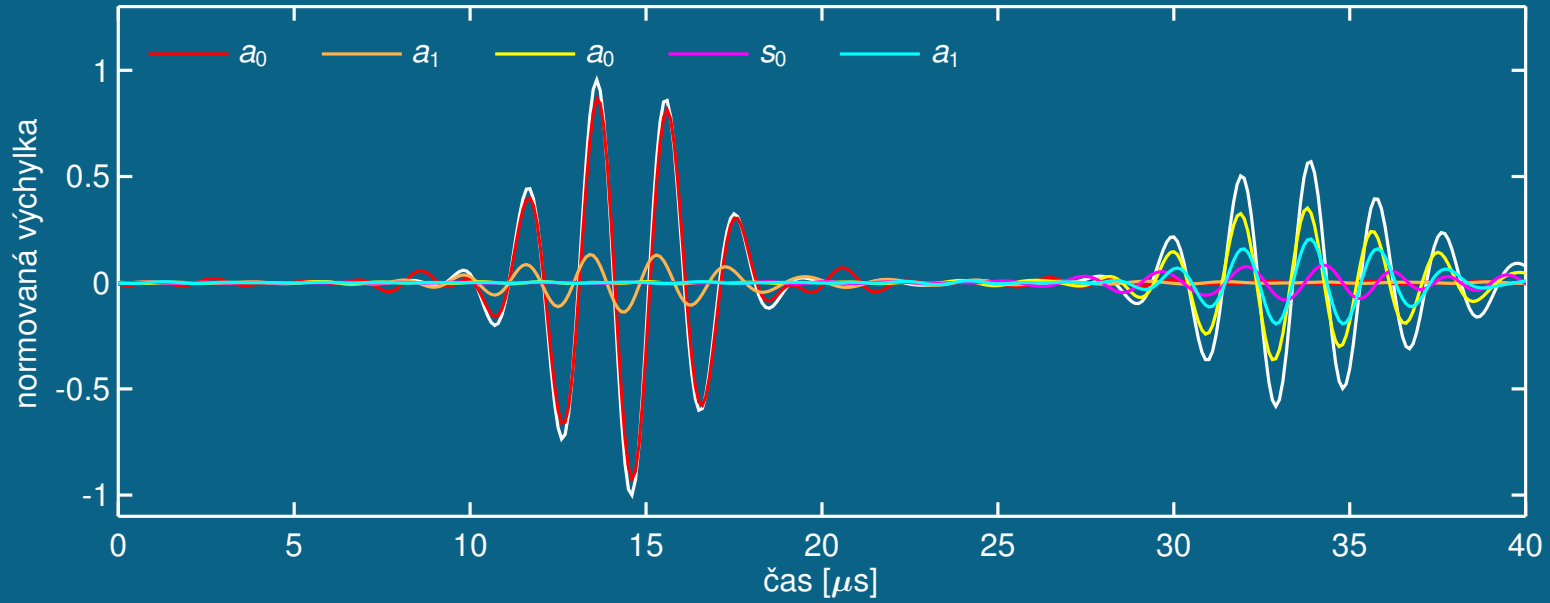
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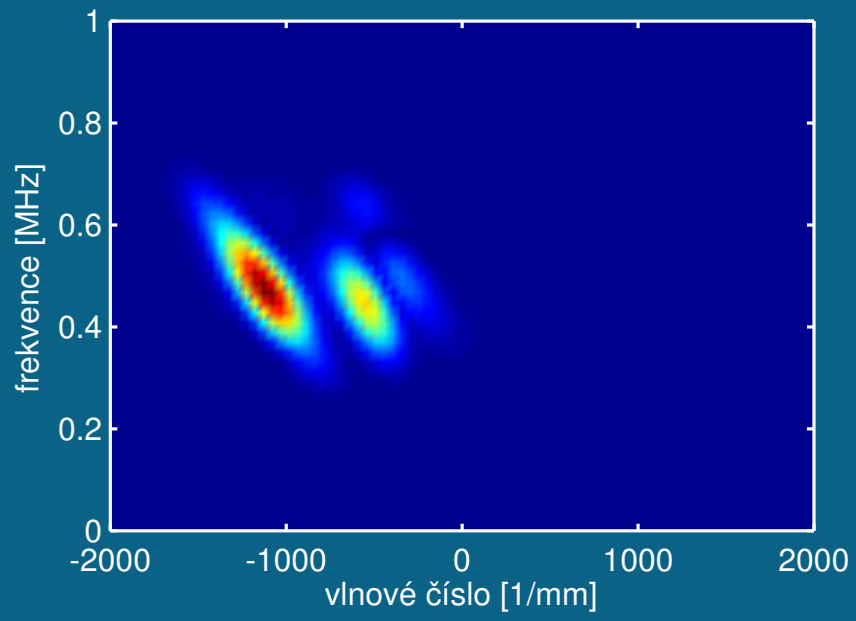
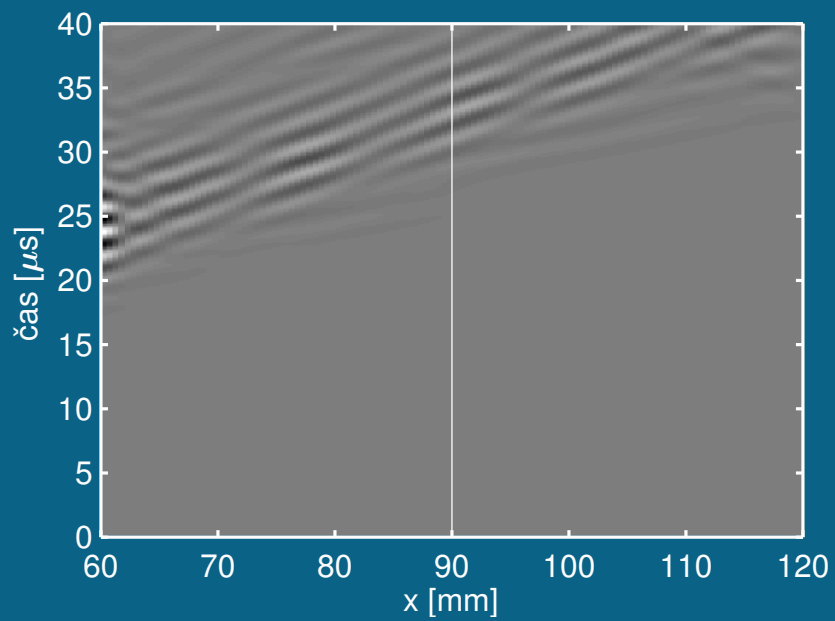
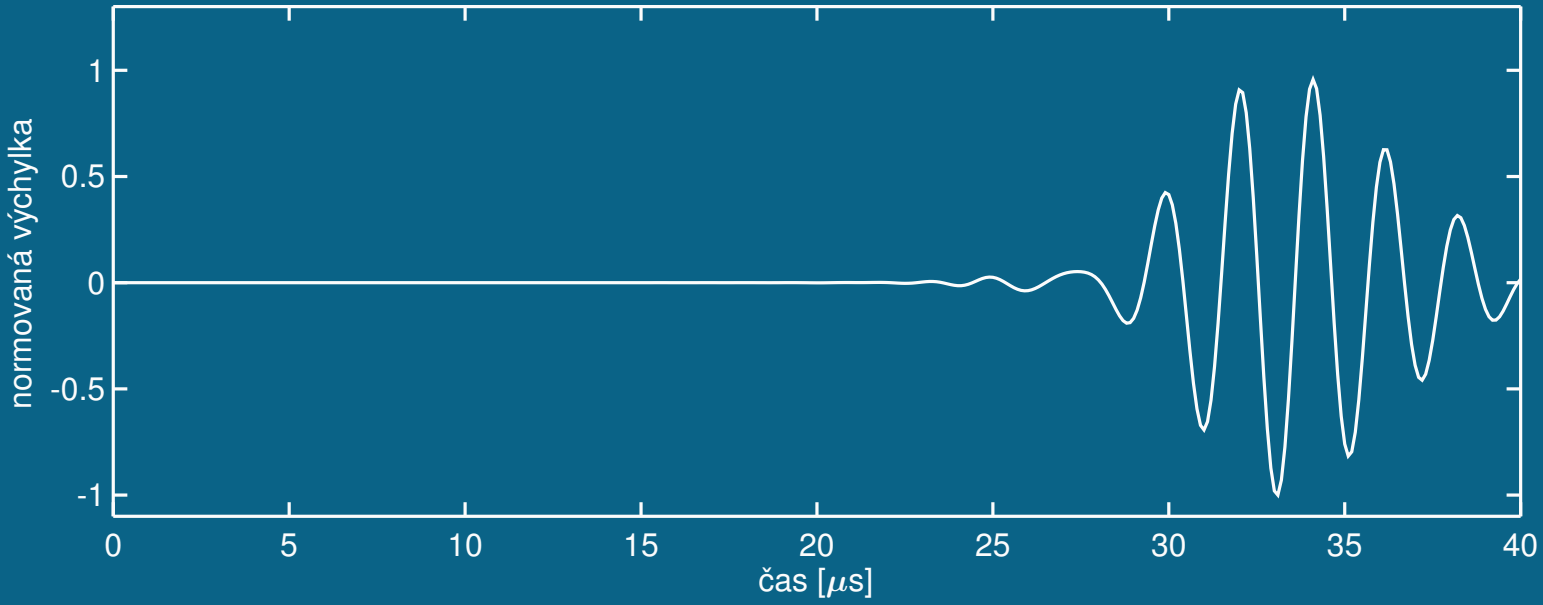
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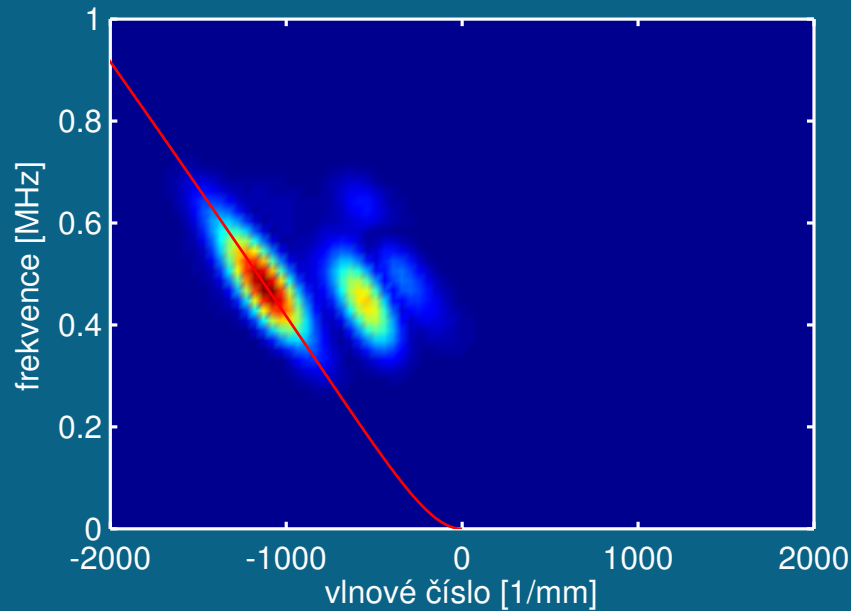
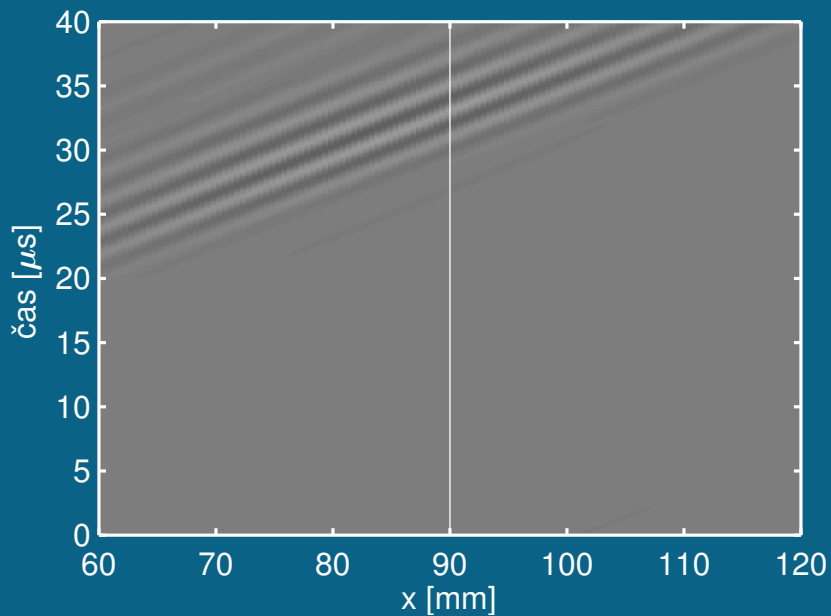
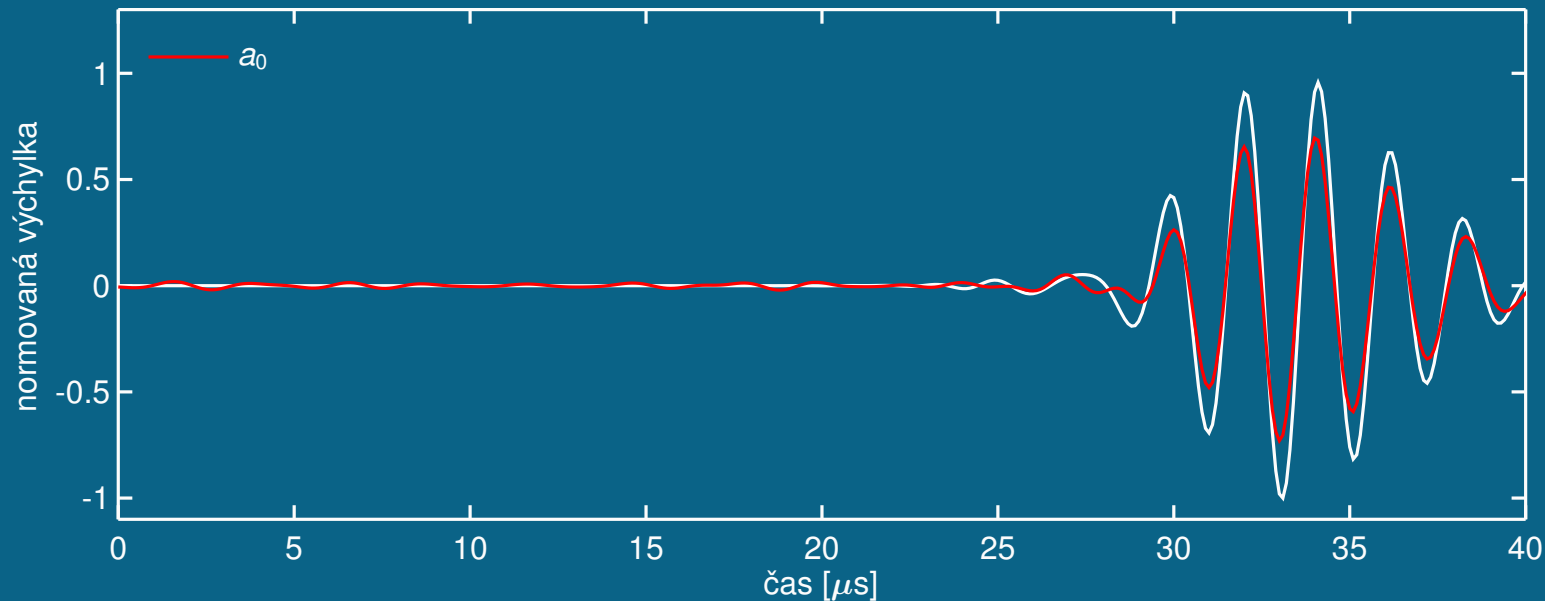
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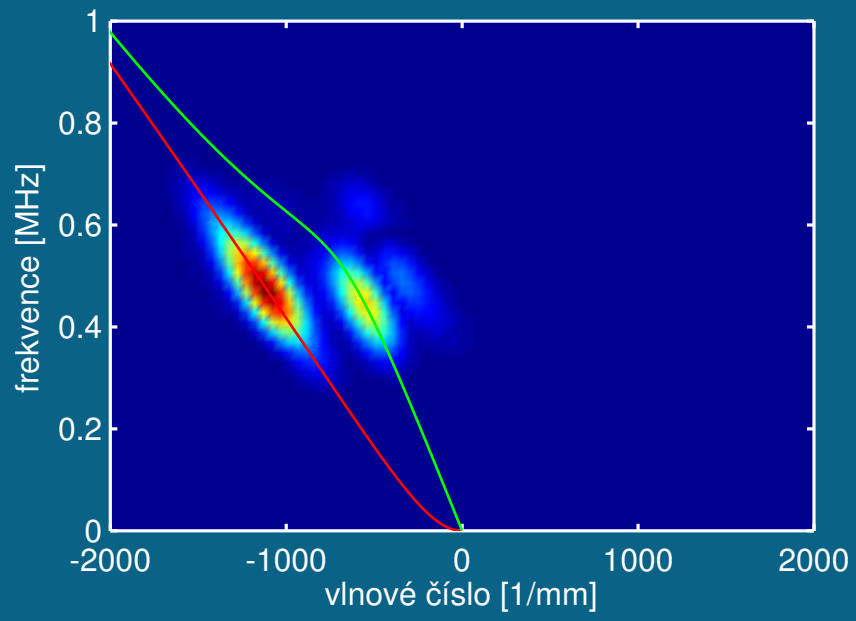
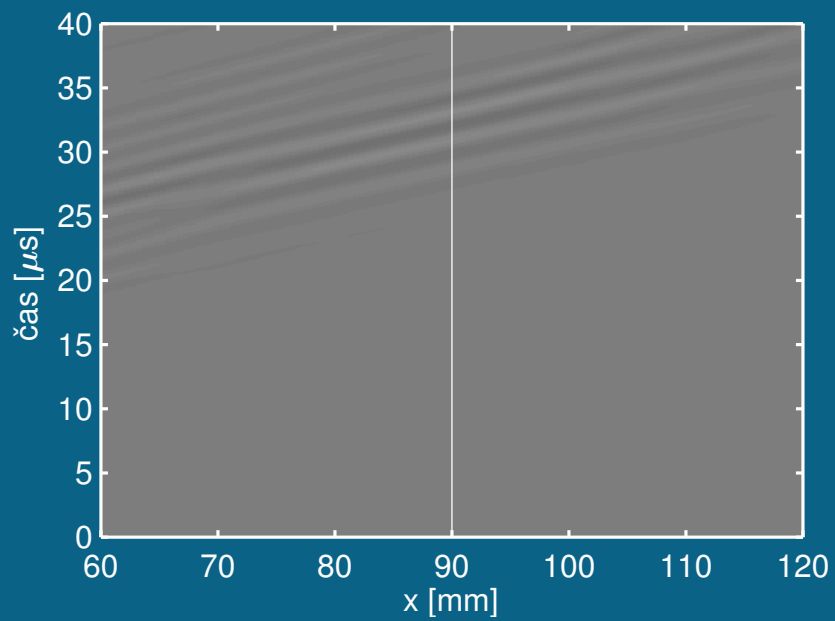
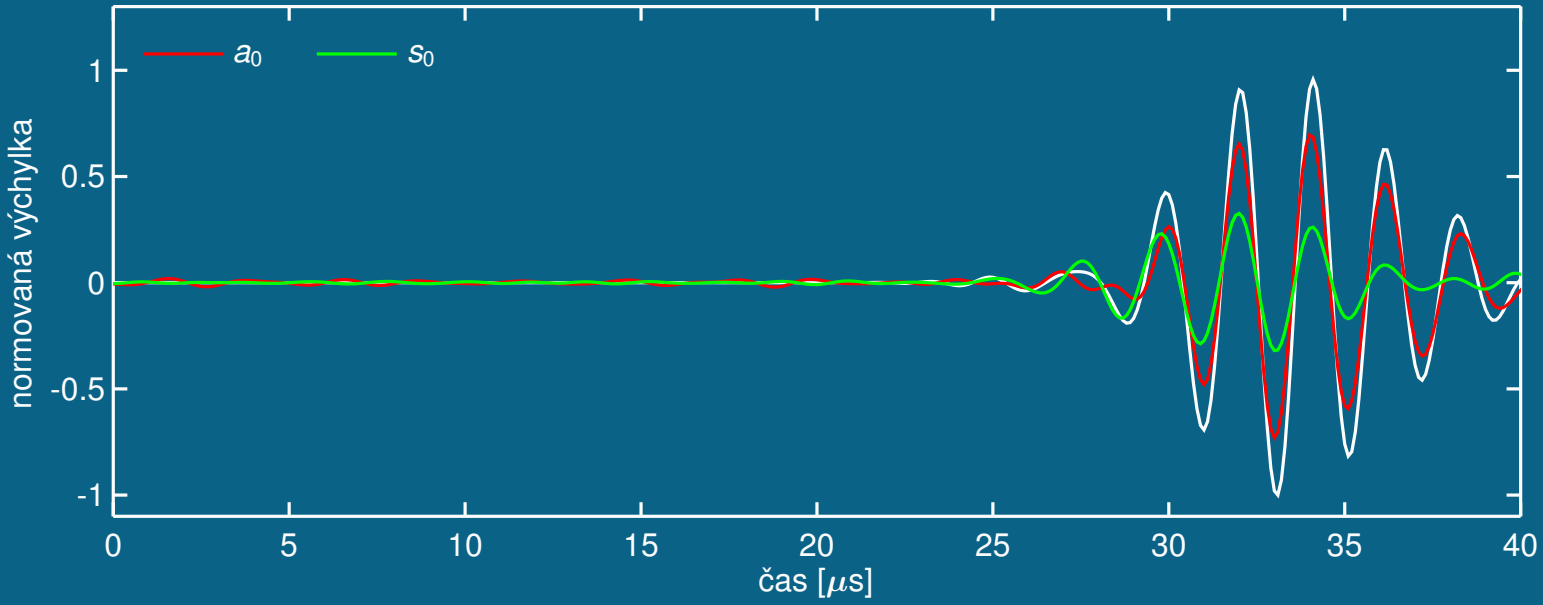
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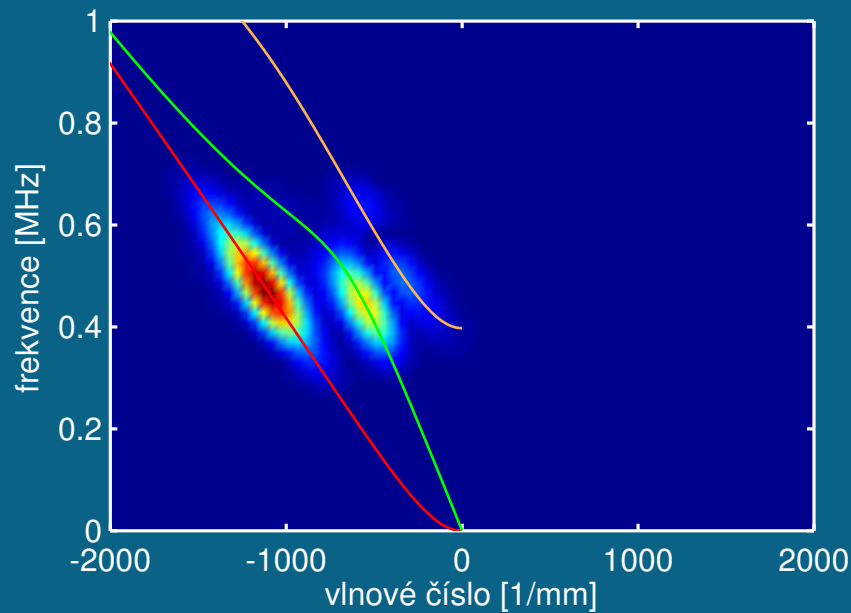
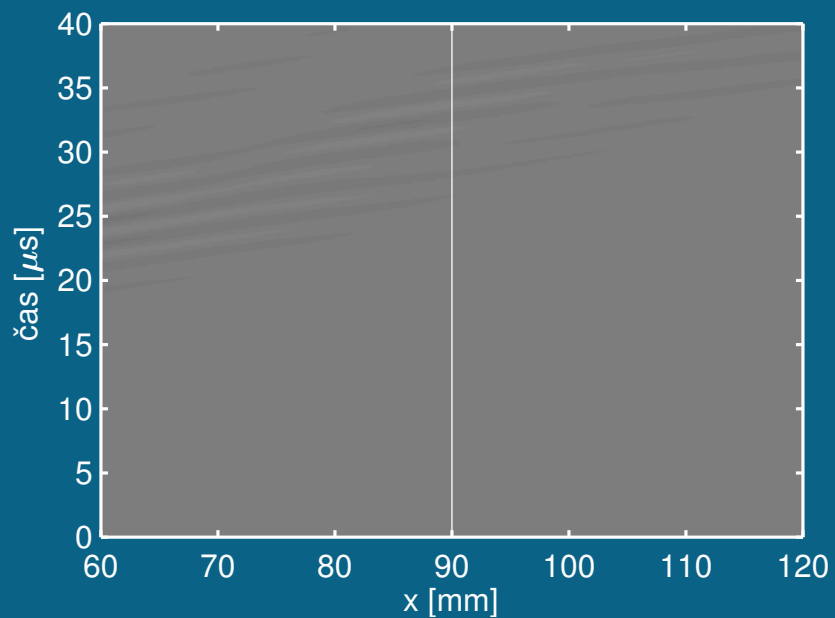
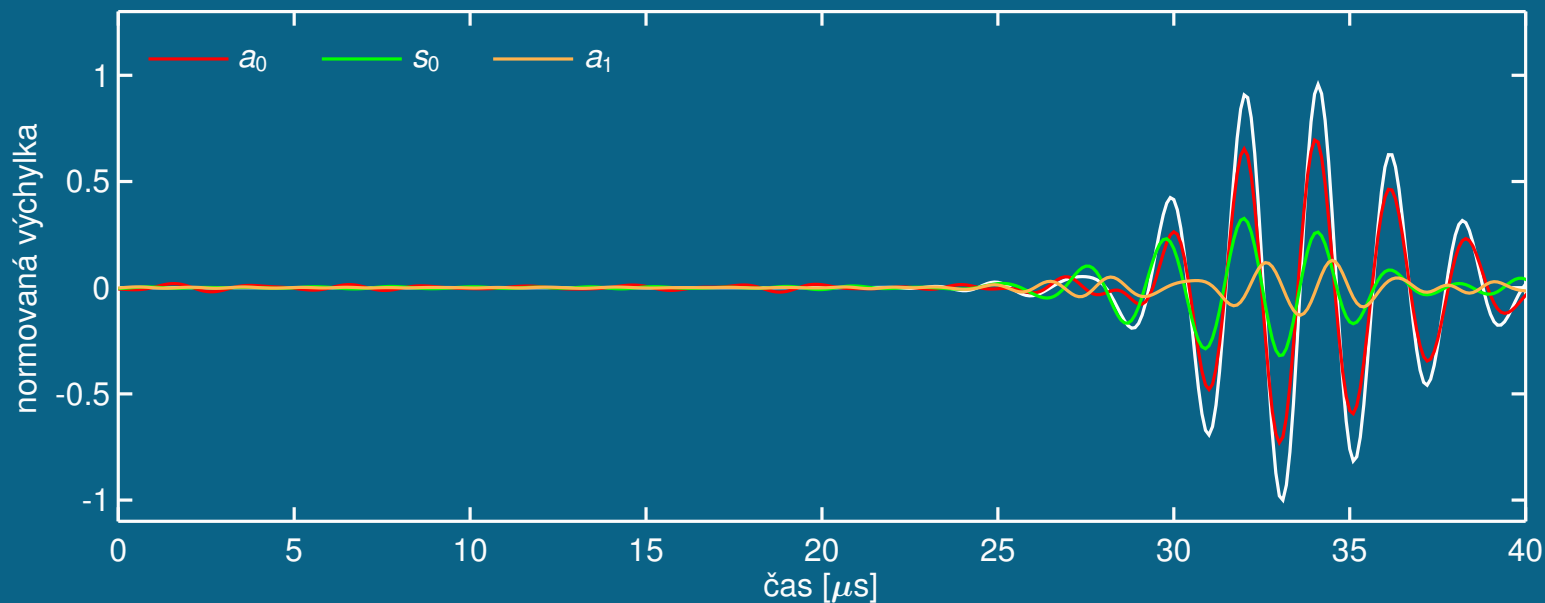
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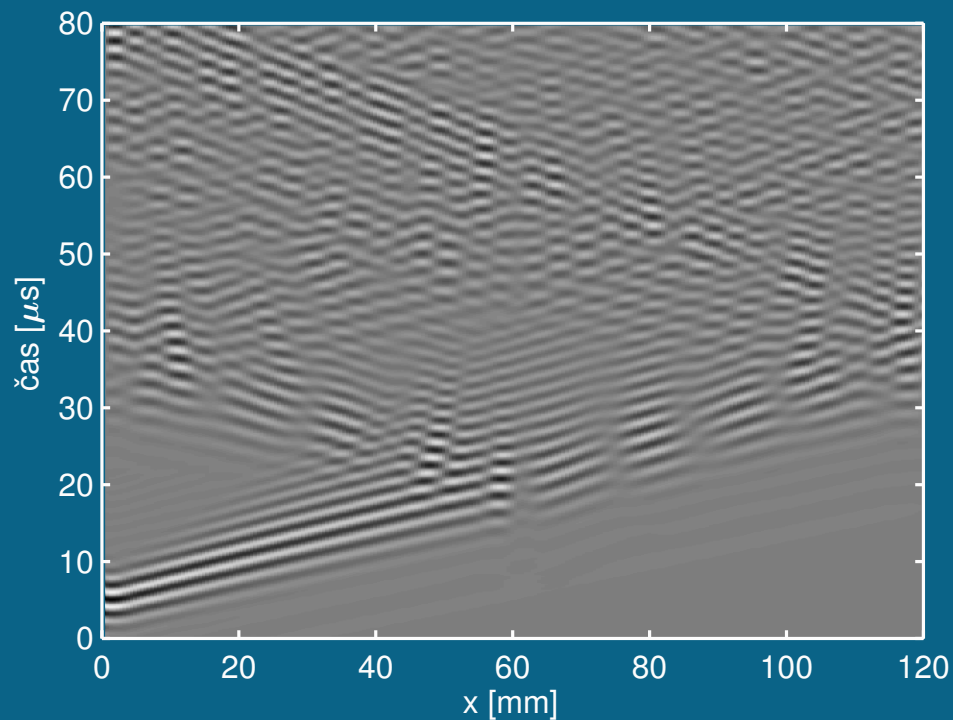
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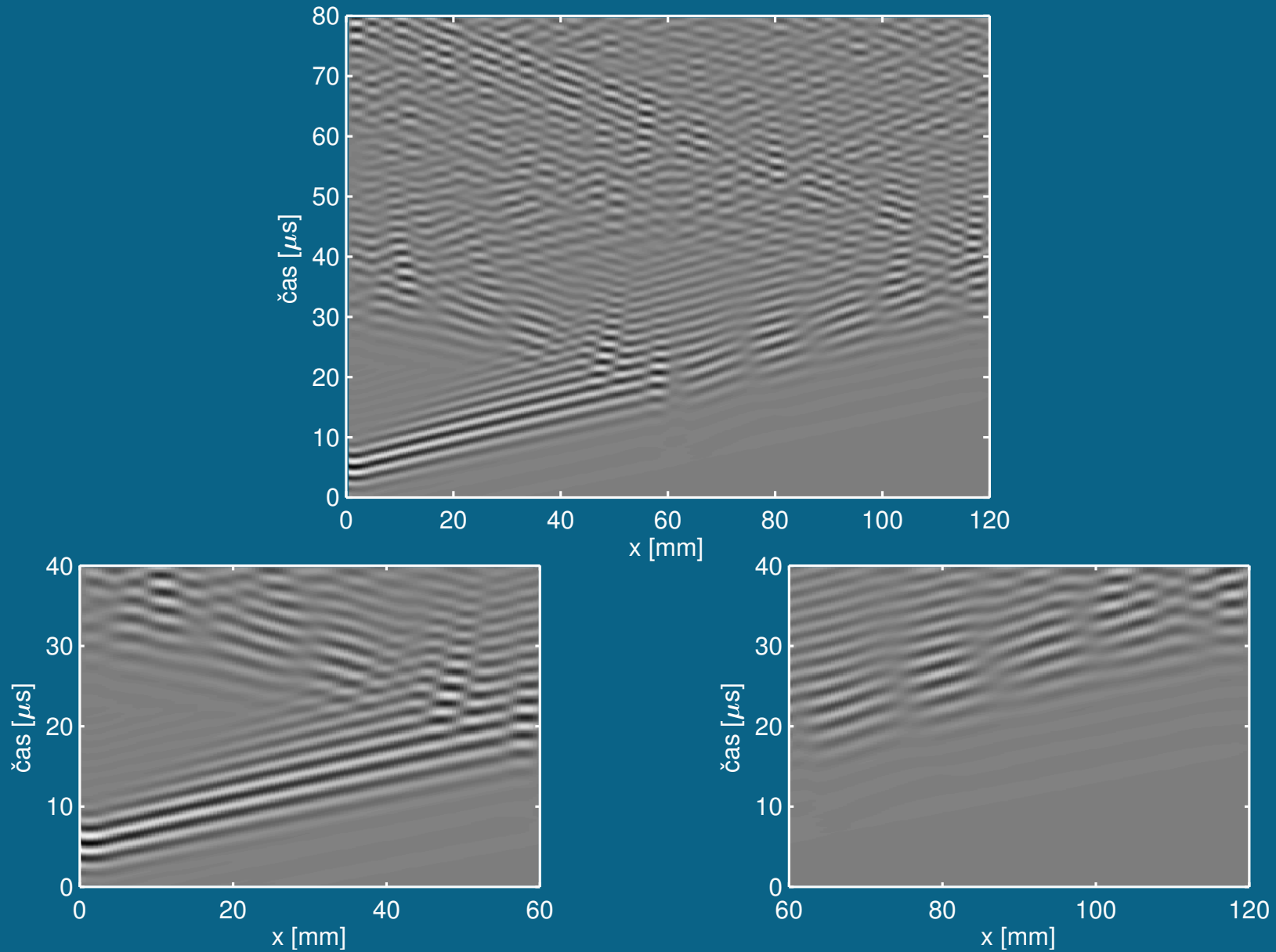


Mód buzení:  $s_0$ ; šířka vrubu: 0,5 mm; hloubka vrubu: 2 mm

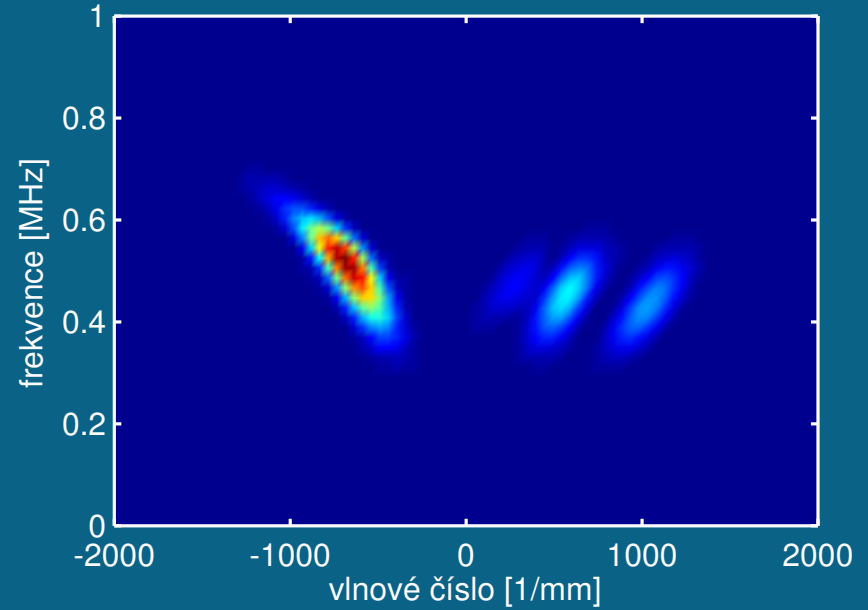
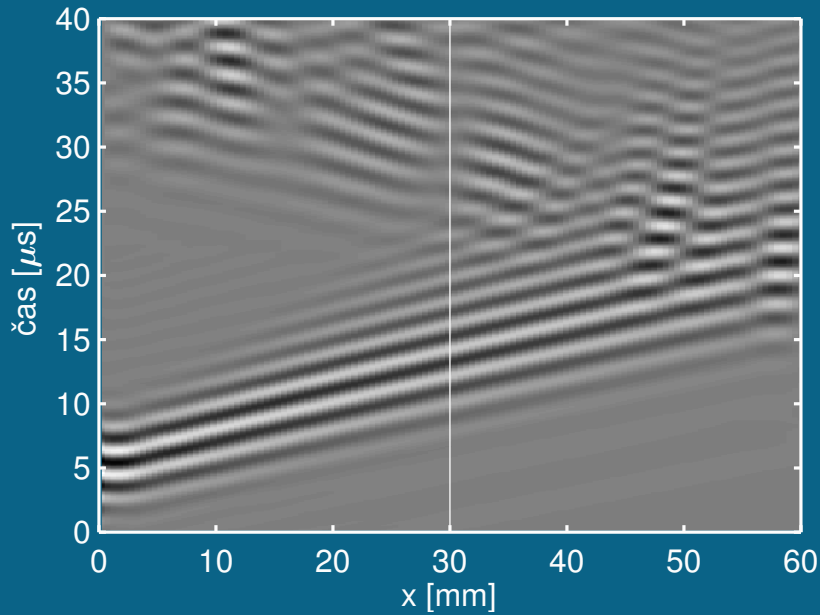
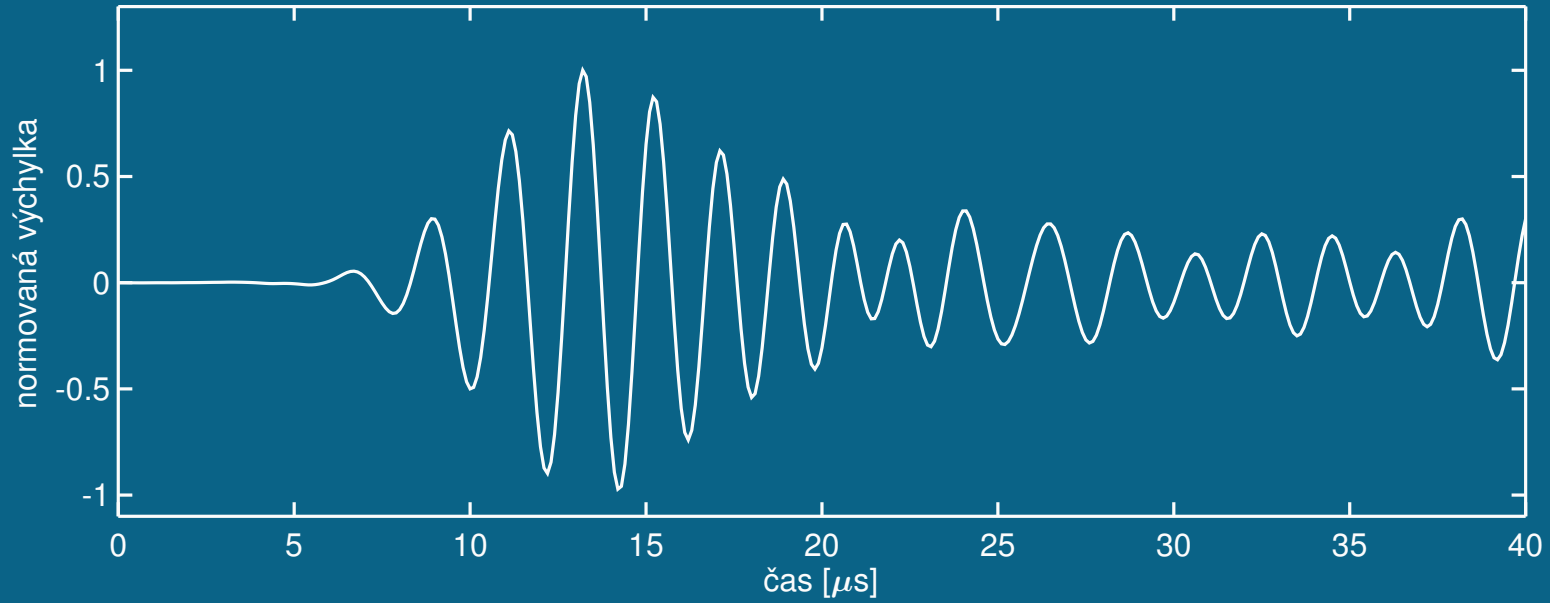




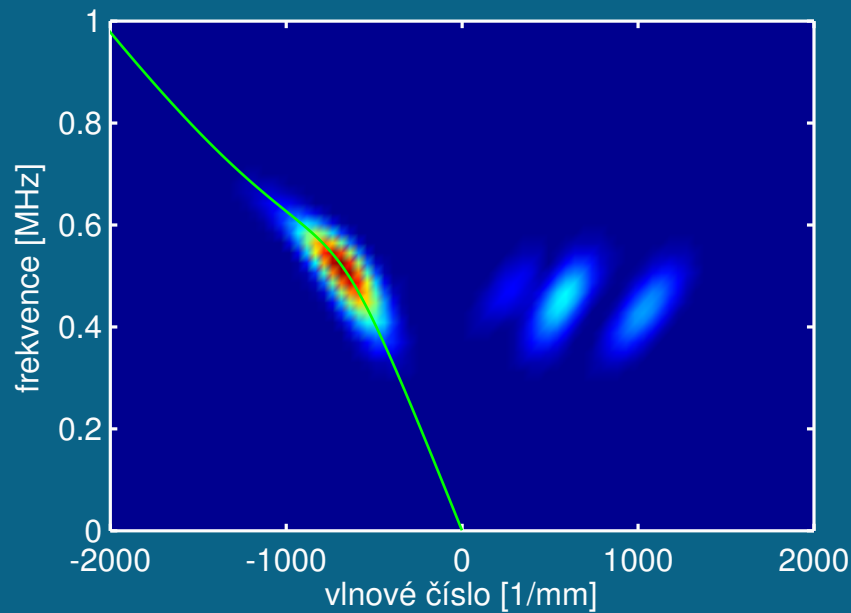
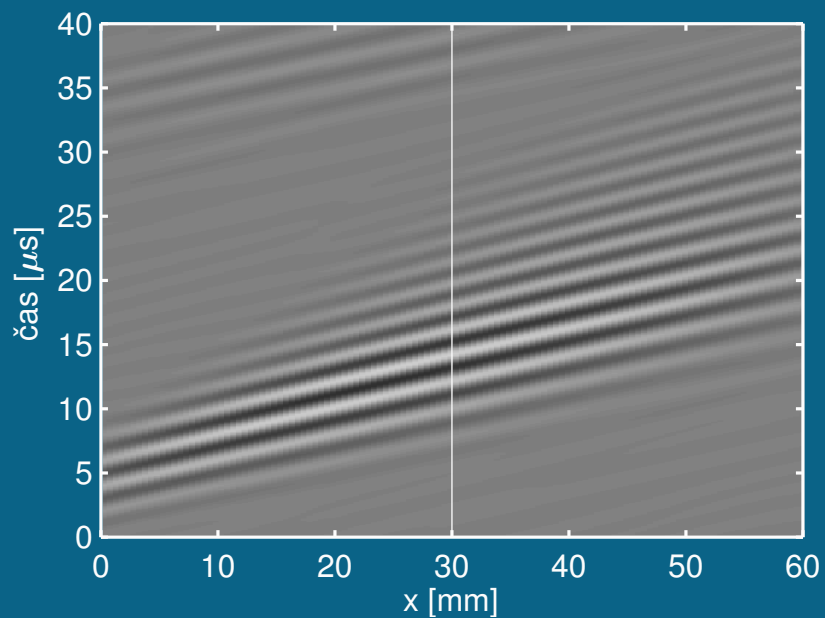
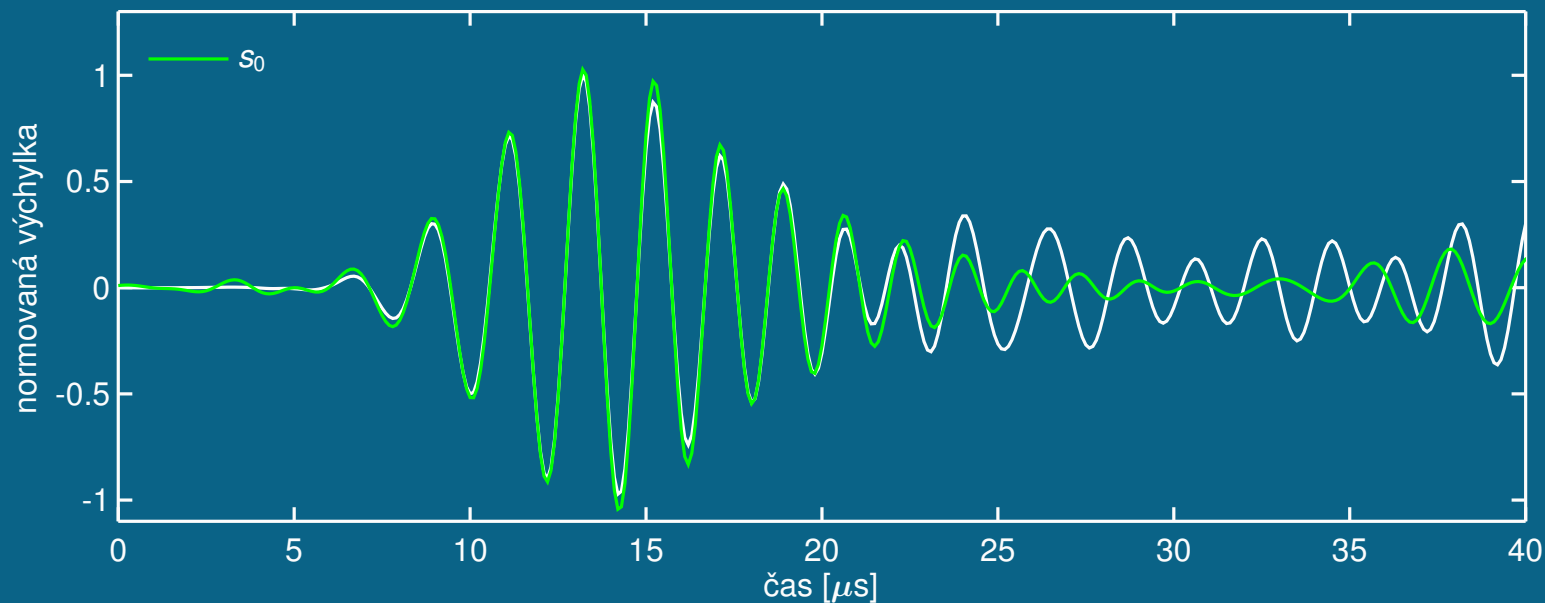
Mód buzení: s0; šířka vrubu: 0,5 mm; hloubka vrubu: 2 mm



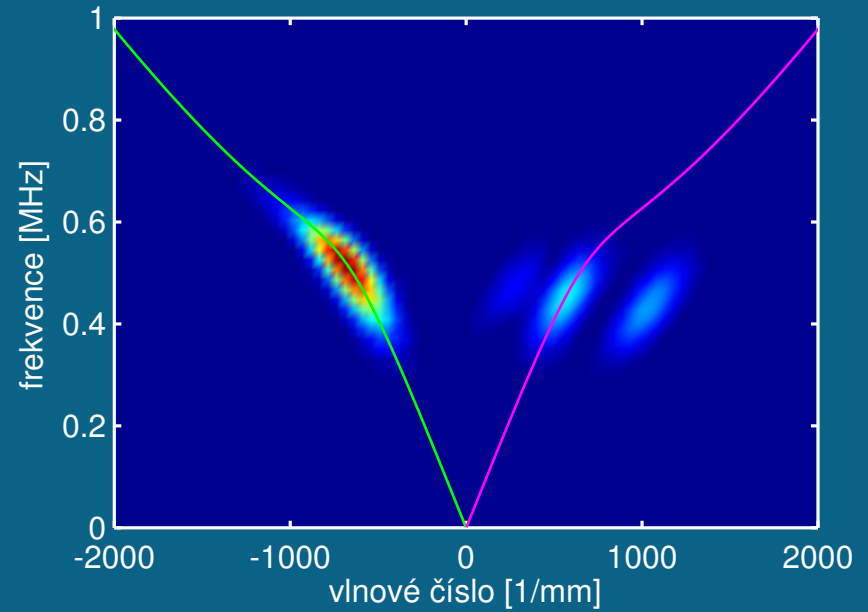
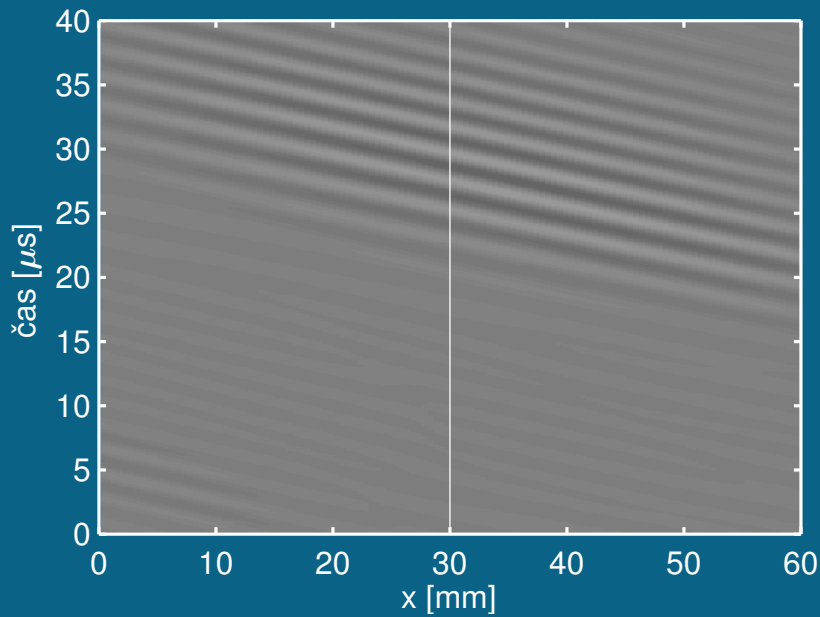
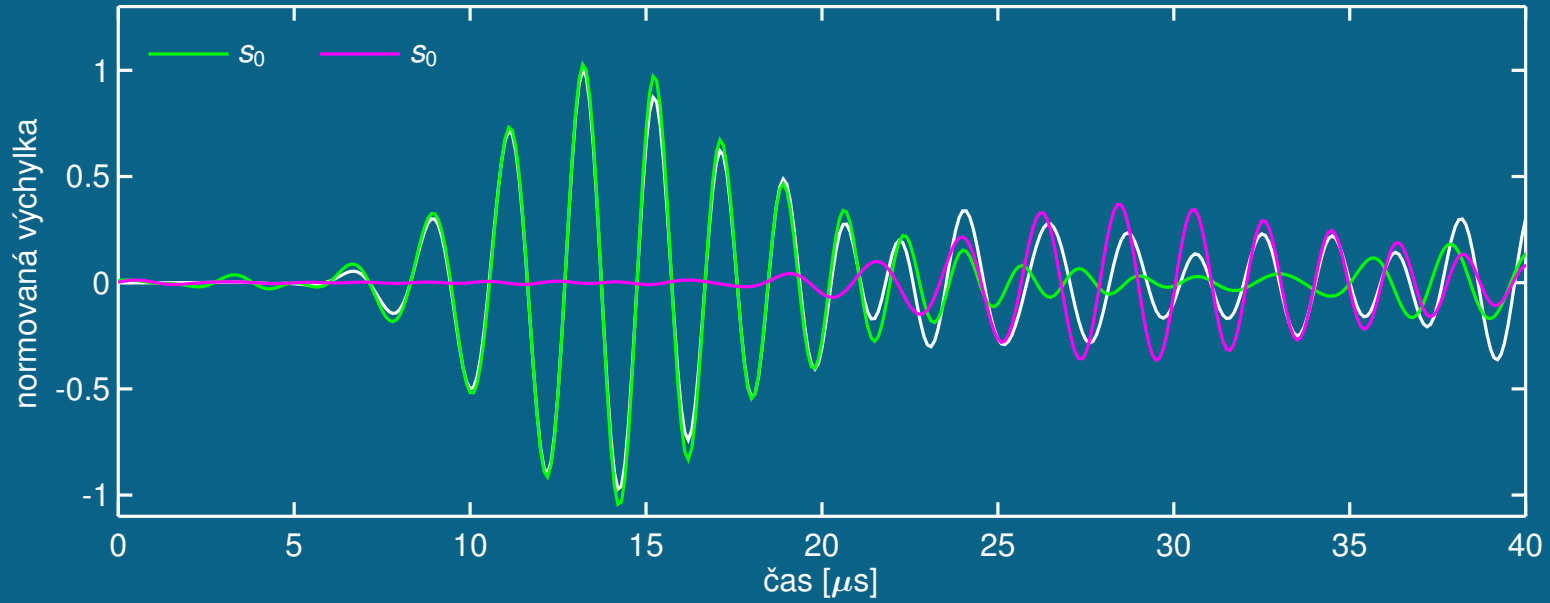
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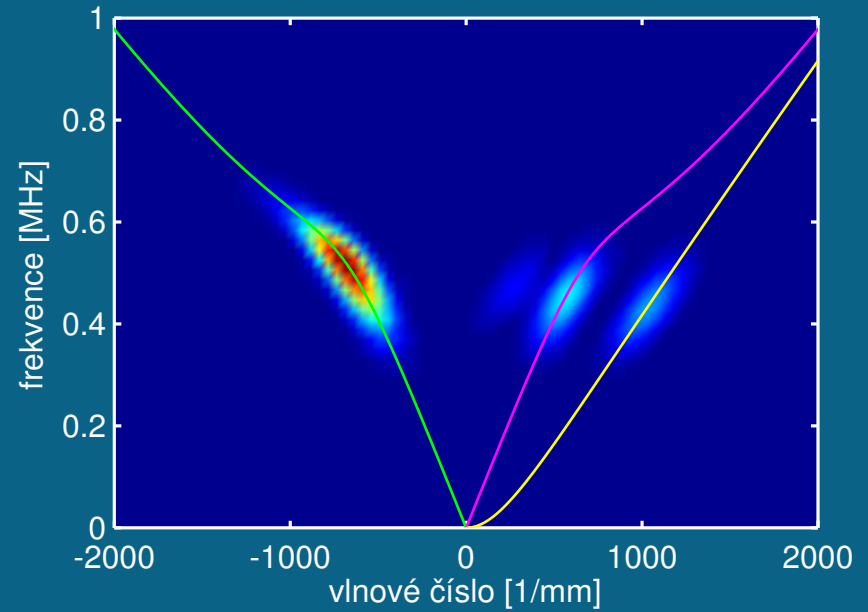
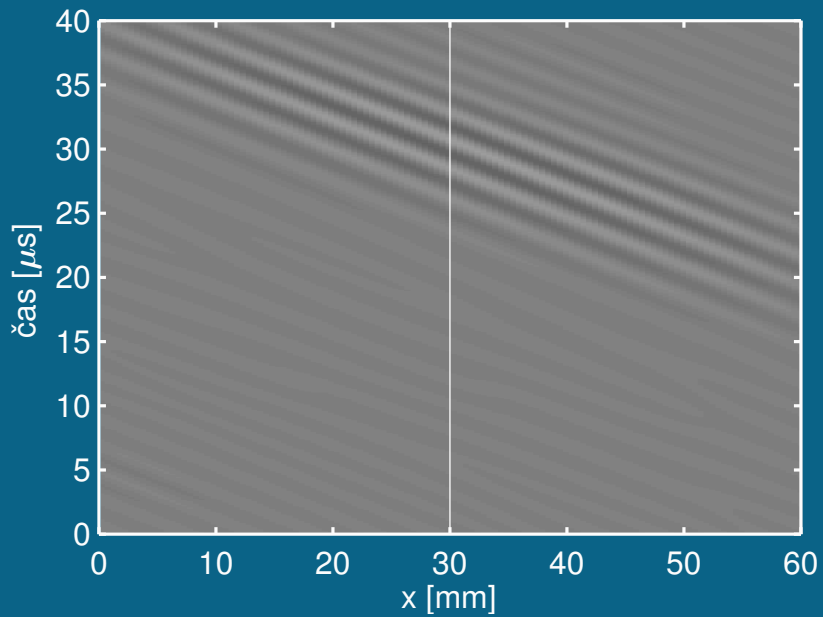
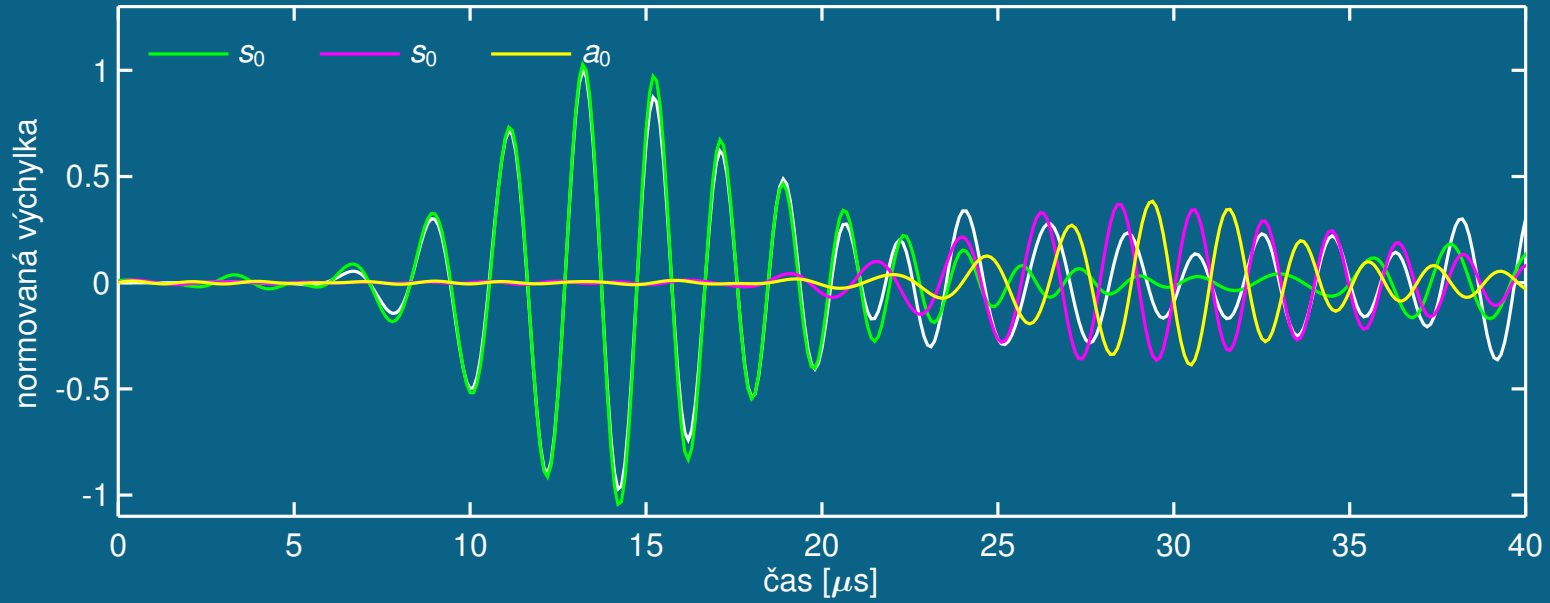
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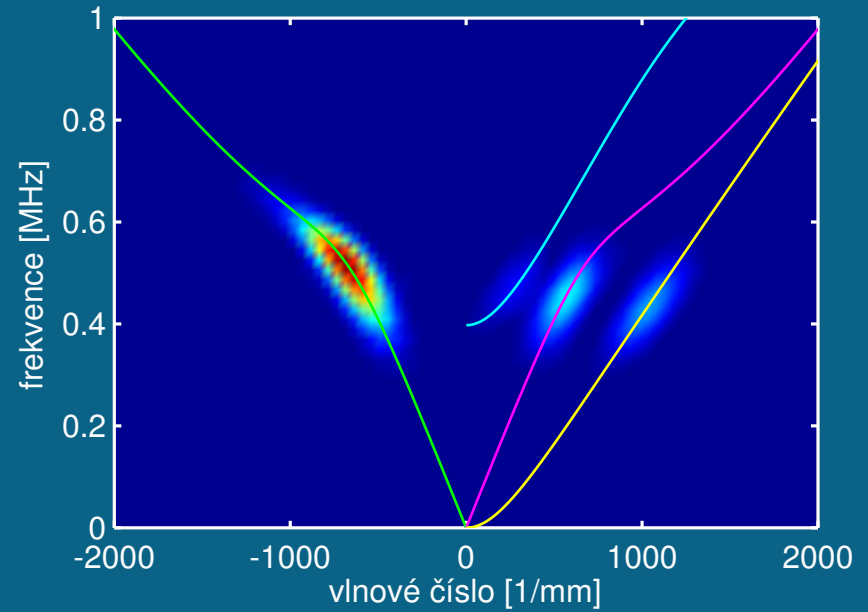
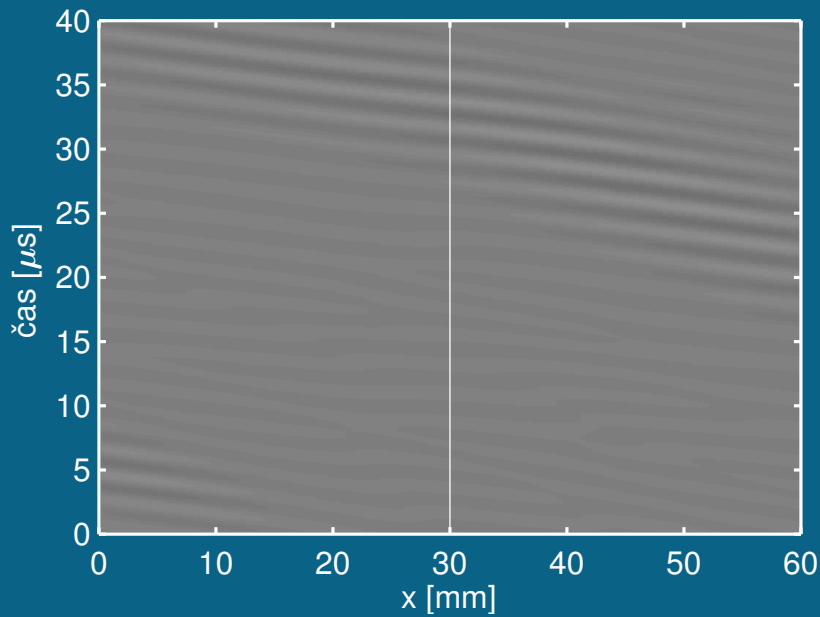
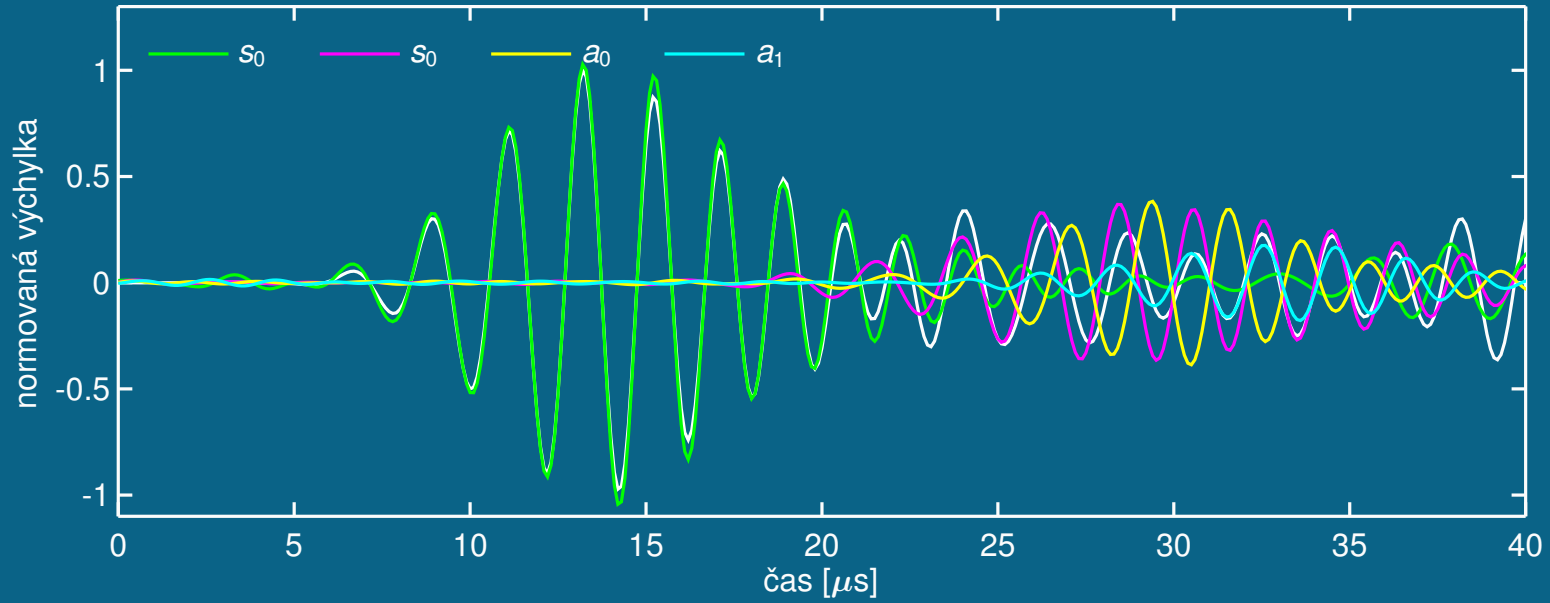
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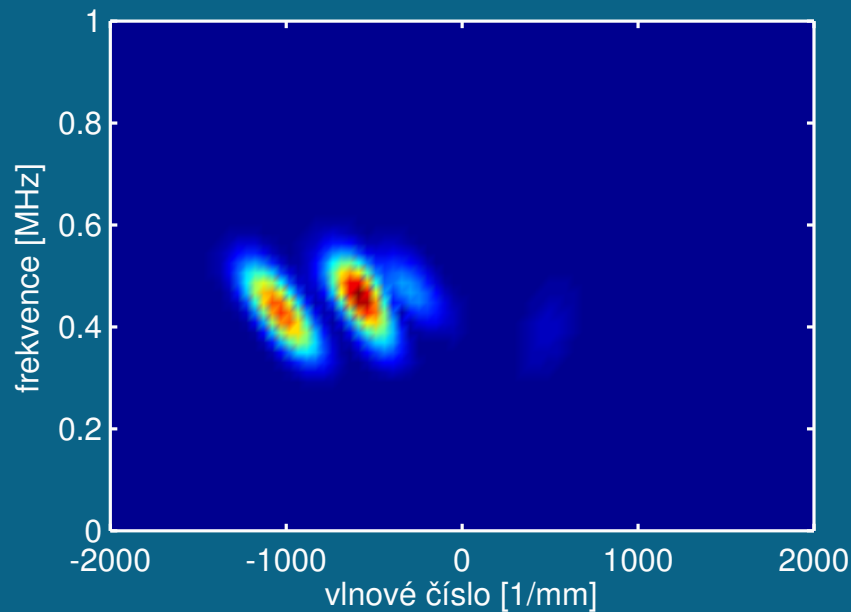
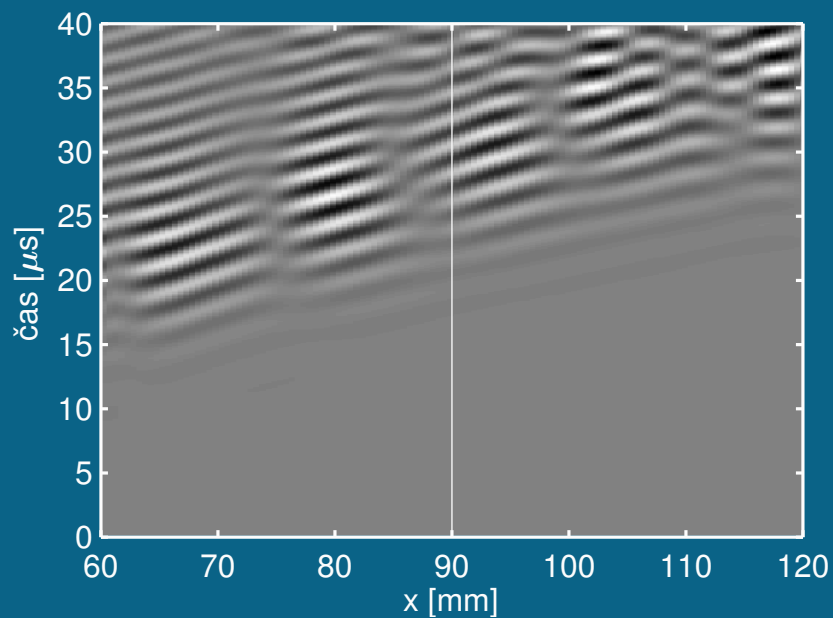
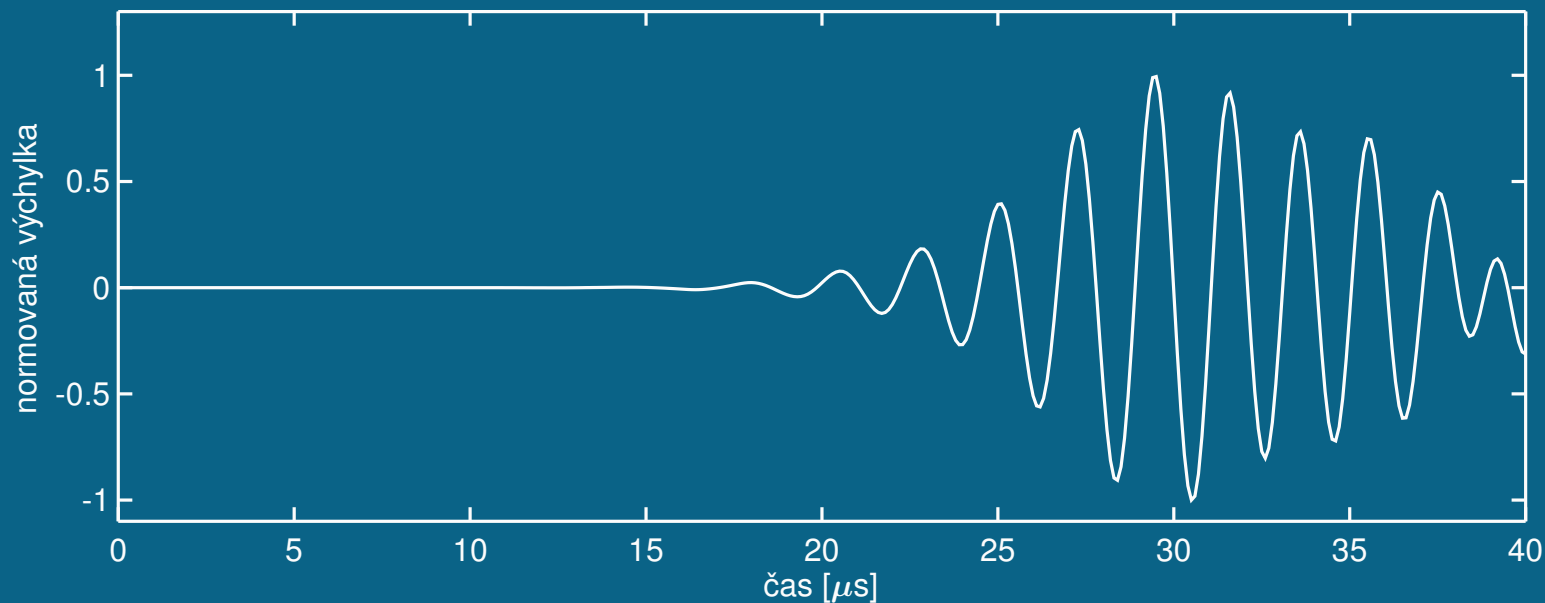
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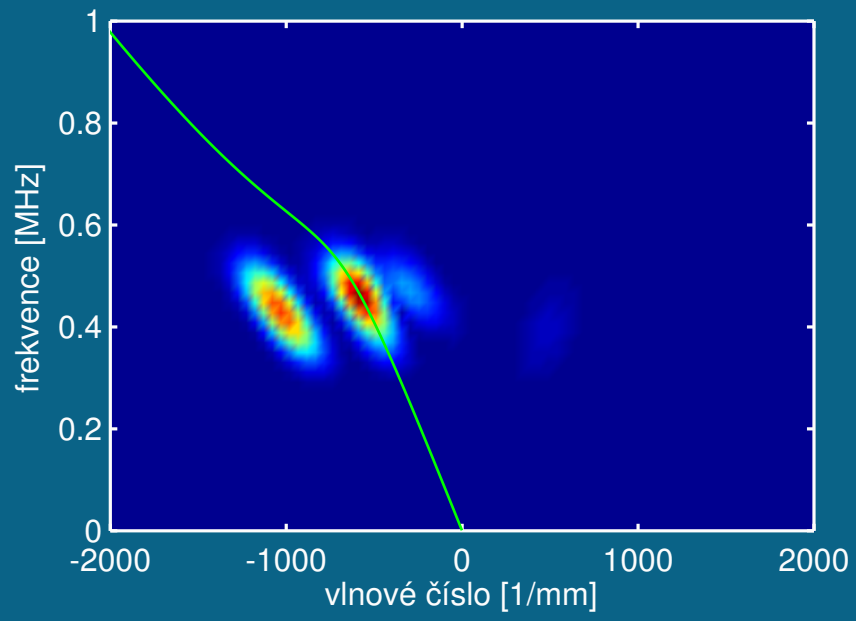
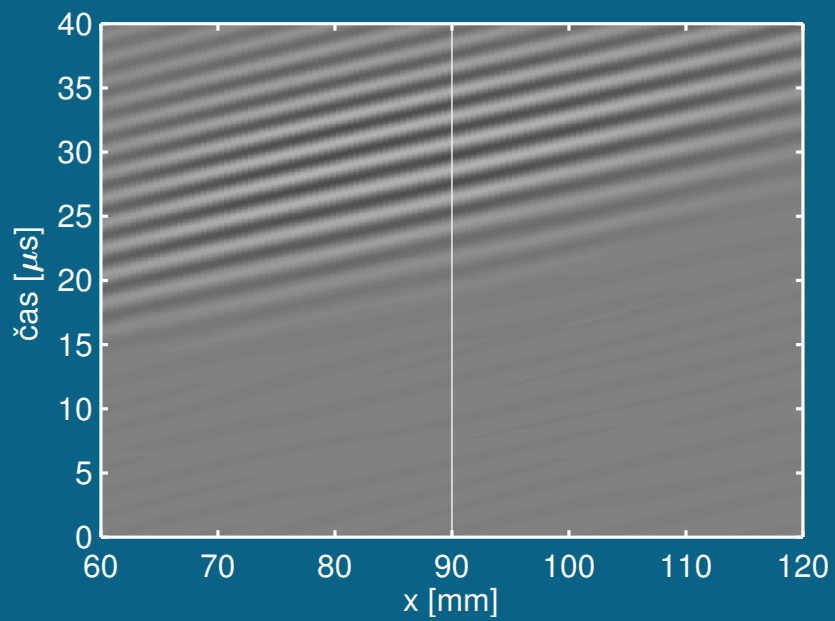
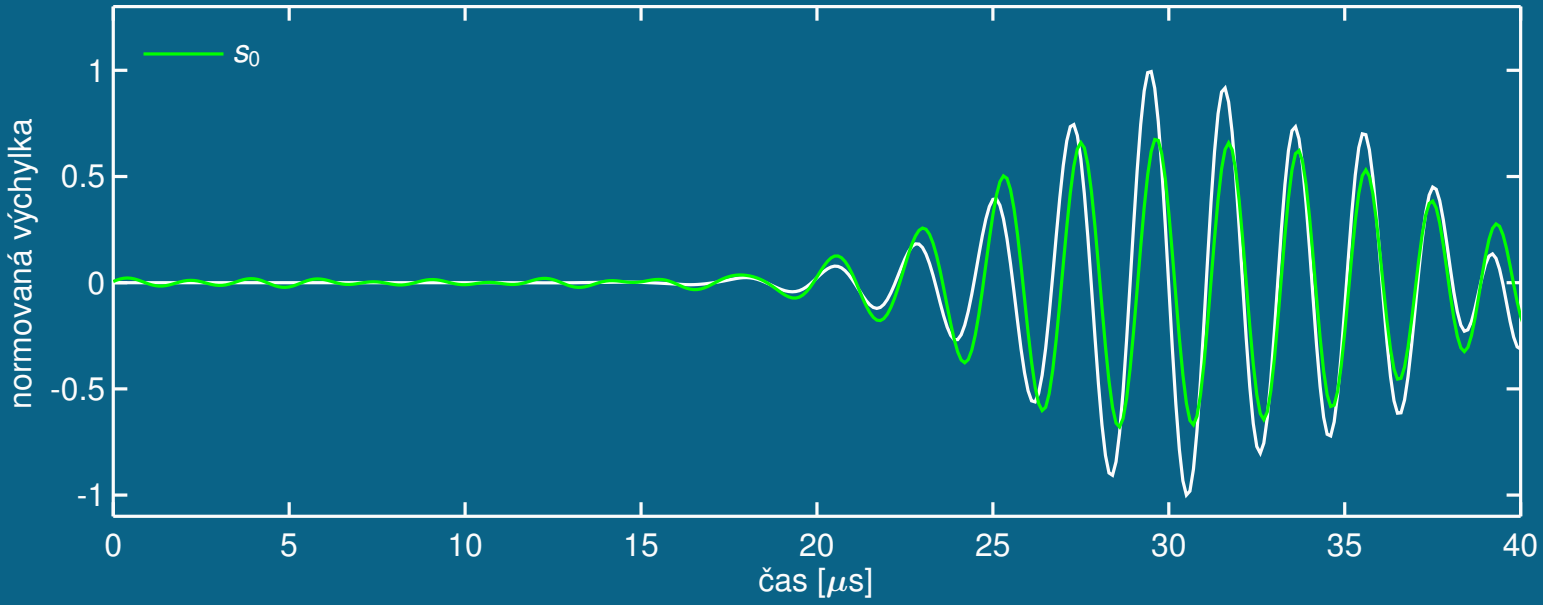
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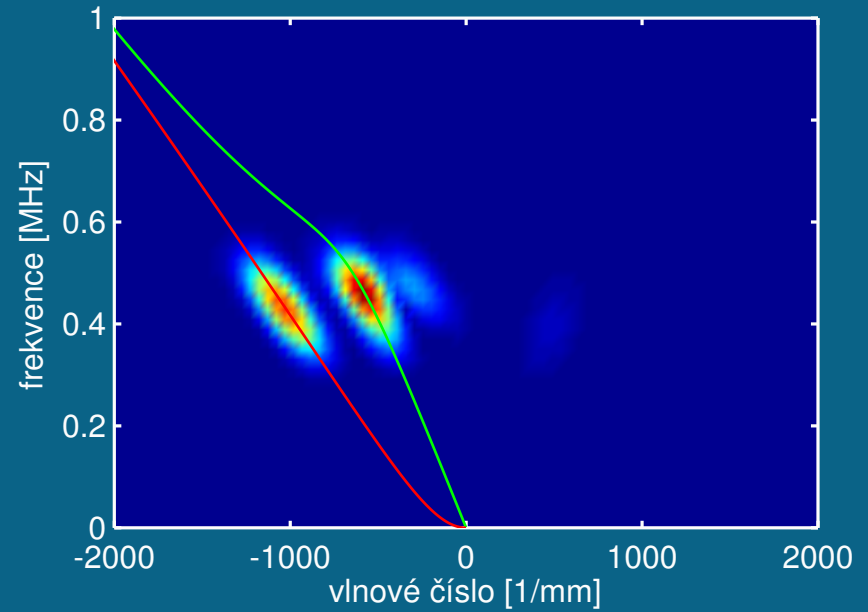
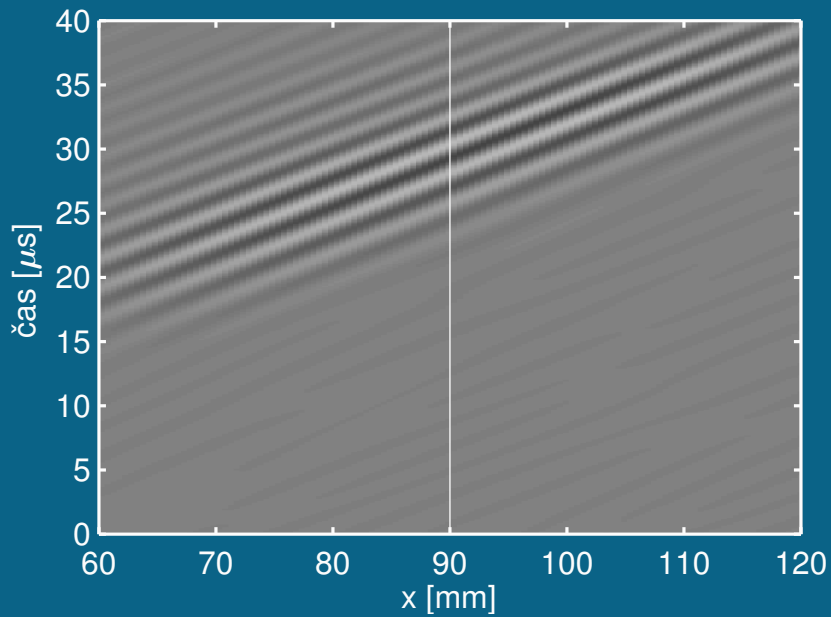
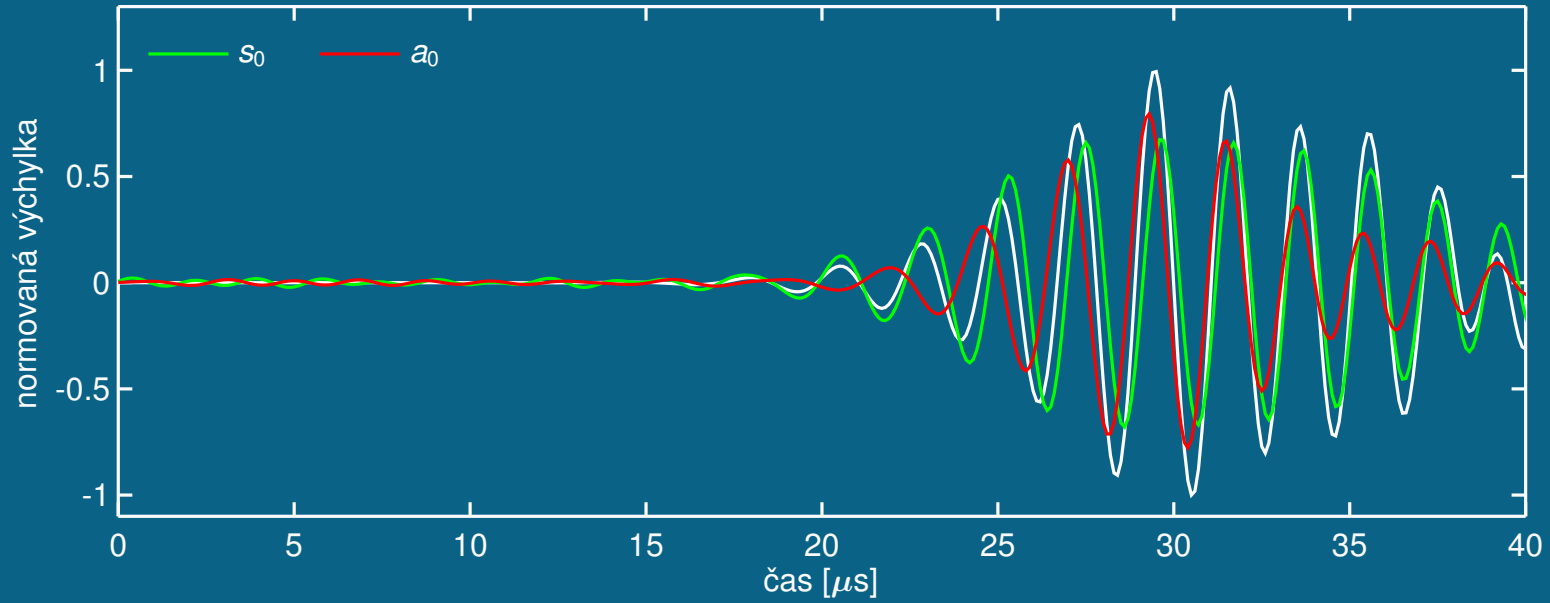


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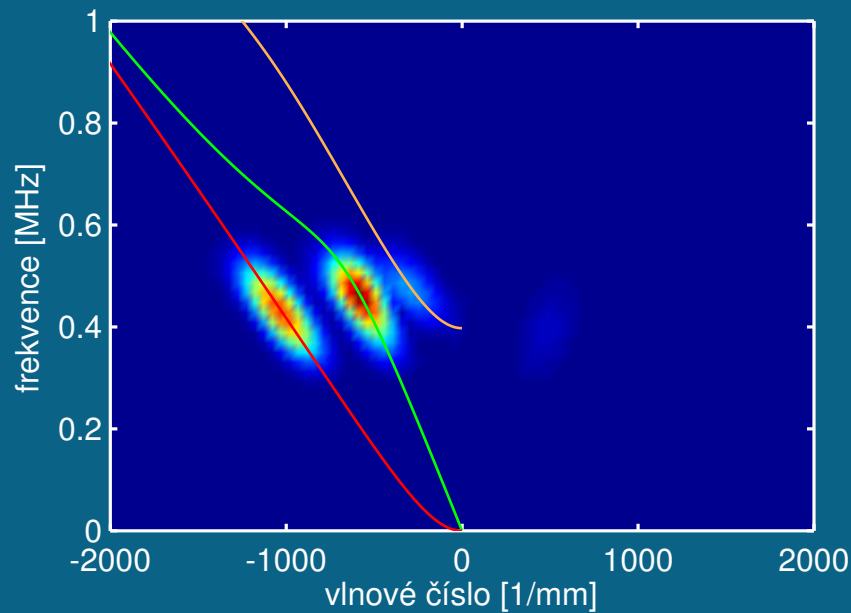
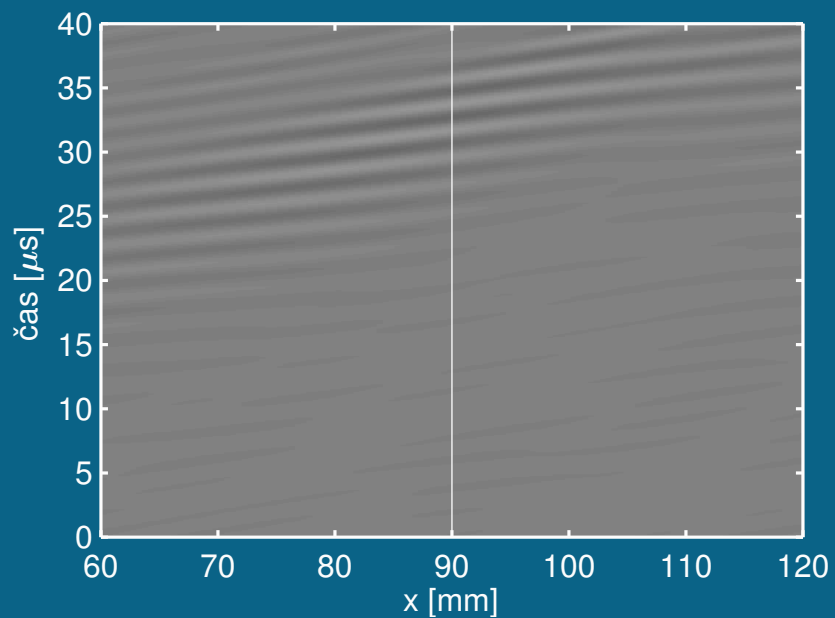
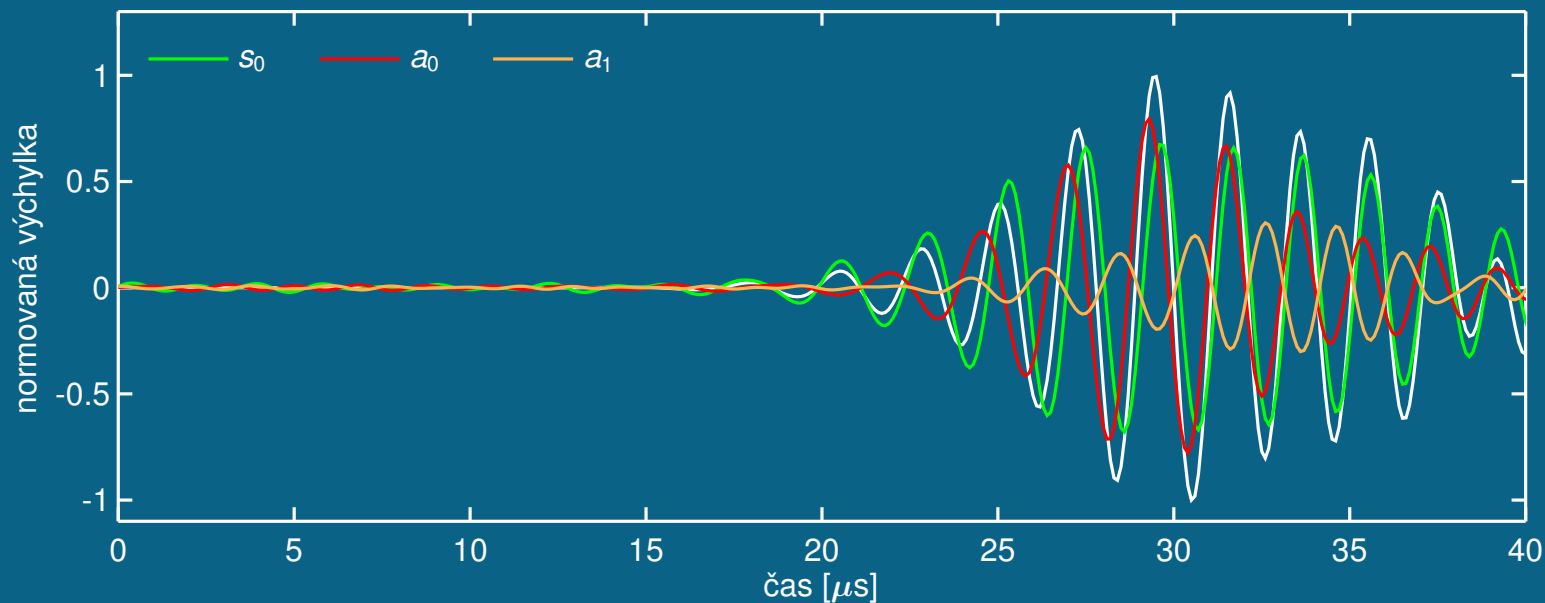




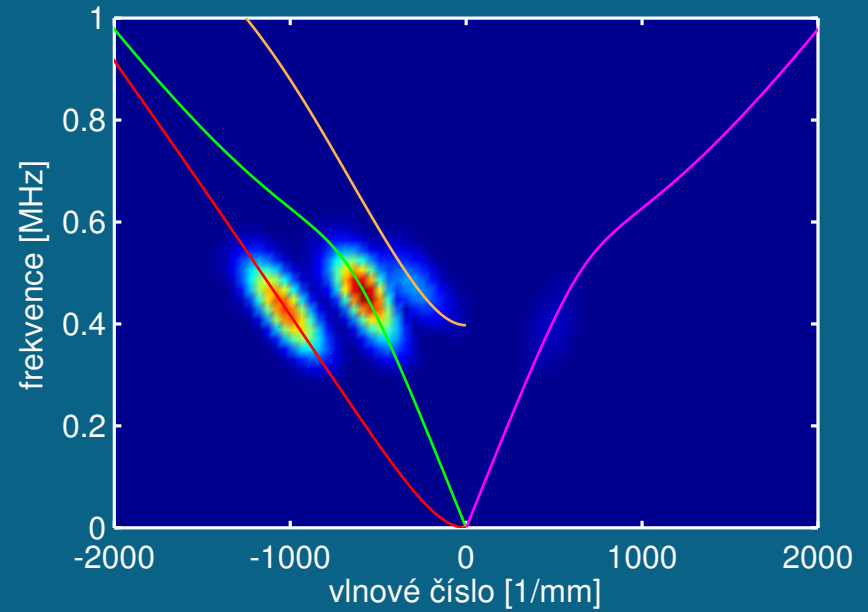
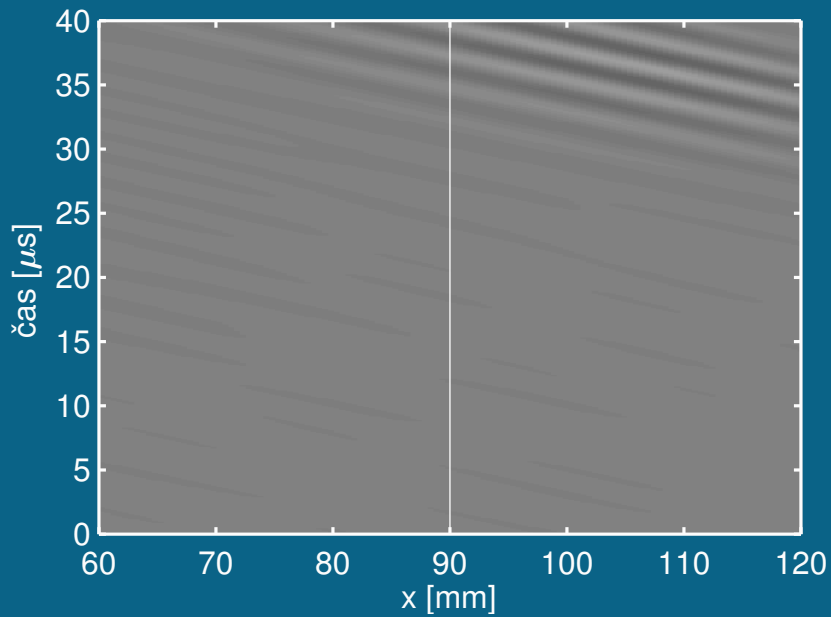
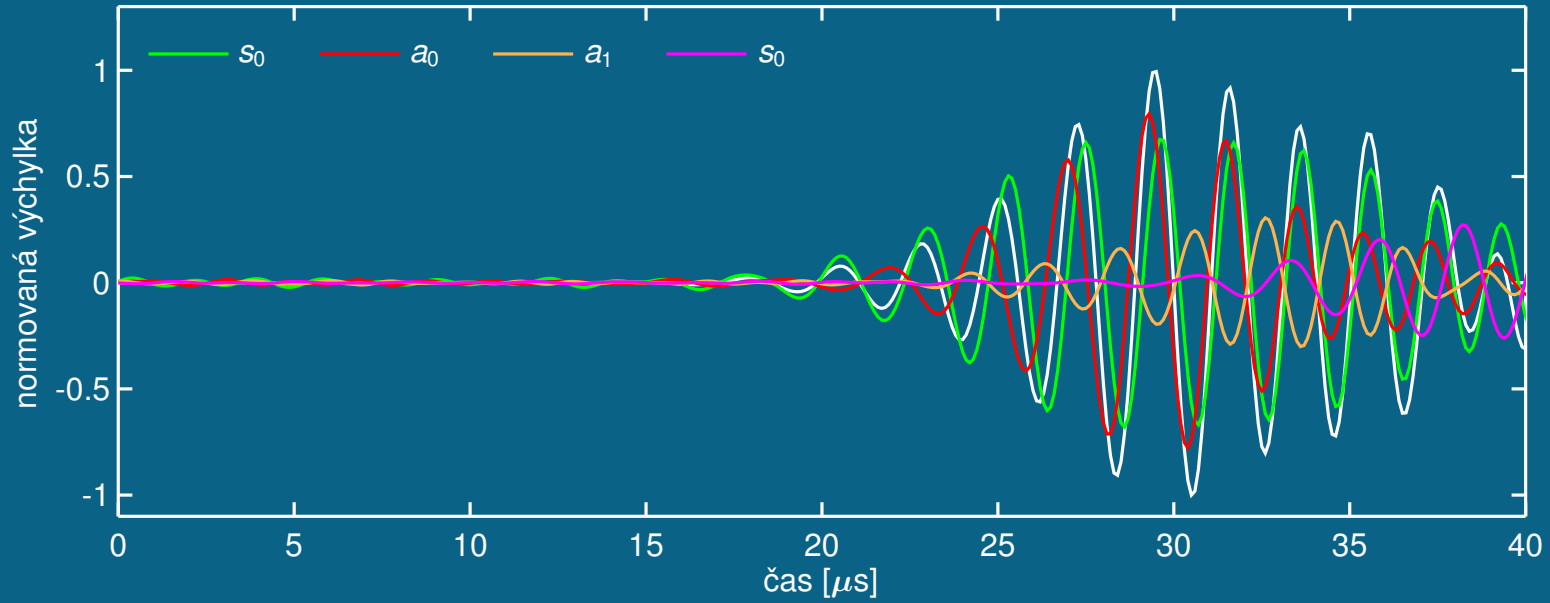
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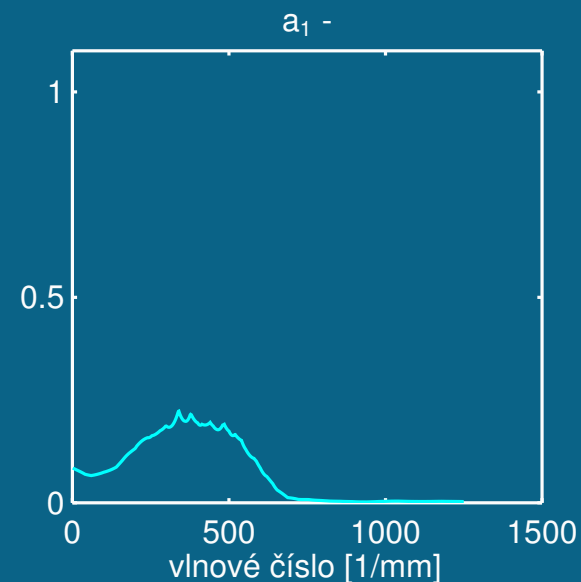
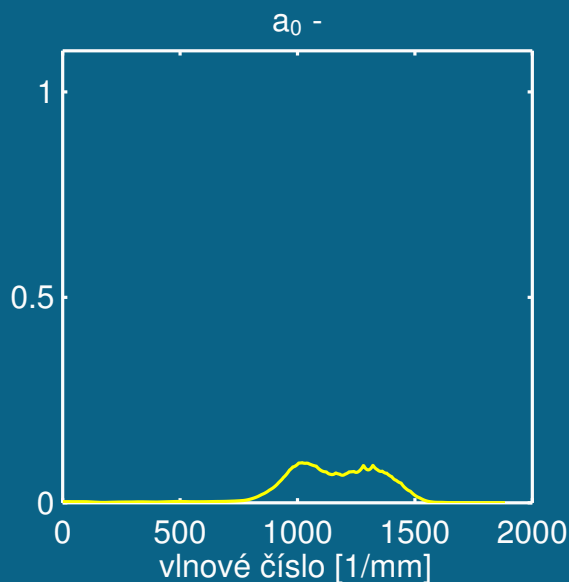
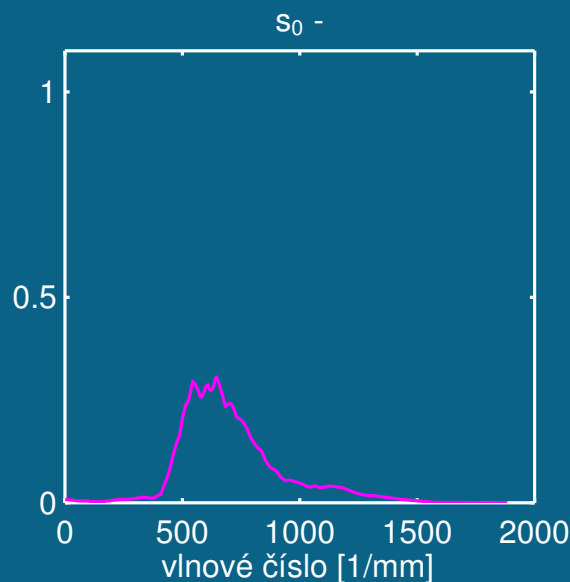
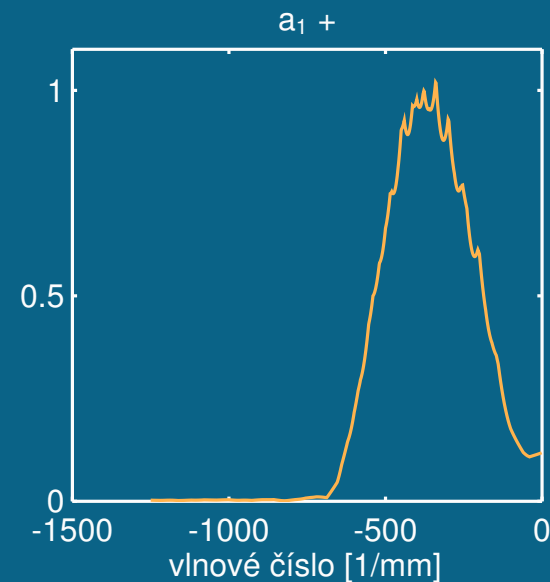
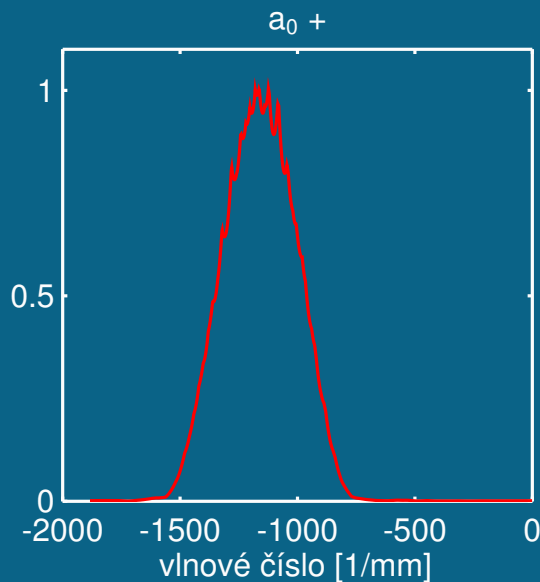
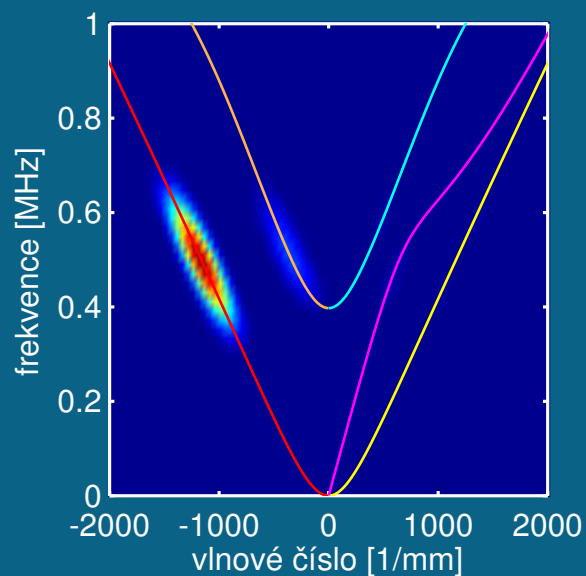


## Oblast za vrubem

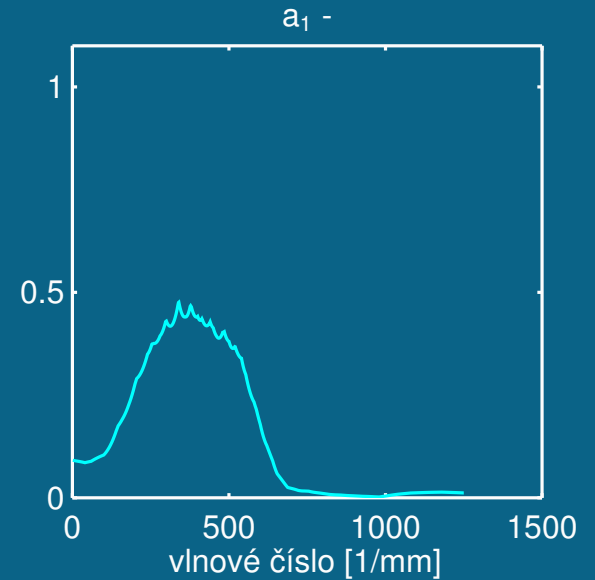
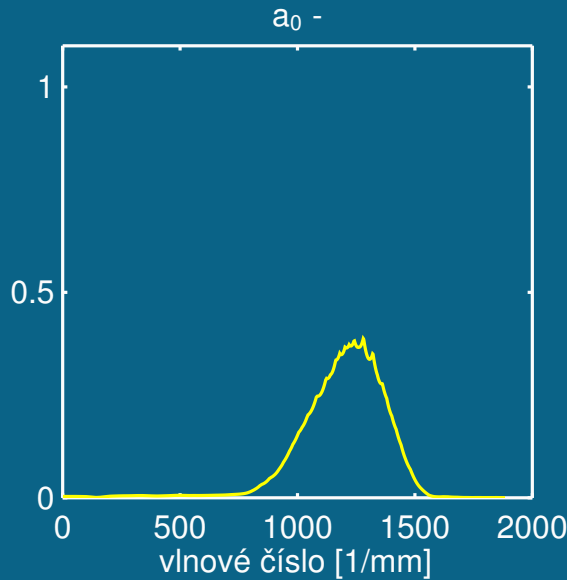
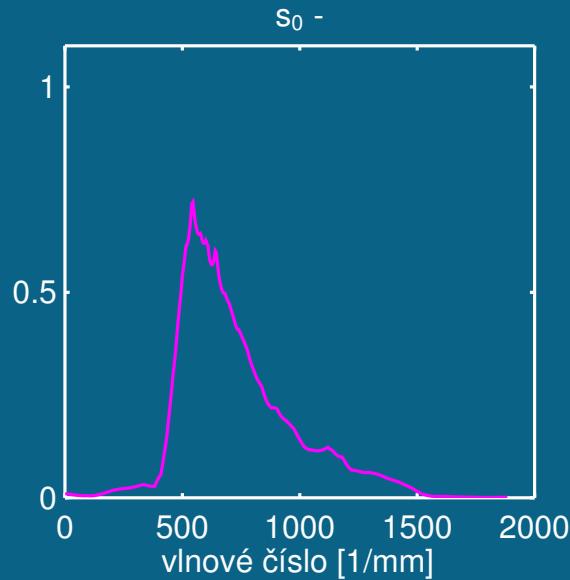
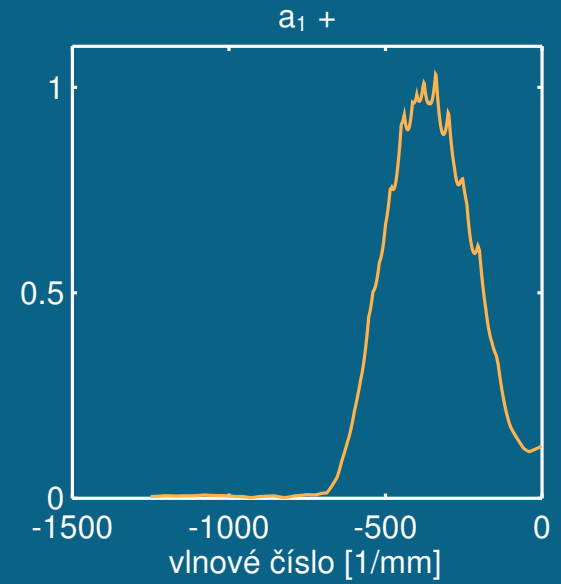
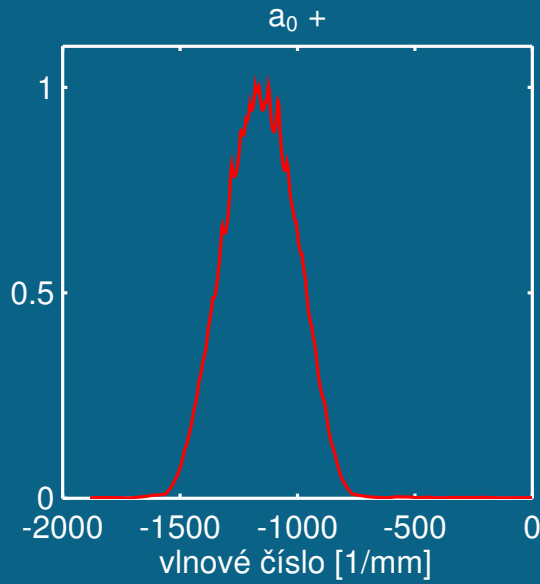
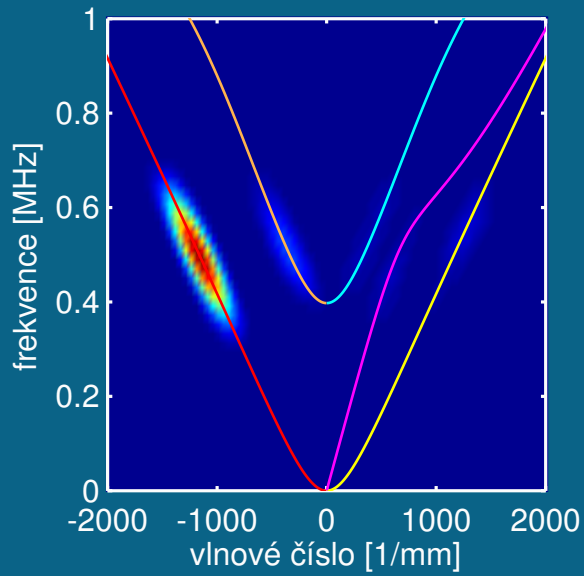


## Vliv hloubky vrubu pro buzení módem $a_0$

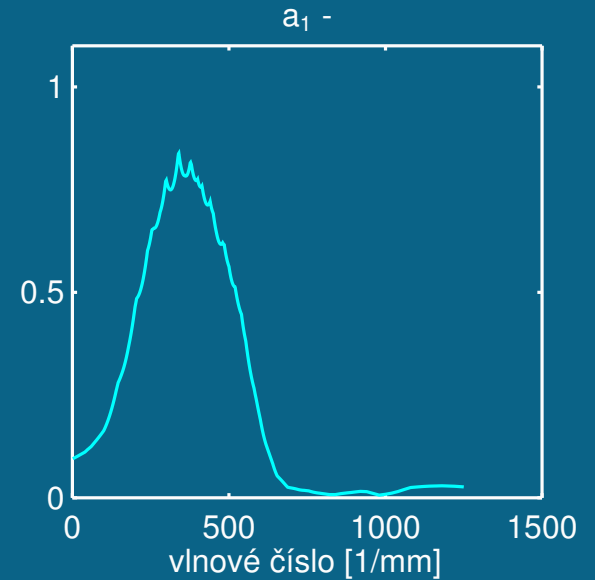
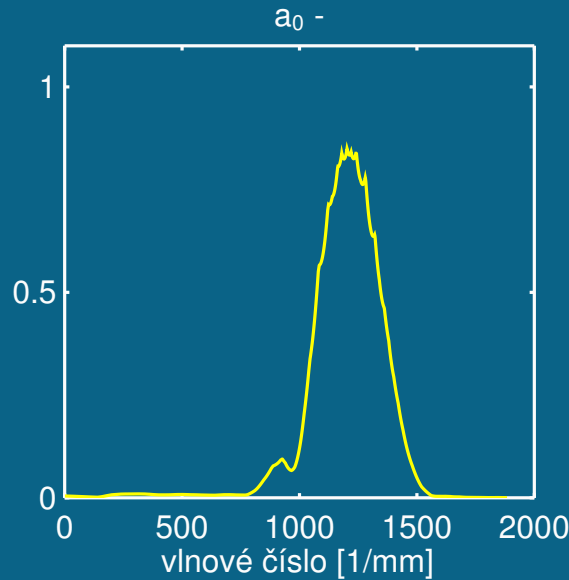
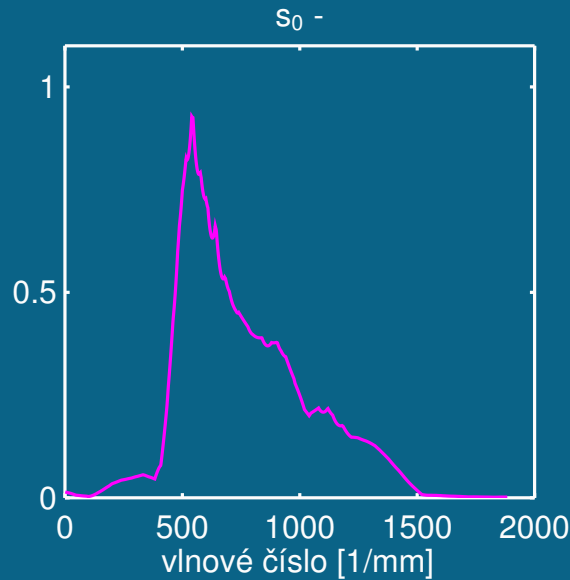
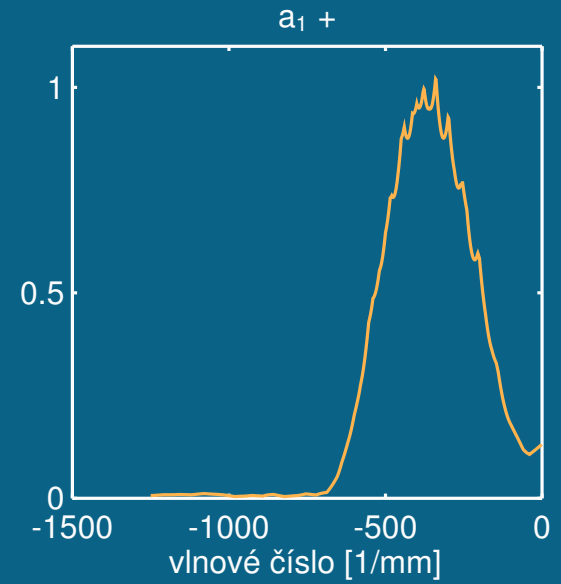
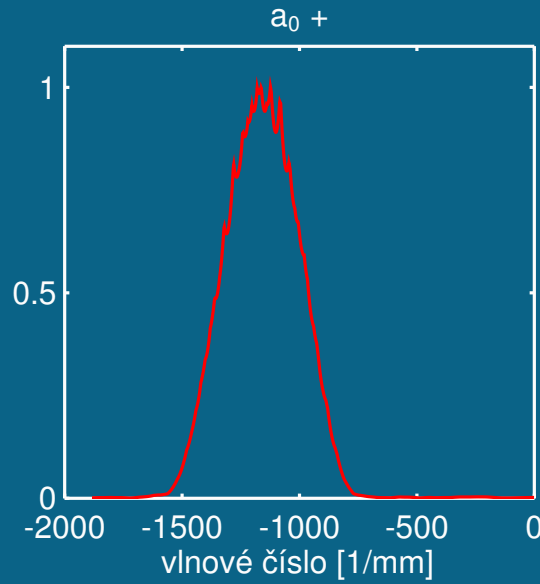
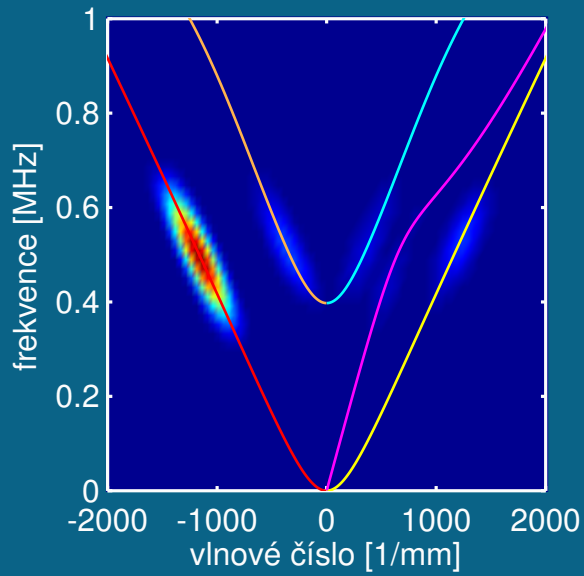
## Oblast před vrubem - hloubka vrubu: 0,5 mm



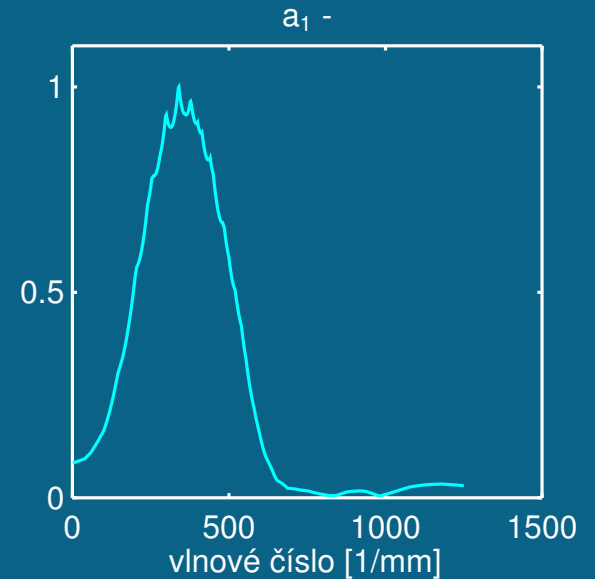
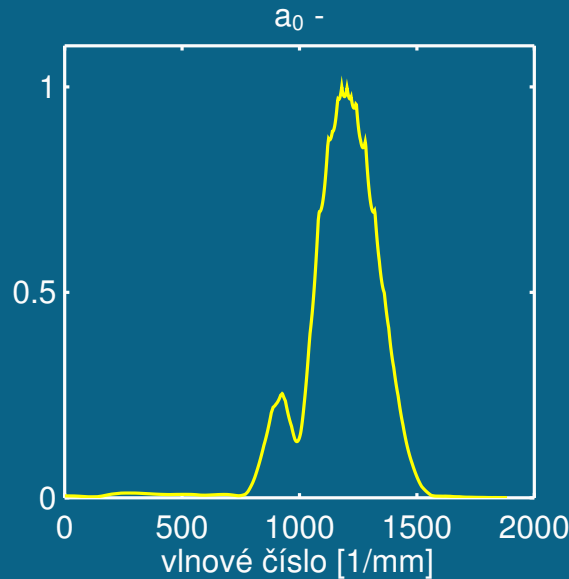
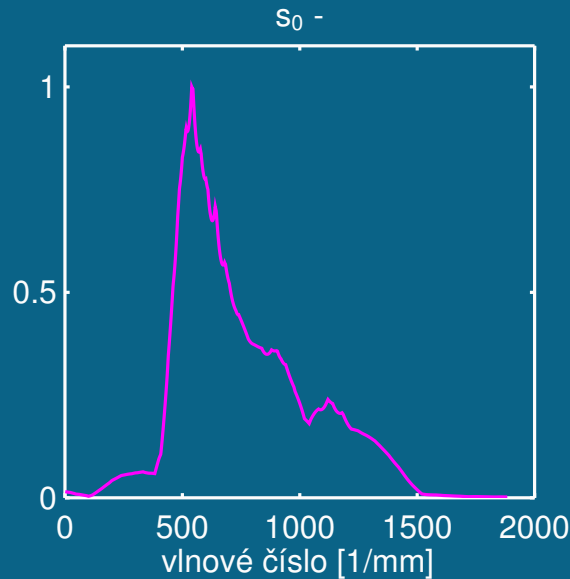
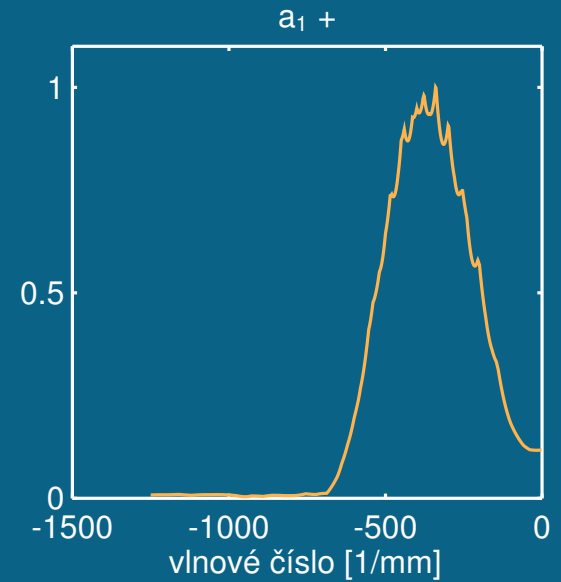
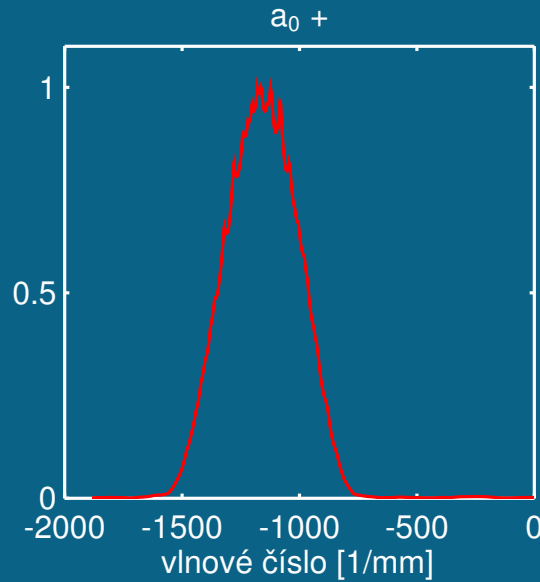
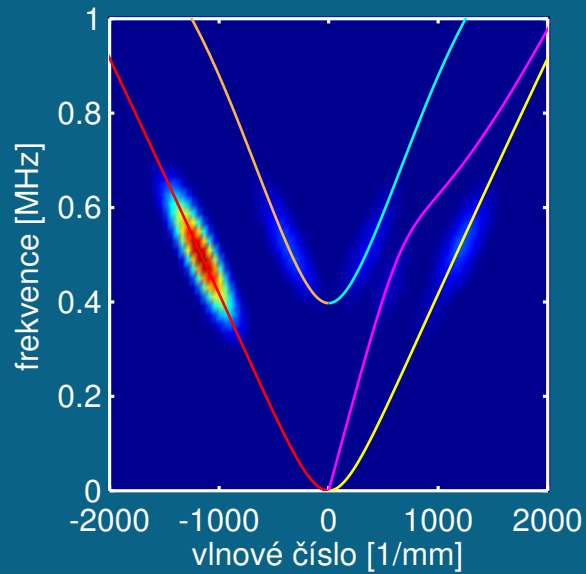
## Oblast před vrubem - hloubka vrubu: 1 mm



## Oblast před vrubem - hloubka vrubu: 1,5 mm

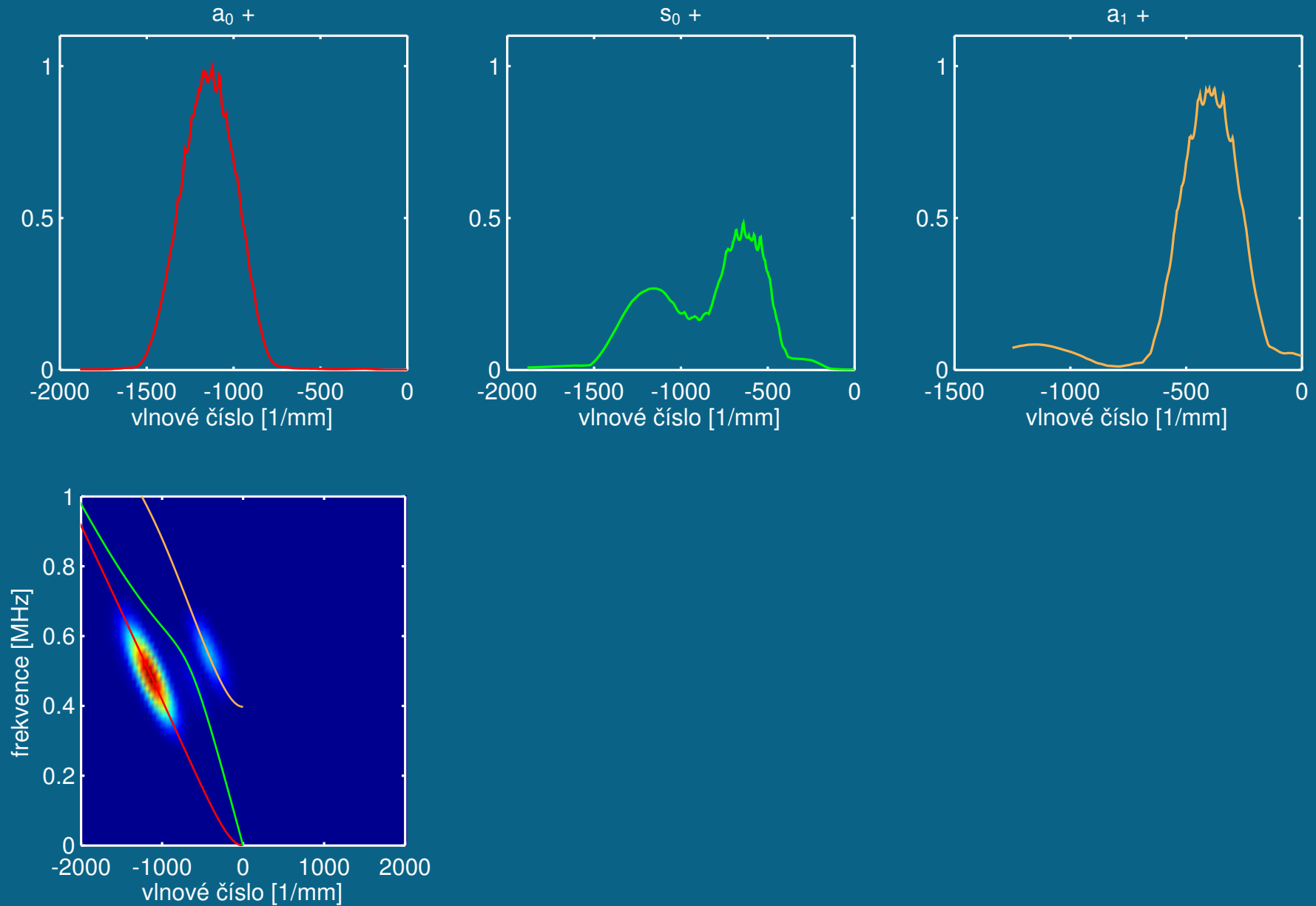


## Oblast před vrubem - hloubka vrubu: 2 mm

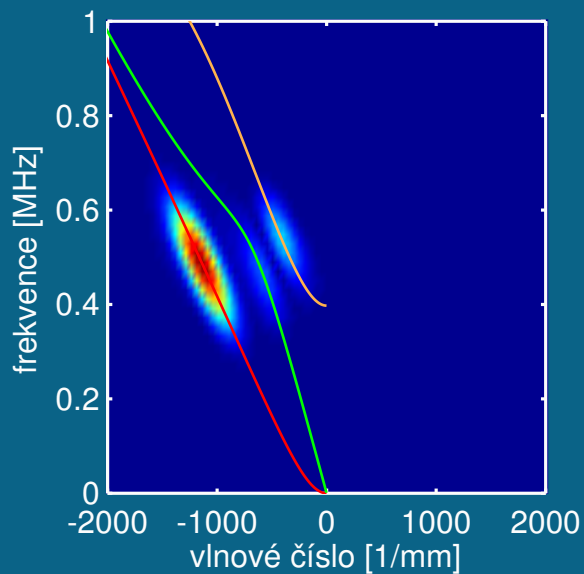
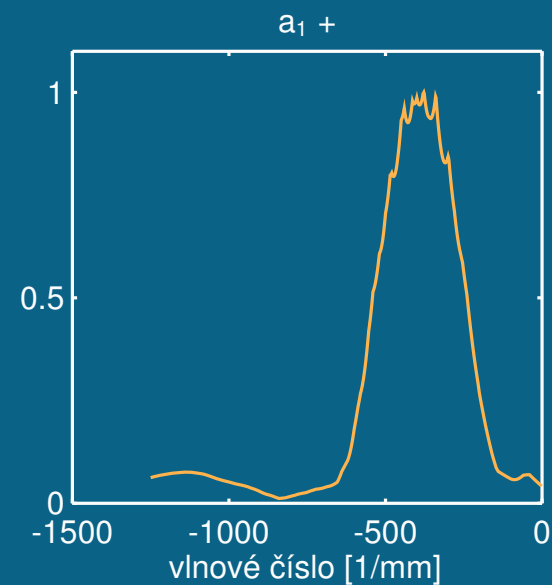
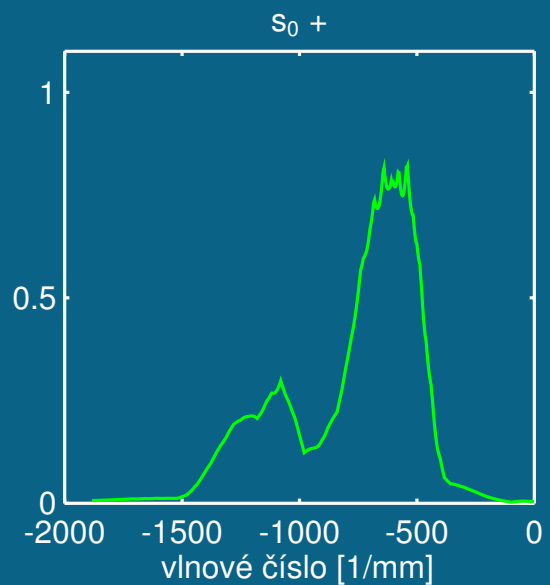
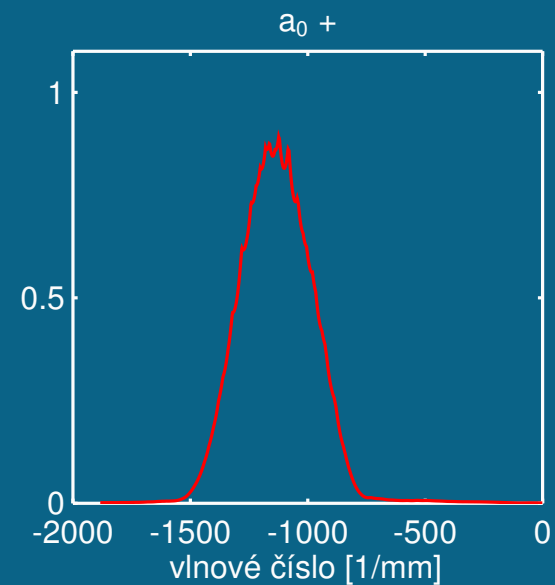




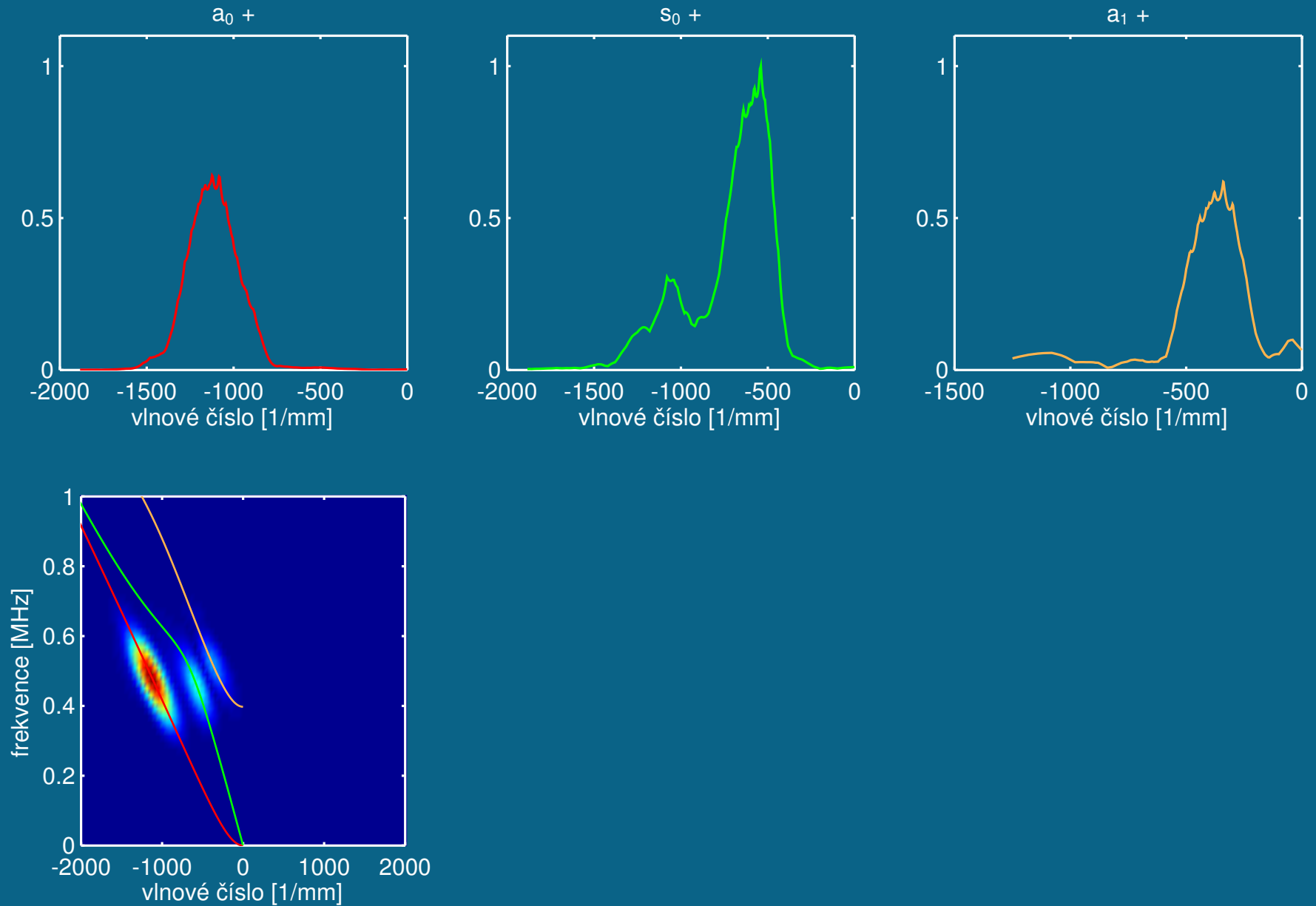
## Oblast za vrubem - hloubka vrubu: 0,5 mm



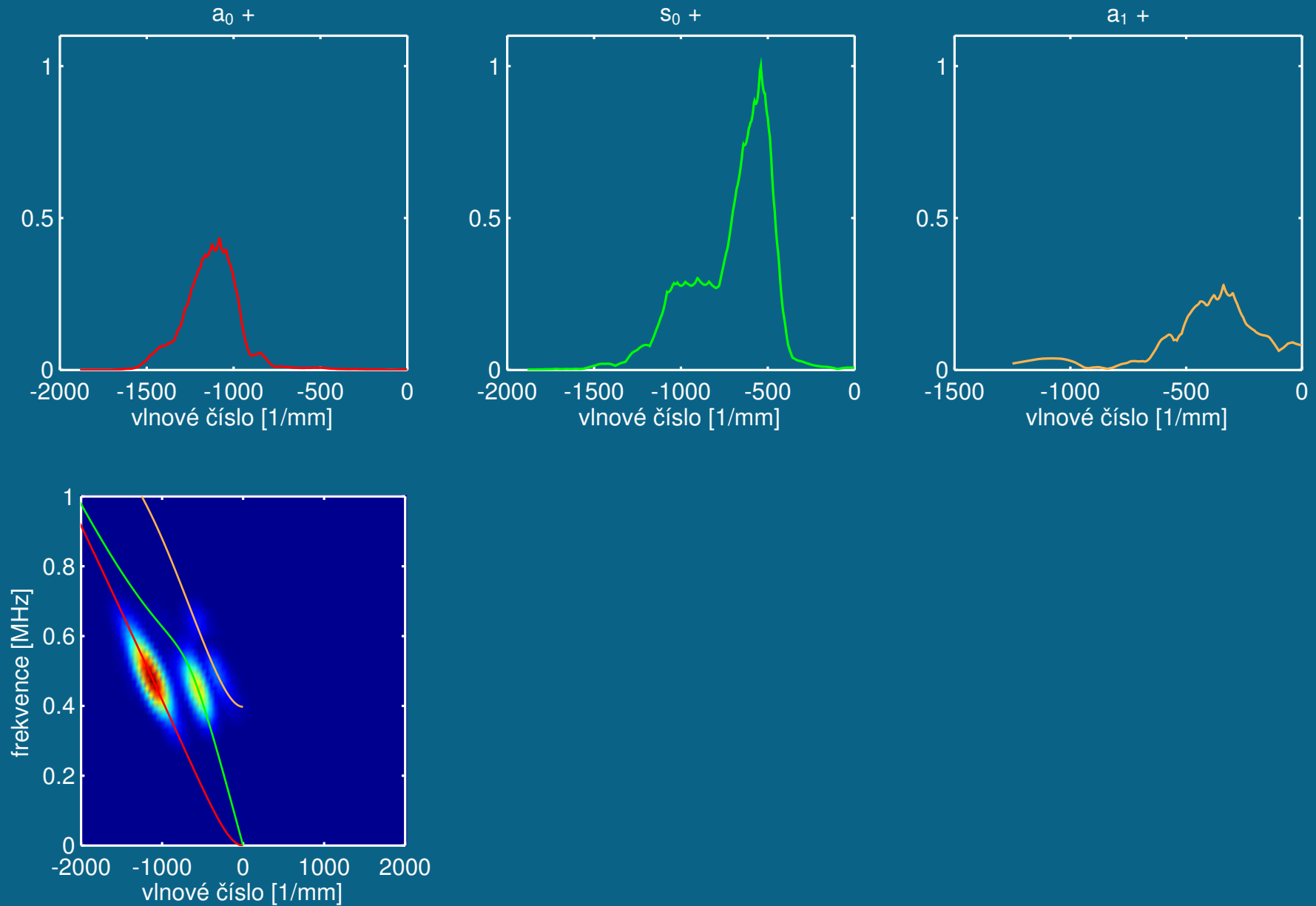
## Oblast za vrubem - hloubka vrubu: 1 mm



## Oblast za vrubem - hloubka vrubu: 1,5 mm

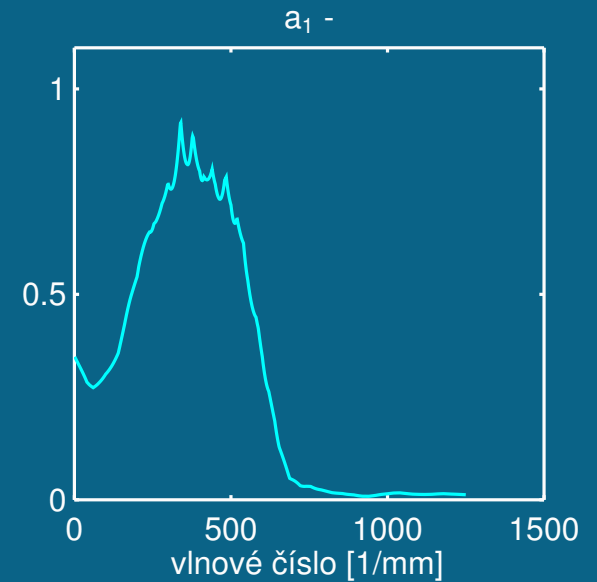
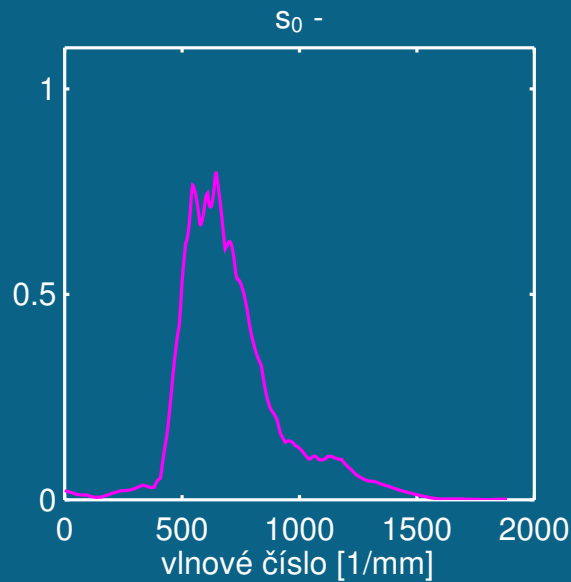
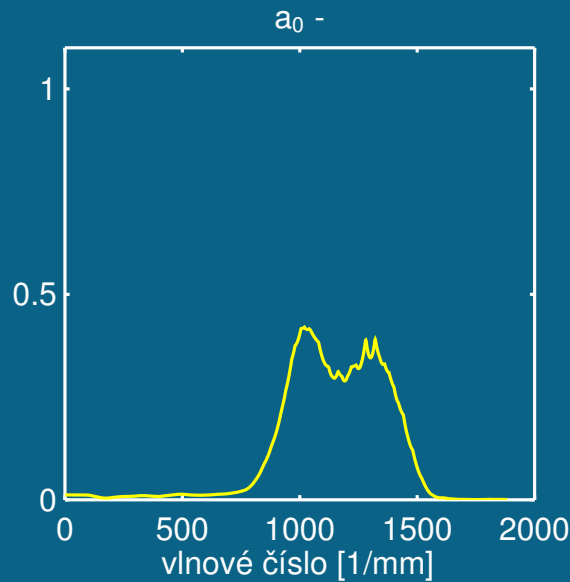
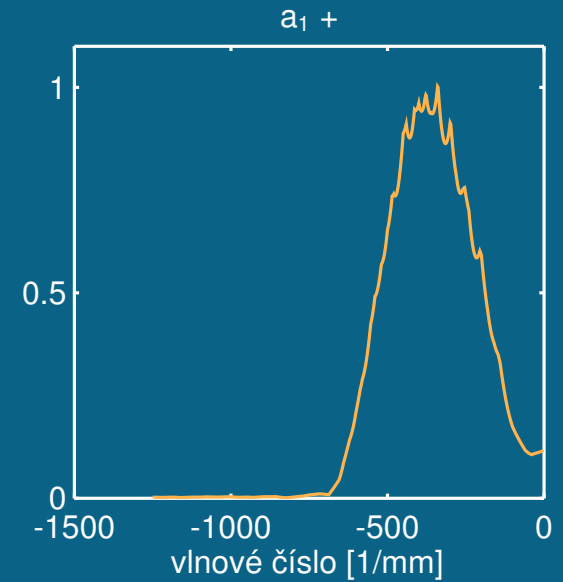
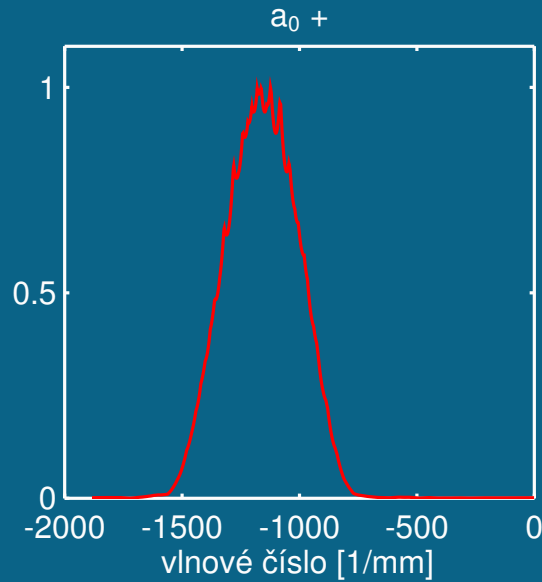
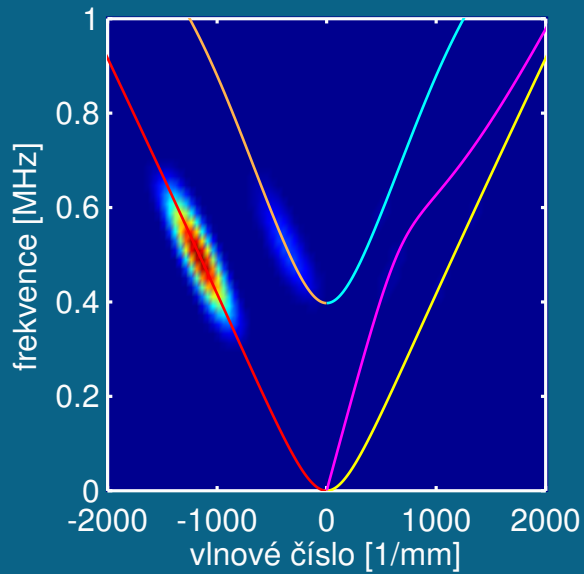


## Oblast za vrubem - hloubka vrubu: 2 mm

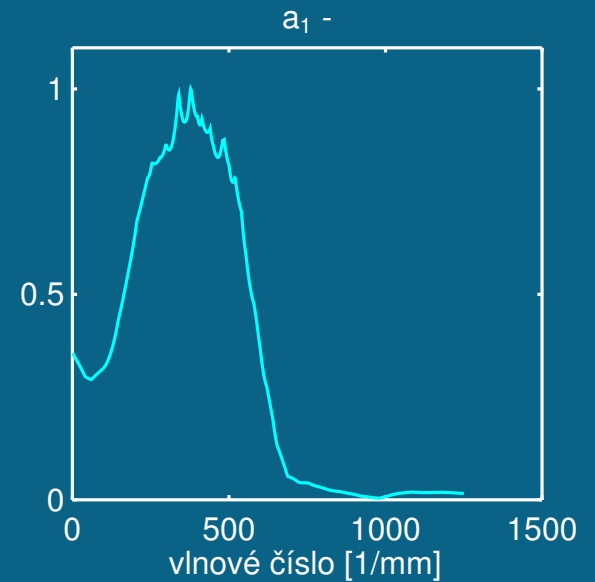
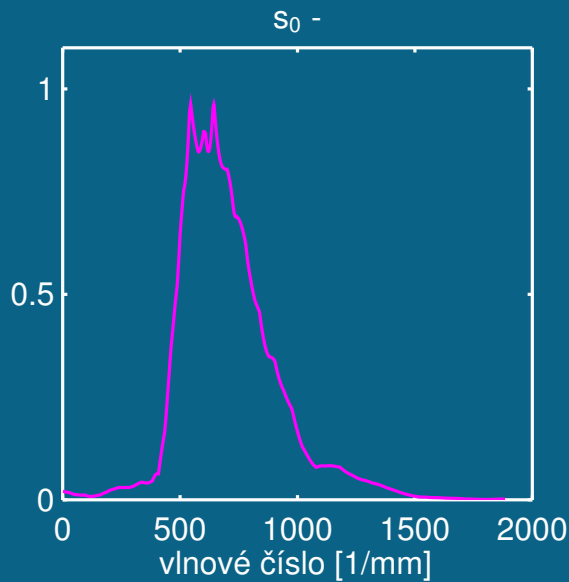
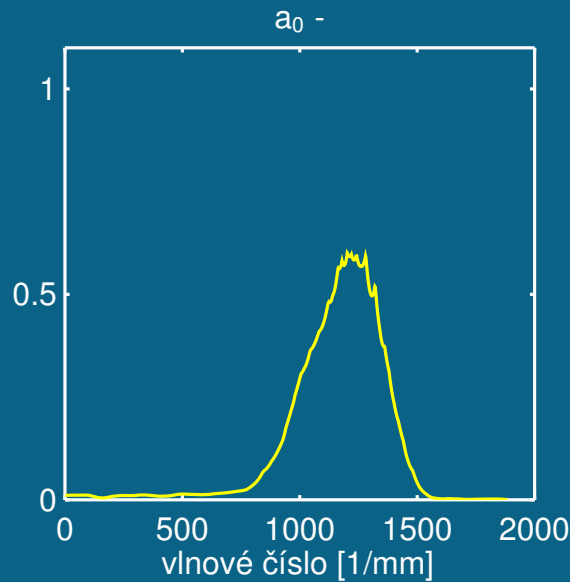
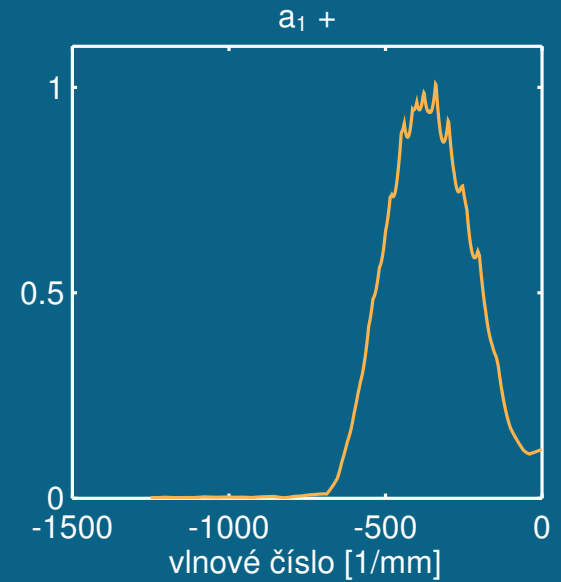
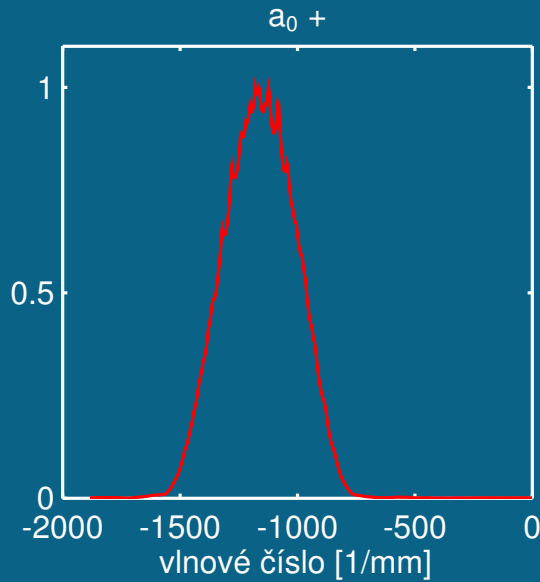
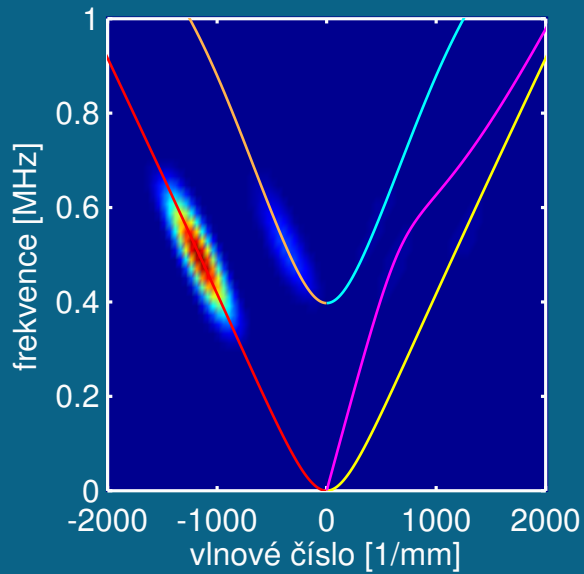


## Vliv šířky vrubu pro buzení módem $a_0$

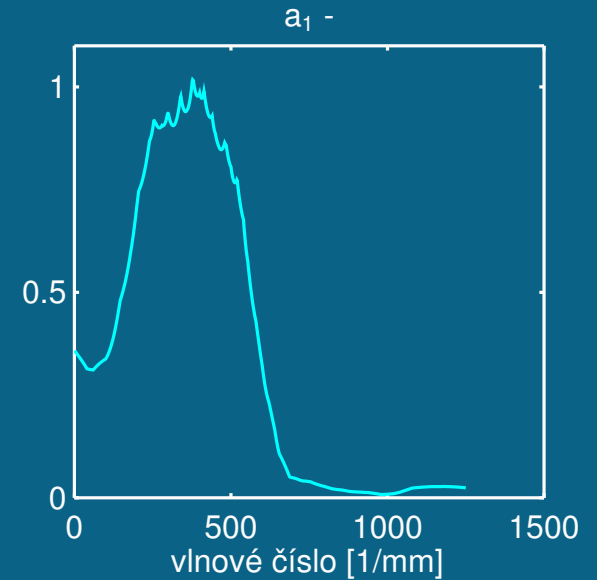
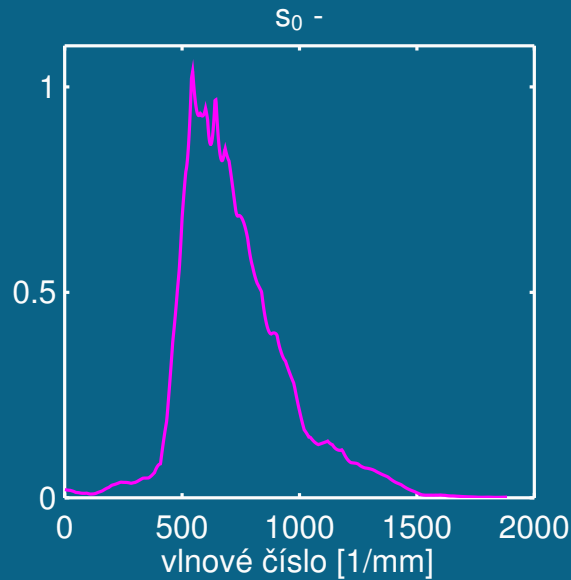
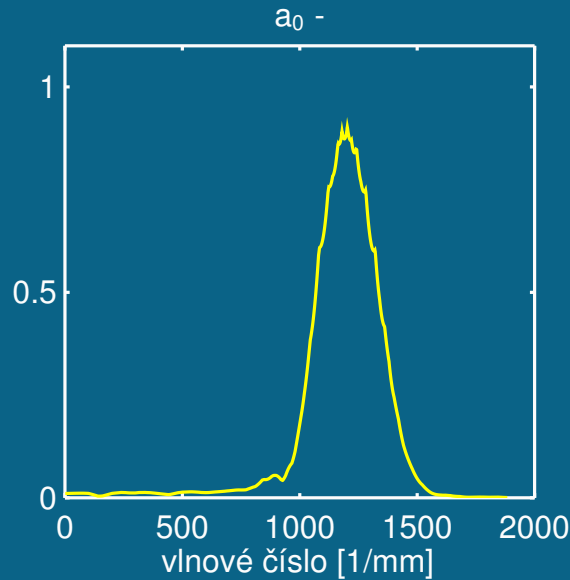
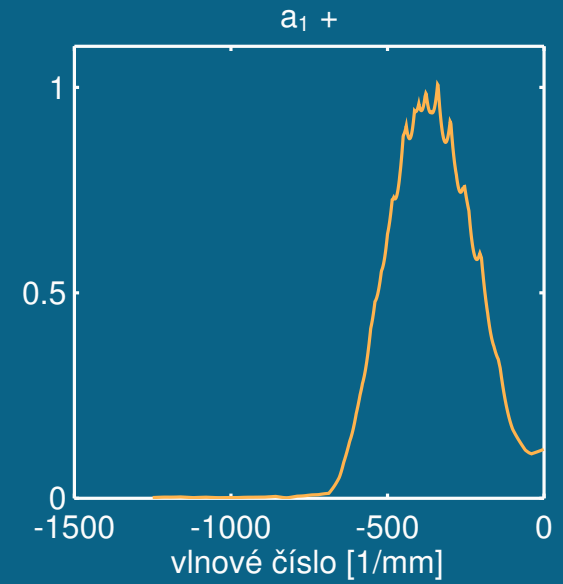
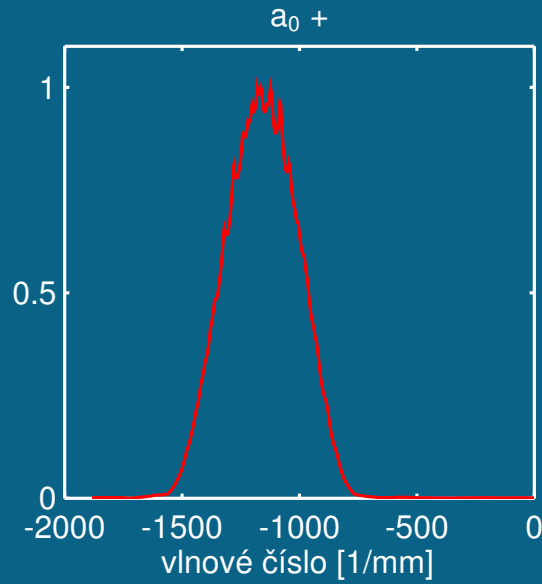
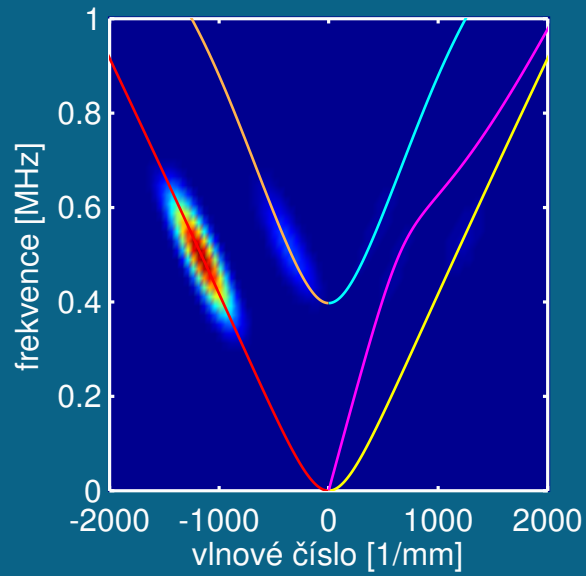
## Oblast před vrubem - šířka vrubu: 0,5 mm



## Oblast před vrubem - šířka vrubu: 1 mm

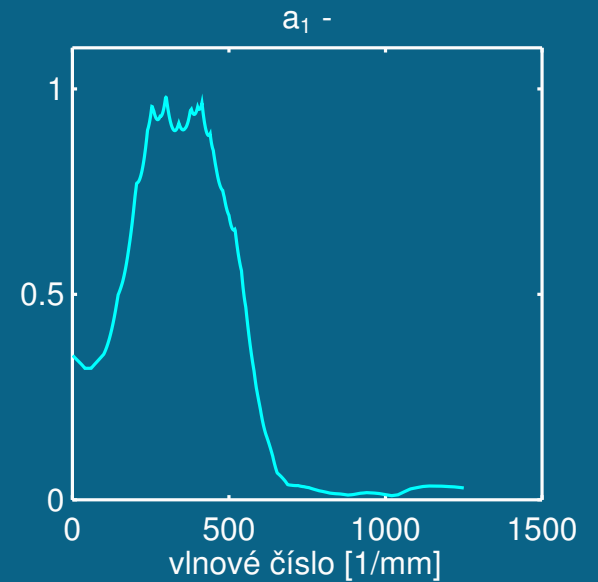
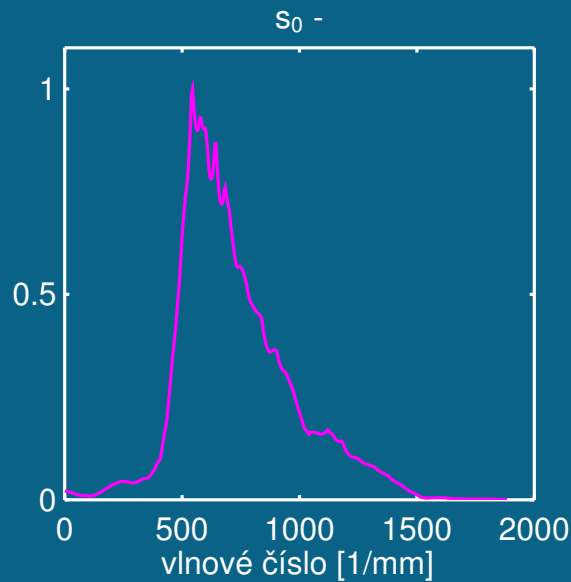
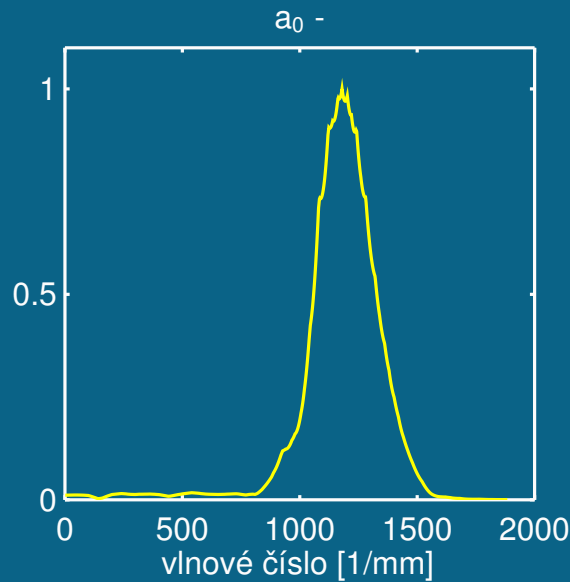
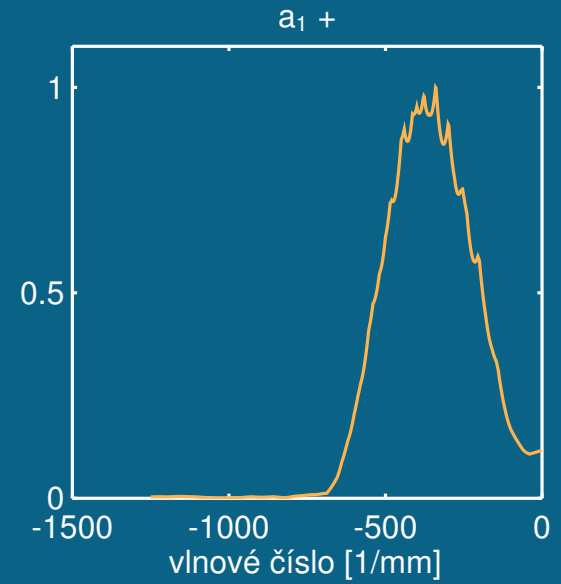
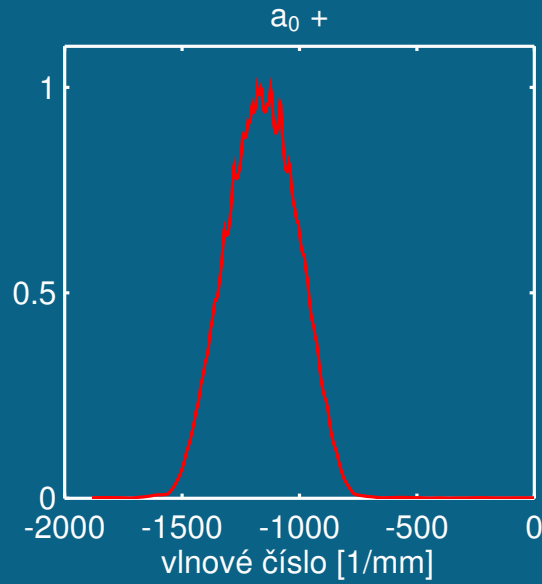
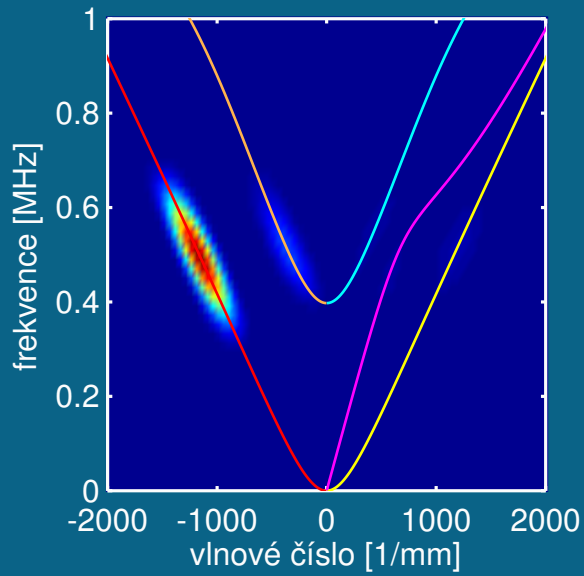


## Oblast před vrubem - šířka vrubu: 1,5 mm

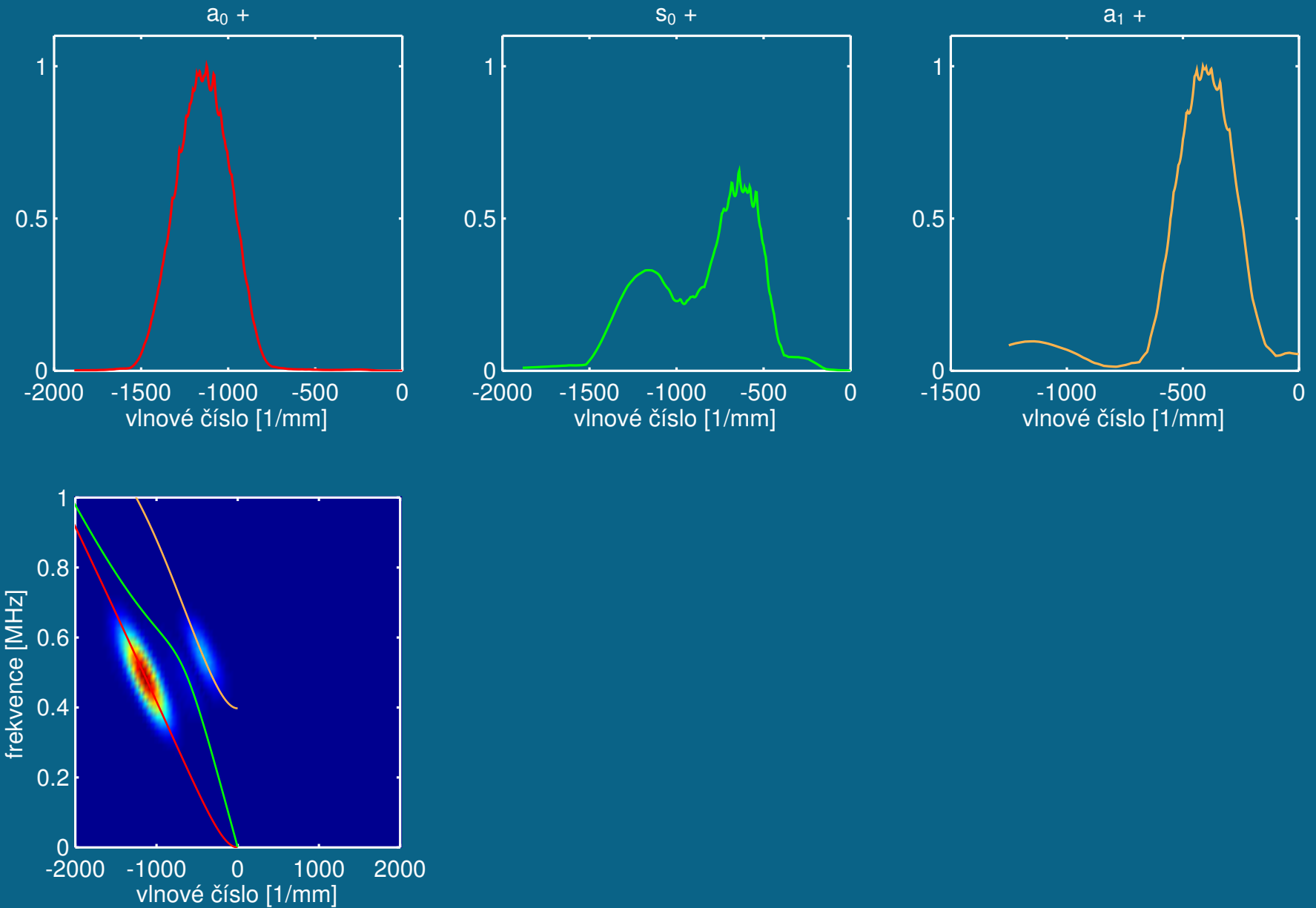




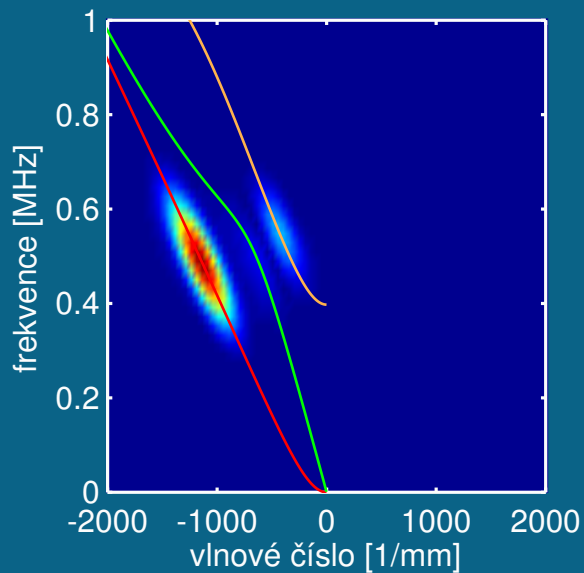
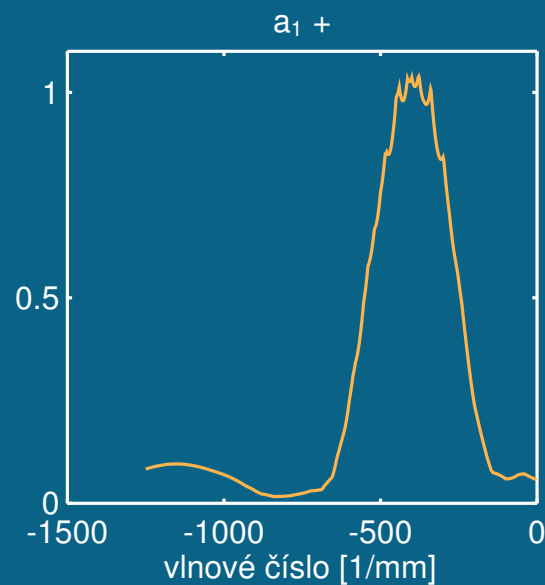
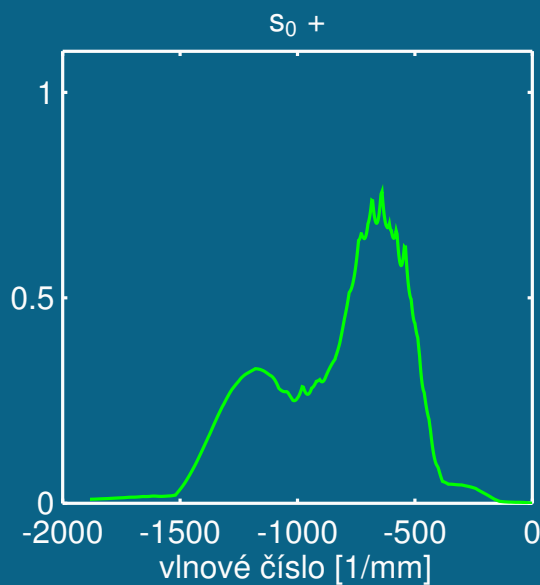
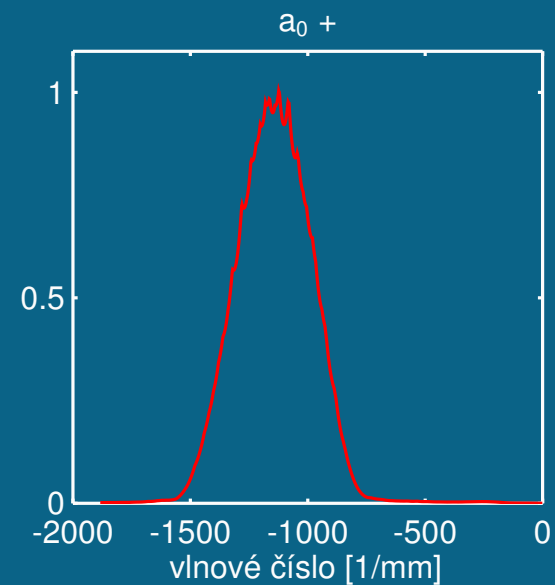
## Oblast před vrubem - šířka vrubu: 2 mm



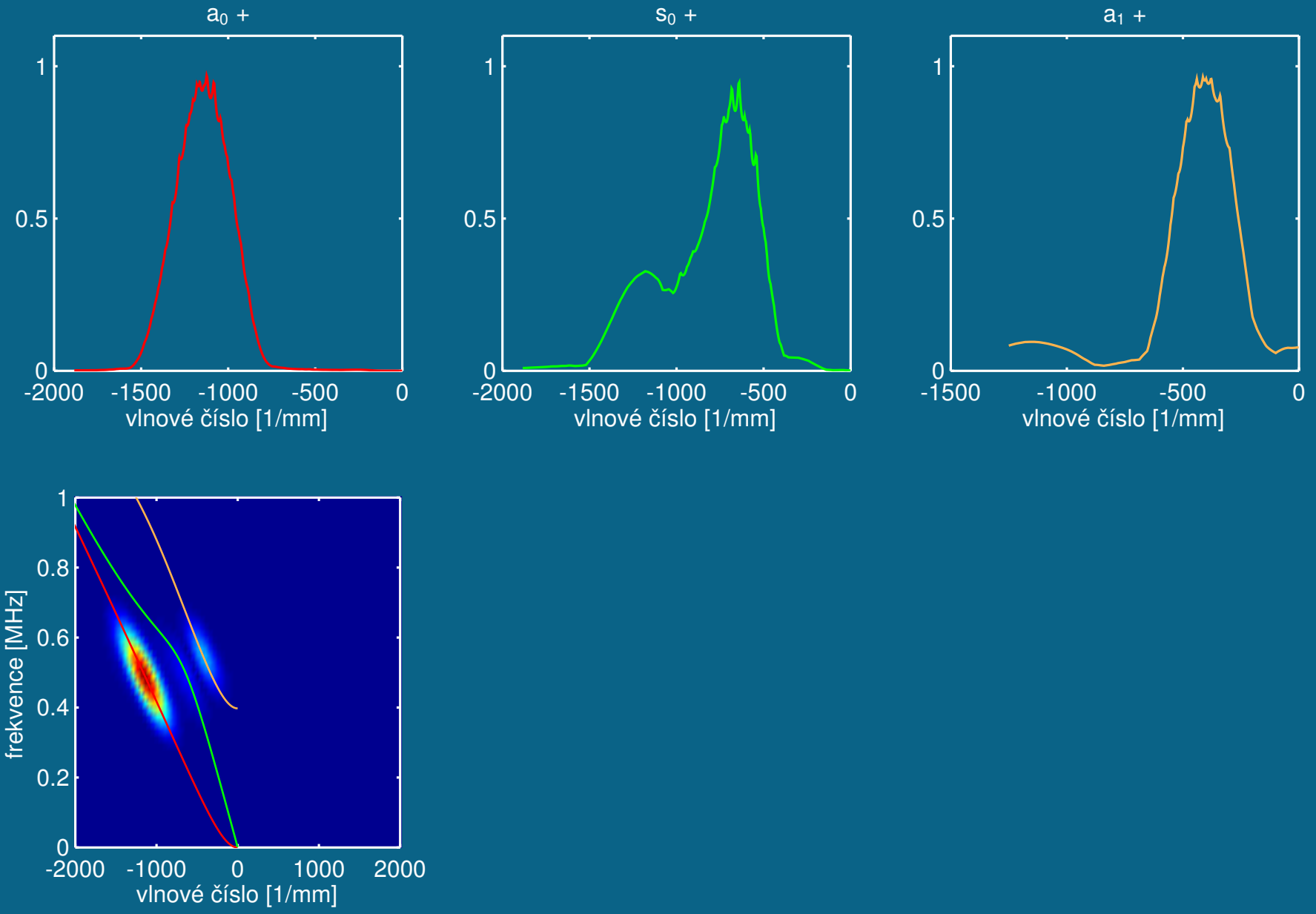
## Oblast za vrubem - šířka vrubu: 0,5 mm



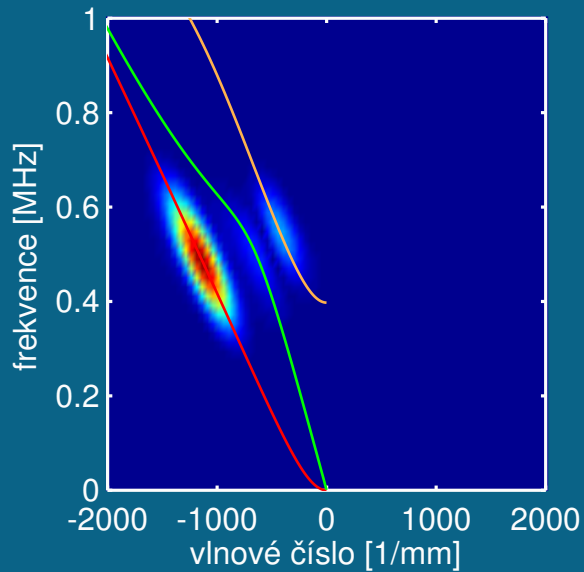
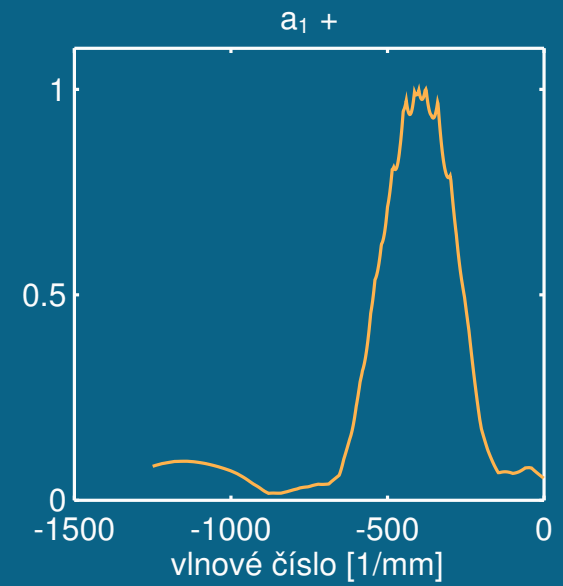
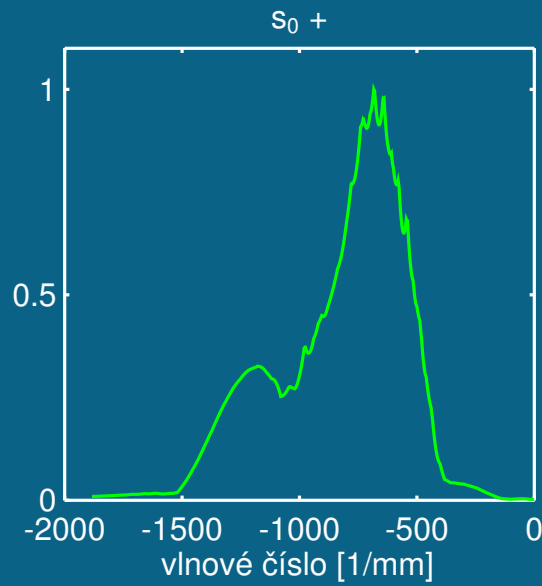
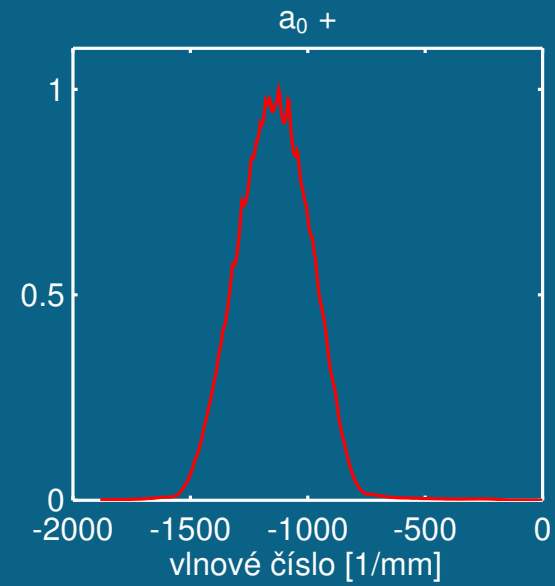
## Oblast za vrubem - šířka vrubu: 1 mm



# Oblast za vrubem - šířka vrubu: 1,5 mm



## Oblast za vrubem - šířka vrubu: 2 mm



## Závěr

Popsaná metoda (2D-FFT analýza) prokázala dostatečnou citlivost na rozlišení velikosti defektu.

### Parametry buzení:

- mód disperzní křivky (symetrický × antisymetrický),
- větev disperzní křivky,
- frekvenční rozsah (šířka budícího pulzu).

### Parametry filtrace:

- mód disperzní křivky,
- větev disperzní křivky,
- frekvenční rozsah.

## Závěr

Popsaná metoda (2D-FFT analýza) prokázala dostatečnou citlivost na rozlišení velikosti defektu.

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### Parametry filtrace:

- mód disperzní křivky,
- větev disperzní křivky,
- frekvenční rozsah.

### Výhled:

- simulace buzení piezoelektrickými budiči,
- simulace a detekce vrubů na válcové a trubkové geometrii.

## OBSAH

Motivace

Geometrie úlohy

Budící pulz

Parametry Comsolu

Disperzní vztahy pro tlustou desku

Disperzní křivky

Fourierova transformace ve 2D

Mód buzení  $a_0$

Mód buzení  $s_0$

Vliv hloubky vrubu

Vliv šířky vrubu

Závěr