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Soliton Interaction with Continuum

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SOLITON INTERACTION WITH CONTINUUM

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Communications

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OUTLINE

- Simulations of Soliton Timing Jitter for Increasing Amplifier Spacings

  Two effects: (a) noise penalty factor
  (b) continuum generation

- Equations of Motion for Non-Soliton Dispersive Wave (NSDW)
- NSDW may be continuum generated by neighboring soliton
- Closed Form Theory
- Comparison of Closed Form Theory with Simulation

SOLITON BASICS

Nonlinear Schrödinger Equation (NSE):

$$-i\frac{\partial u}{\partial z} = -\frac{\beta''}{2}\frac{\partial^2 u}{\partial t^2} + \kappa|u|^2 u$$

where

$u =$ pulse envelope

$z =$ propagation distance

$t =$ pulse time

$\beta'' =$ group vel. dispersion < 0

$\kappa =$ nonlinearity

Solution:

$$u(t,z) = A\,\mathrm{sech}\left(\frac{t}{\tau}\right)\exp\left(i\frac{|\beta''|\,z}{2\tau^2}\right)$$

where pulse FWHM $= 1.763\,\tau$

Fixed area property: $A\tau = \sqrt{-\beta''/\kappa}$

Soliton period: $z_0 = 0.5\,\pi\tau^2/|\beta''|$

PATH-AVERAGED SOLITON WITH OTHER EFFECTS

More general equation:

$$-i\frac{\partial u}{\partial z} = -i(g(z)-\alpha)u + \left(-\frac{\beta''}{2} - i\frac{1}{\Omega_{eff}^2}\right)\frac{\partial^2 u}{\partial t^2} + \kappa r^2|u|^2 u$$

where

$\Omega_{eff} =$ effective filtering

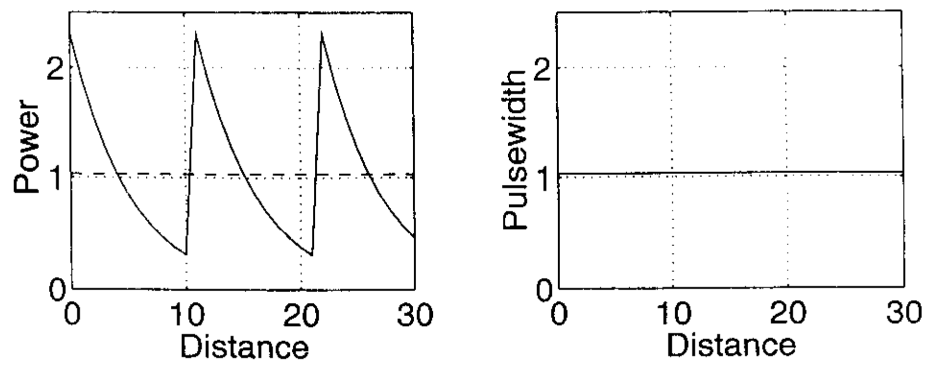
$g(z) =$ periodic gain

$\alpha =$ loss

$r^2 =$ path-averaging factor

where

$$r^2 = \frac{1-\exp[-\alpha Z_a]}{\alpha Z_a}; \quad Z_a = \text{amplifier spacing}$$



THE GORDON-HAUS EFFECT

Amplifier noise and group velocity dispersion cause random frequency shifts which lead to timing-jitter:

$$\left\langle \Delta T^2 \right\rangle \propto f z^3$$

Noise penalty factor:

$$f = \frac{(G-1)^2}{G(\ln G)^2}$$

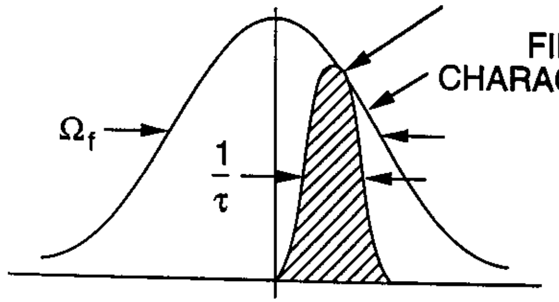
ONE CURE

In-line filters:

$$\left\langle \Delta T^2 \right\rangle \propto f z \qquad \text{for large } z$$

NOTE: For solitons, timing errors are more numerous than amplitude errors!

CONTROL OF GORDON-HAUS EFFECT BY FILTERS



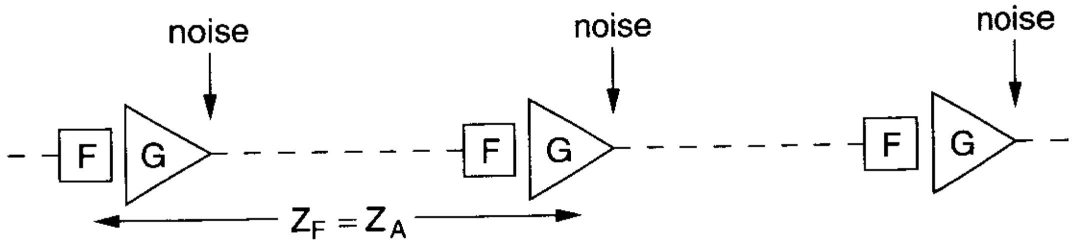
A. Mecozzi, J. D. Moores, H. A. Haus, & Y. Lai, Opt. Lett. (1991);
Y. Kodama and A. Hasegawa, Opt. Lett. (1992).

SIMULATIONS OF SOLITON PERTURBATIONS

(a) For varying amplifier and filter spacing; noise and continuum

(b) With continuum only.

LONG DISTANCE SOLITON PROPAGATION: TYPICAL PARAMETERS



loss = 0.25 dB/km

FWHM = 20 ps = 1.76 τ

D = 0.5 ps/nm/km

$A_{eff} = 50\ \mu m^2$

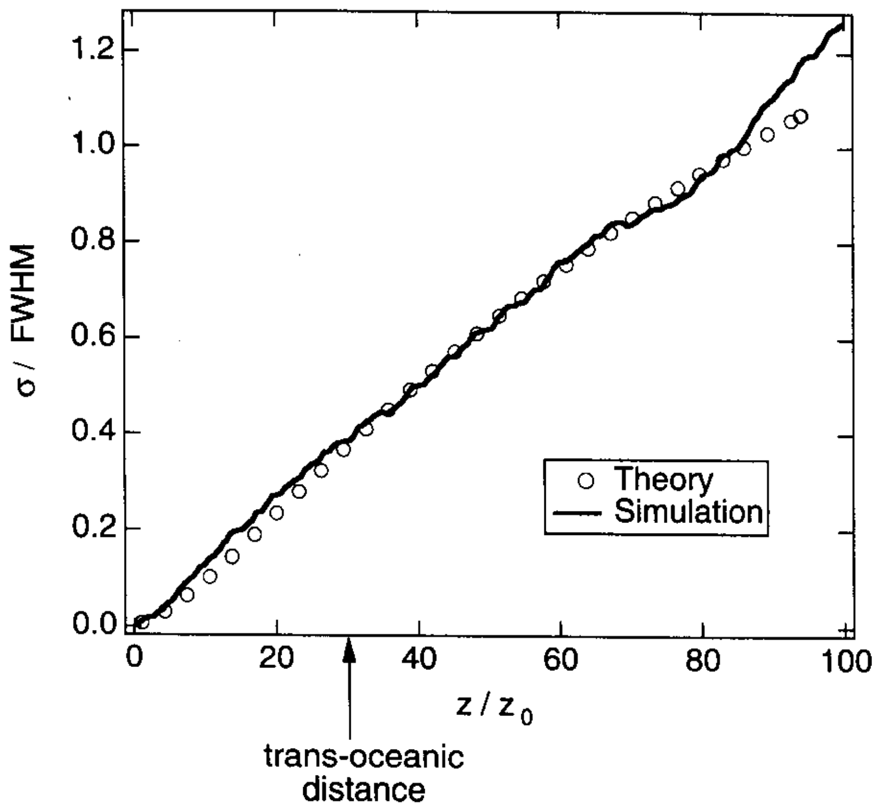
(effective filter length) $L_F = \Omega_F{}^2 \tau^2 Z_F = 9.4$ Mm

soliton period $Z_0 = 314$ km

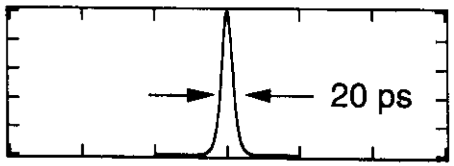
Z_A = amplifier spacing

Z_F = filter spacing

Timing jitter vs. distance for $z_A = 10$ km

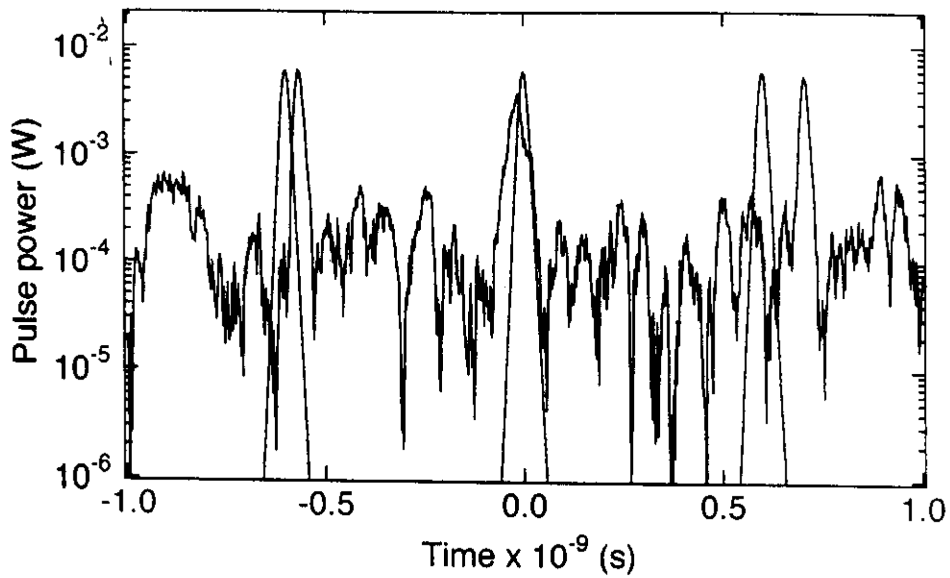


Initital condition



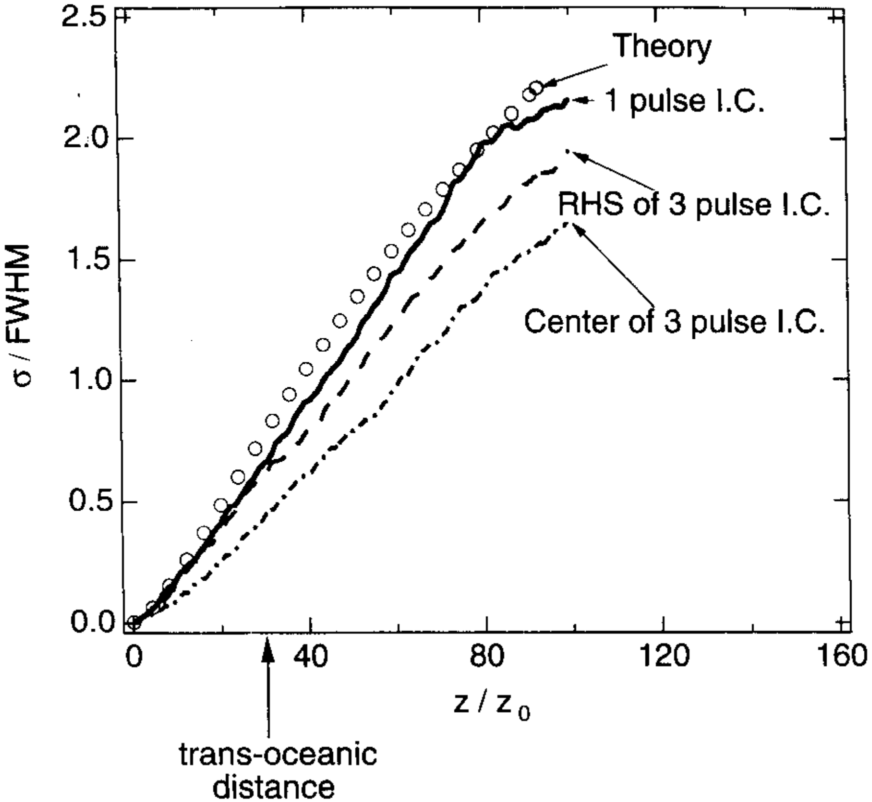
A. Mecozzi, J.D. Moores, H.A. Haus, and Y. Lai, *Optics Letters* **16**, 1841 (1991).
Y. Kodama and A. Hasegawa, *Optics Letters* **17**, 31 (1992).

Input and output pulse triplets

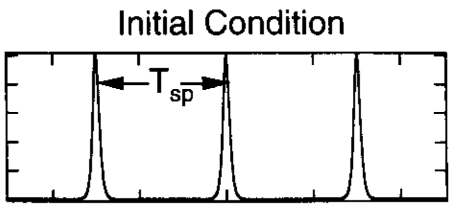


- Input pulses (red) are three N=1 solitons
- Output pulses are shown after propagating 100 z_0

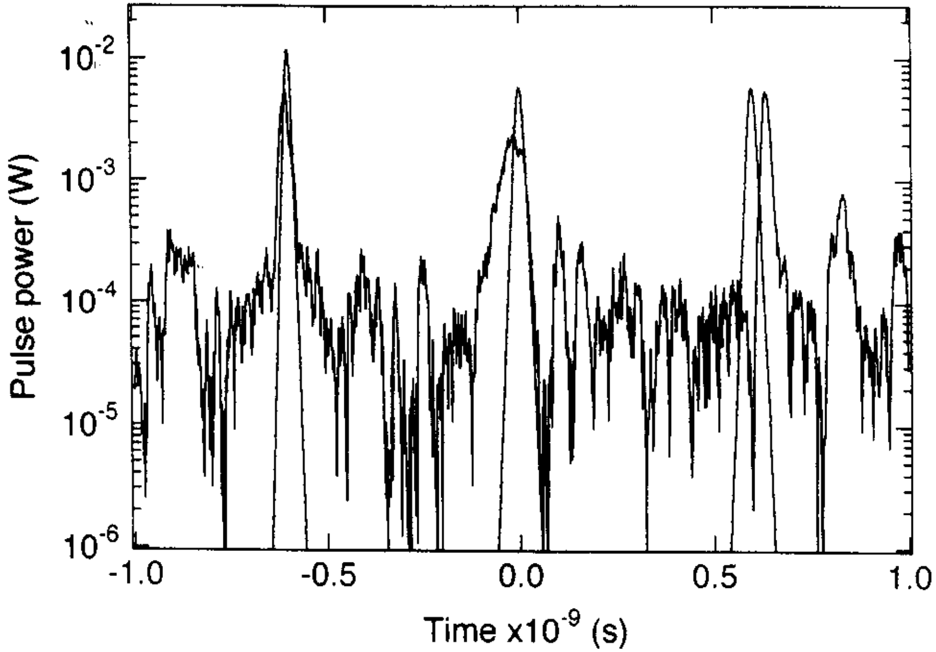
Timing jitter vs. distance for z_A = 50 km



τ_{FWHM} = 20 ps
T_{sp} = 30 τ_{FWHM}

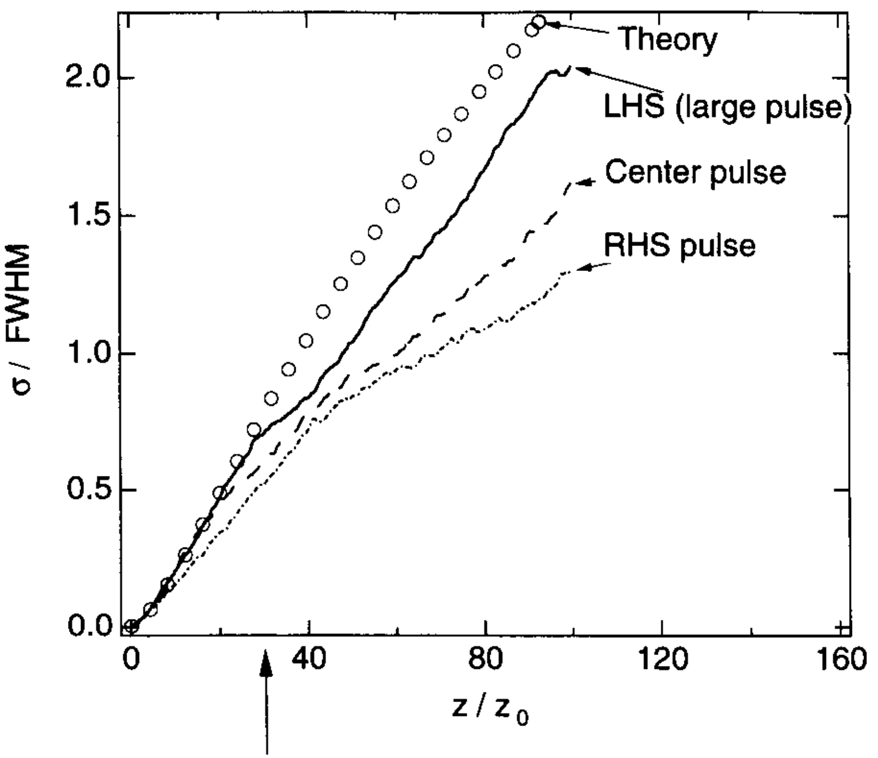


Input and output pulse triplets



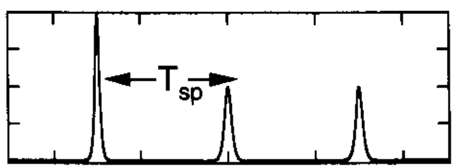
Input pulses (red) are three N=1 solitons where the LHS pulse has a normalized height of 1.4 .

Timing jitter for z_A = 50 km with one large pulse

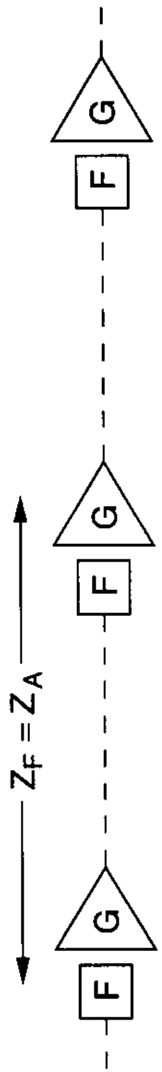


$\tau_{FWHM} = 20$ ps
$T_{sp} = 30\ \tau_{FWHM}$

Initial condition

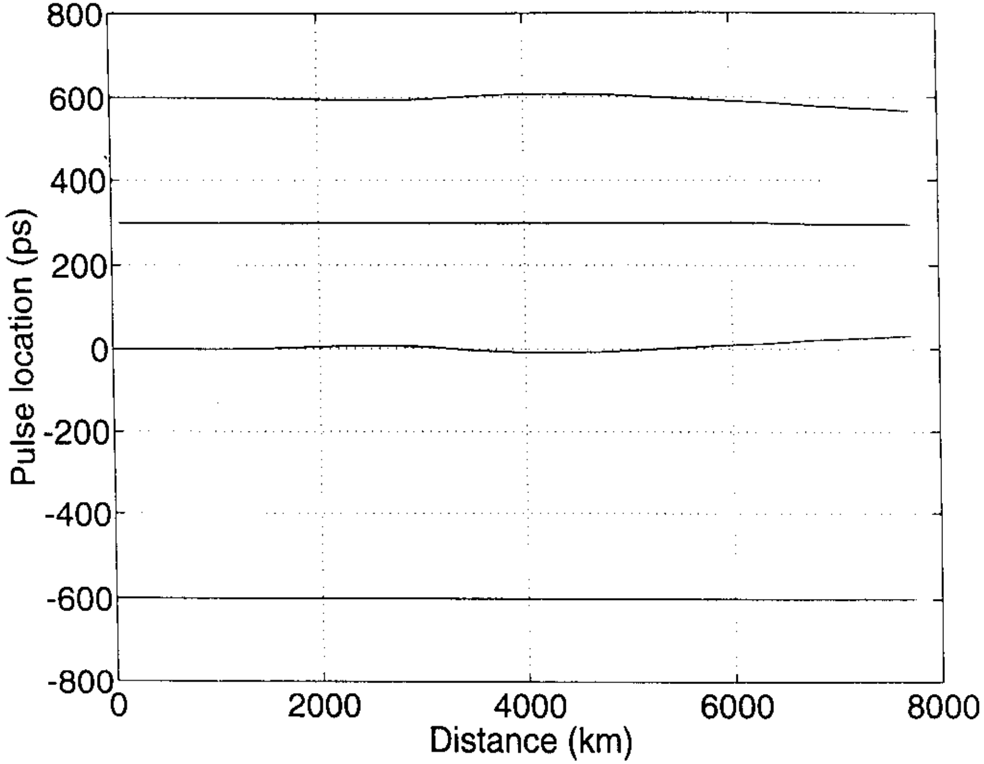


LONG DISTANCE SOLITON PROPAGATION: TYPICAL PARAMETERS

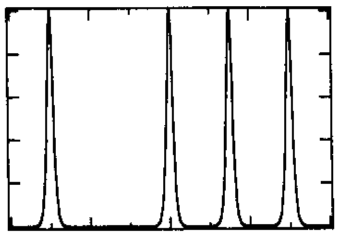


loss = 0.25 dB/km
FWHM = 10 ps = 1.76 τ
D = 0.5 ps/nm/km
$A_{eff} = 50\ \mu m^2$
$L_F = \Omega_F^2 \tau^2 Z_F = 18$ Mm

Pulse position vs. z for Z_A = 75 km without ASE noise

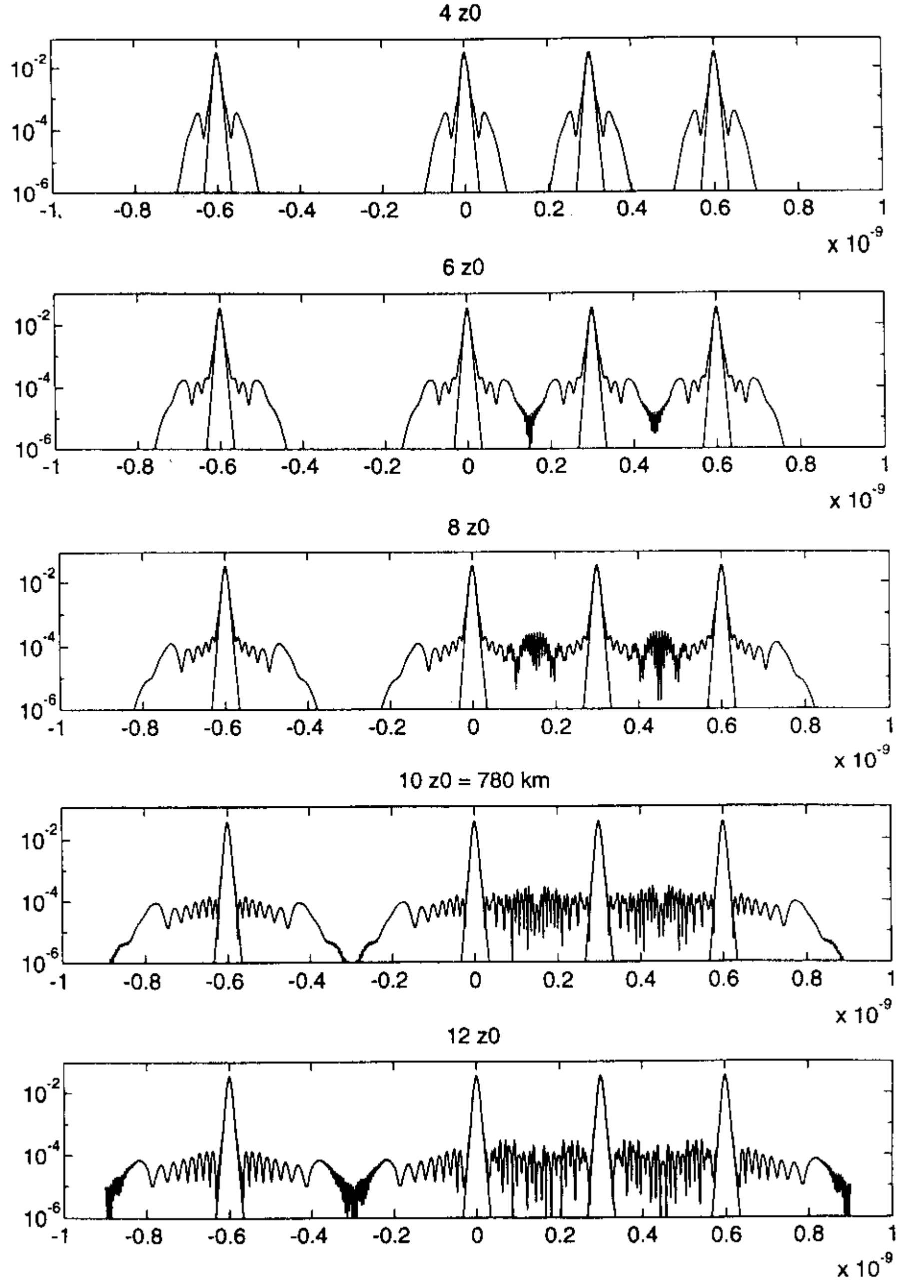


Intitial condition

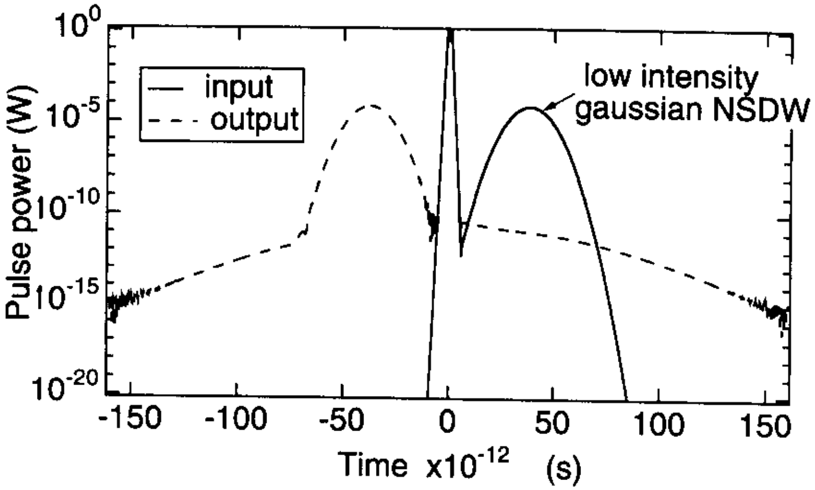


Total distance = 100 z_0

Log plots of pulses



Soliton interaction with a gaussian NSDW



$D = 10.45$ ps/nm/km
$\tau_{FWHM} = 0.64$ ps
$A_{eff} = 90\ \mu m^2$

<u>Gaussian NSDW normalized parameters</u>

width = 20
amplitude = 0.001
frequency = -4

Collision of a soliton with a gaussian NSDW