PLLSim

- An Ultra Fast Phase locked Loop Simulation Tool

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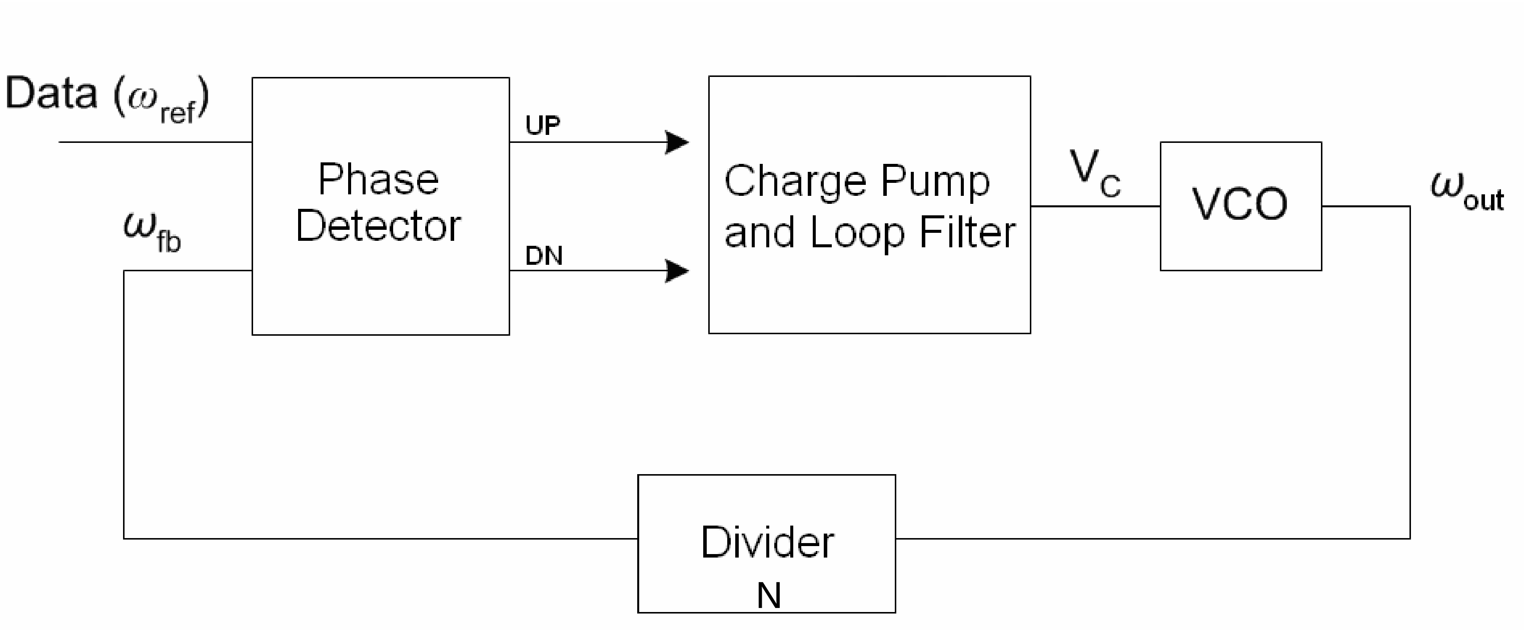
Presentation Overview

- PLLs, and why they are hard to simulate
- A behavioral model for bang-bang type PLLs
- Applying this model to make PLLSim
- Performance of PLLSim
- Modeling the non-ideal behavior typical of bang-bang PLLs
- Summary & Questions

Basic Charge Pump PLL

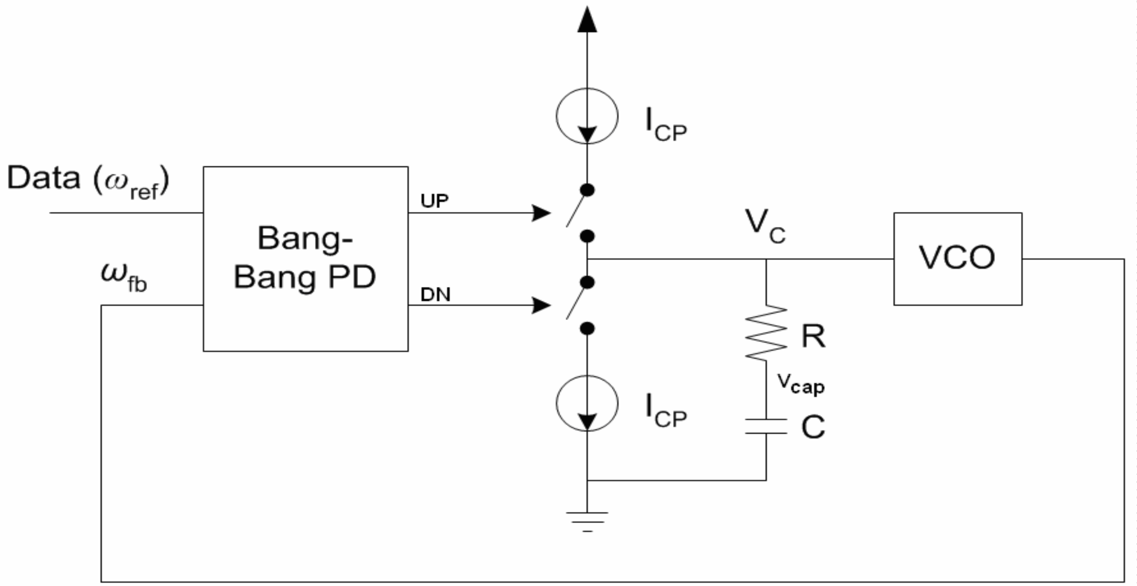


- For bang-bang type PLL's, parameters such as locking time, and capture range are not well understood.
- The design process relies heavily on simulation.

The Problem With Simulation

- Time step simulators such as Matlab Simulink, and SPICE are typically used
- We require tens to hundreds of time slices to simulate a period of the recovered clock
- The recovered clock can be significantly higher than the reference clock due to the divider
- A PLL typically requires several tens of thousands of cycles in order to achieve lock
- = **Excessively Long Simulation Times**

Modeling a 2nd order Bang-bang Phased Locked Loop



We Define:

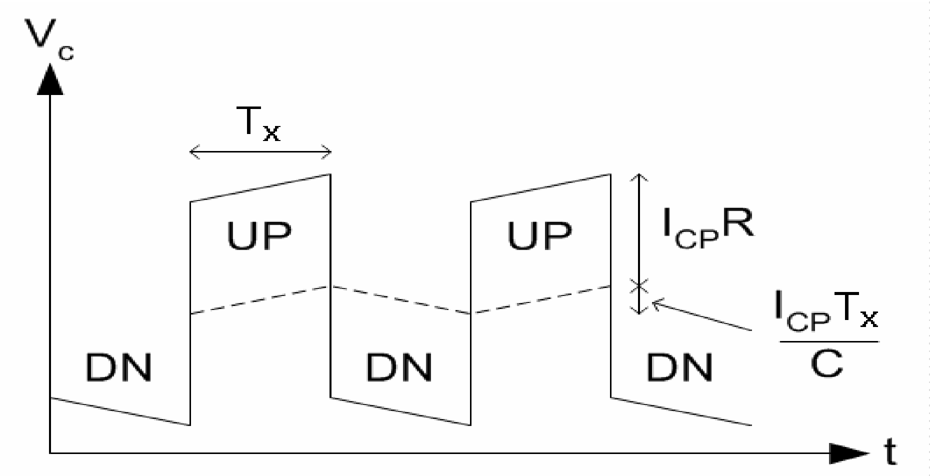
$\omega_{err}(t)$

$\varphi_{err}(t)$

$T_X(t)$

- PLL State is characterized by a frequency error and a phase error
- We calculate how these change every period of the reference signal

Ripple on the VCO control voltage due to UP and DN pulses



Based on the graph, we can calculate the change on phase and frequency error due to an UP or DN pulse

- $\Delta\omega(t) = K_{VCO}\, I_{cp}\, T_X(t) \,/\, C$
- $\Delta\varphi(t) = K_{VCO}\, I_{cp}\, R\, T_X(t) + 0.5\, T_X(t)\, \Delta\omega$
- $\omega_{err}(t + T_X(t)) = \omega(t) + \zeta\, \Delta\omega(t)$
- $\varphi_{err}(t + T_x(t)) = \varphi(t) + \zeta\, \Delta\varphi(t) + \omega_{err}(t)\, T_X(t)$
- $\zeta = 1$ for an UP pulse, $\zeta = -1$ for a DN pulse

2^{nd} order Bang-bang PLL Model

We define $\Delta\omega`$ and $\Delta\varphi`$ as:

$$\Delta\omega` = K_{VCO} I_{cp} T_{ref} / C$$

$$\Delta\varphi` = K_{VCO} I_{cp} R T_{ref} + ½ T_{ref} \Delta\omega`$$

∞

$$\Delta\omega(t) = \Delta\omega` T_X(t) / T_{ref}$$

$$\Delta\varphi(t) = (\Delta\varphi` - ½ T_{ref} \Delta\omega`) + ½ T_X(t) \Delta\omega(t)$$

PLL system can be summarised by $\Delta\omega`$ and $\Delta\varphi`$

2^{nd} order Bang-bang PLL Model

During an UP pulse:

$$T_X(t) = 2\pi / (\omega_{fb}(t) + K_{VCO} I_{cp} R + ½ \Delta\omega(t))$$

During a DN pulse:

$$T_X(t) = 2\pi / (\omega_{fb}(t) - K_{VCO} I_{cp} R - ½ \Delta\omega(t))$$

The third term is very small comapared to the other terms, so can be approximated by $\Delta\omega`$ with negligible loss in accuracy.

We have:

$$T_X(t) = 2\pi / (\omega_{fb} (t) + \zeta (\Delta\varphi` / T_{ref)}))$$

$$= 2\pi / (\omega_{ref} + \omega_{err}(t) + \zeta (\Delta\varphi` / T_{ref)}))$$

In Summary

$$\omega_{err}(t + T_X(t)) = \omega(t) + \zeta\,\Delta\omega(t)$$

$$\varphi_{err}(t + T_x(t)) = \varphi(t) + \zeta\,\Delta\varphi(t) + \omega_{err}(t)\,T_X(t)$$

$\zeta = 1$ for an UP pulse, $\zeta = -1$ for a DN pulse

$$\Delta\omega(t) = \Delta\omega`\ T_X(t) / T_{ref}$$

$$\Delta\varphi(t) = (\Delta\varphi` - ½\ T_{ref}\,\Delta\omega`) + ½\ T_X(t)\,\Delta\omega(t)$$

$$T_X(t) = 2\pi / (\omega_{ref} + \omega_{err}(t) + \zeta\,(\Delta\varphi` / T_{ref)}))$$

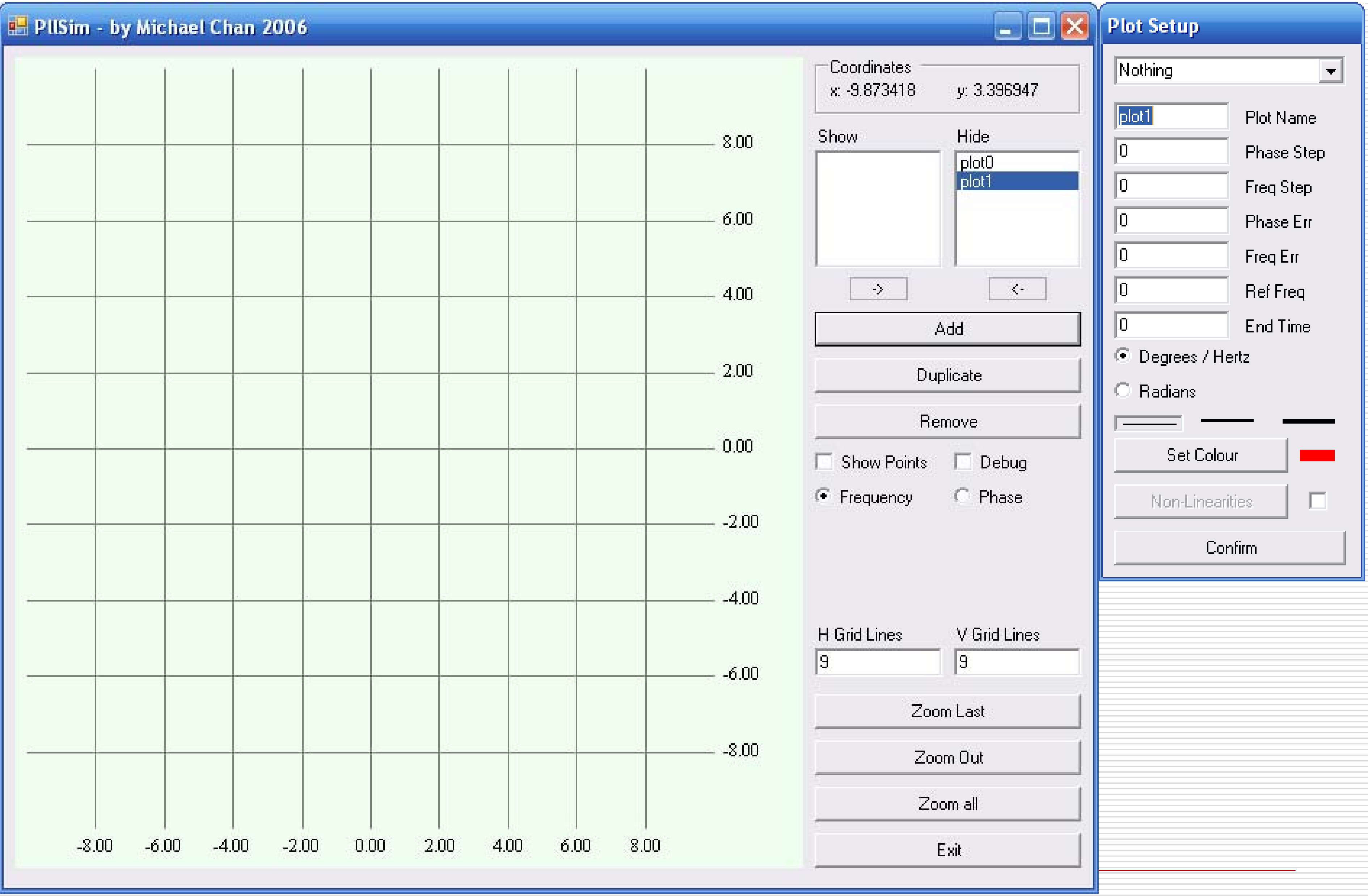
$$\Delta\omega` = K_{VCO}\,I_{cp}\,T_{ref} / C$$

$$\Delta\varphi` = K_{VCO}\,I_{cp}\,R\,T_{ref} + ½\ T_{ref}\,\Delta\omega`$$

PLLSim Engine

We have state variables: ω_{err}, φ_{err}, *and t*

1) Check our phase error: +ve = DN pulse, -ve = UP pulse
2) Calculate $T_X(t)$, and update t, $\omega_{err}(t)$, and $\varphi_{err}(t)$ according to our equations
3) Store results (t, ω_{err}) and (t, φ_{err})
4) Goto 1)


PllSim - by Michael Chan 2006
8.00
6.00
4.00
2.00
0.00
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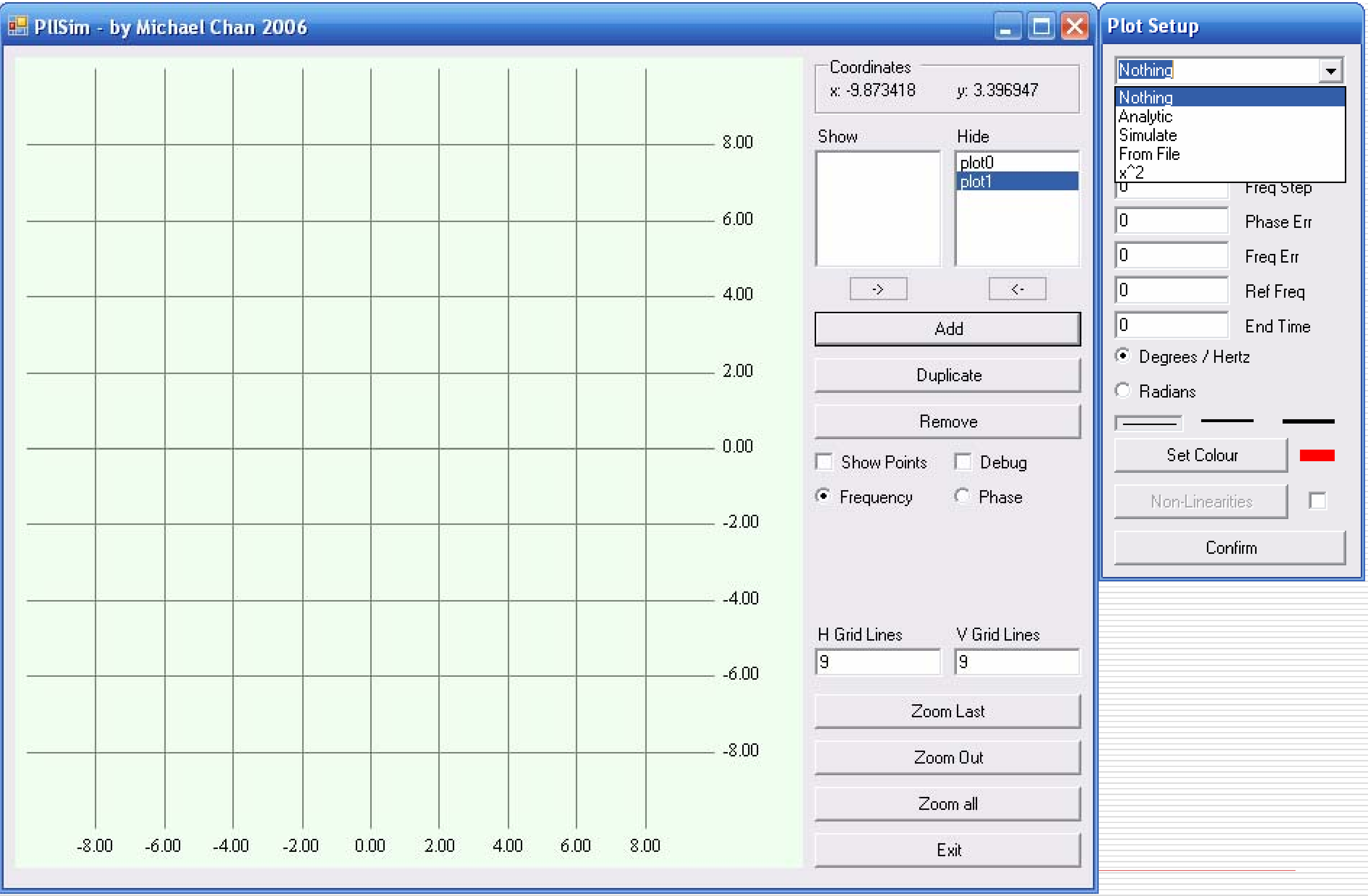
-4.00
-6.00
-8.00
-8.00
-6.00
-4.00
-2.00
0.00
2.00
4.00
6.00
8.00
Coordinates
x: -9.873418
y: 3.396947
Show
Hide
plot0
plot1
->
<-
Add
Duplicate
Remove
Show Points
Debug
Frequency
Phase
H Grid Lines
V Grid Lines
9
9
Zoom Last
Zoom Out
Zoom all
Exit
Plot Setup
Nothing
plot1
Plot Name
0
Phase Step
0
Freq Step
0
Phase Err
0
Freq Err
0
Ref Freq
0
End Time
Degrees / Hertz
Radians
Set Colour
Non-Linearities
Confirm


PllSim - by Michael Chan 2006
Coordinates
x: -9.873418 y: 3.396947
Show
Hide
plot0
plot1
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Add
Duplicate
Remove
Show Points
Debug
Frequency
Phase
H Grid Lines
V Grid Lines
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Zoom Last
Zoom Out
Zoom all
Exit
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-8.00 -6.00 -4.00 -2.00 0.00 2.00 4.00 6.00 8.00
Plot Setup
Nothing
Nothing
Analytic
Simulate
From File
x^2
Freq Step
Phase Err
Freq Err
Ref Freq
End Time
0
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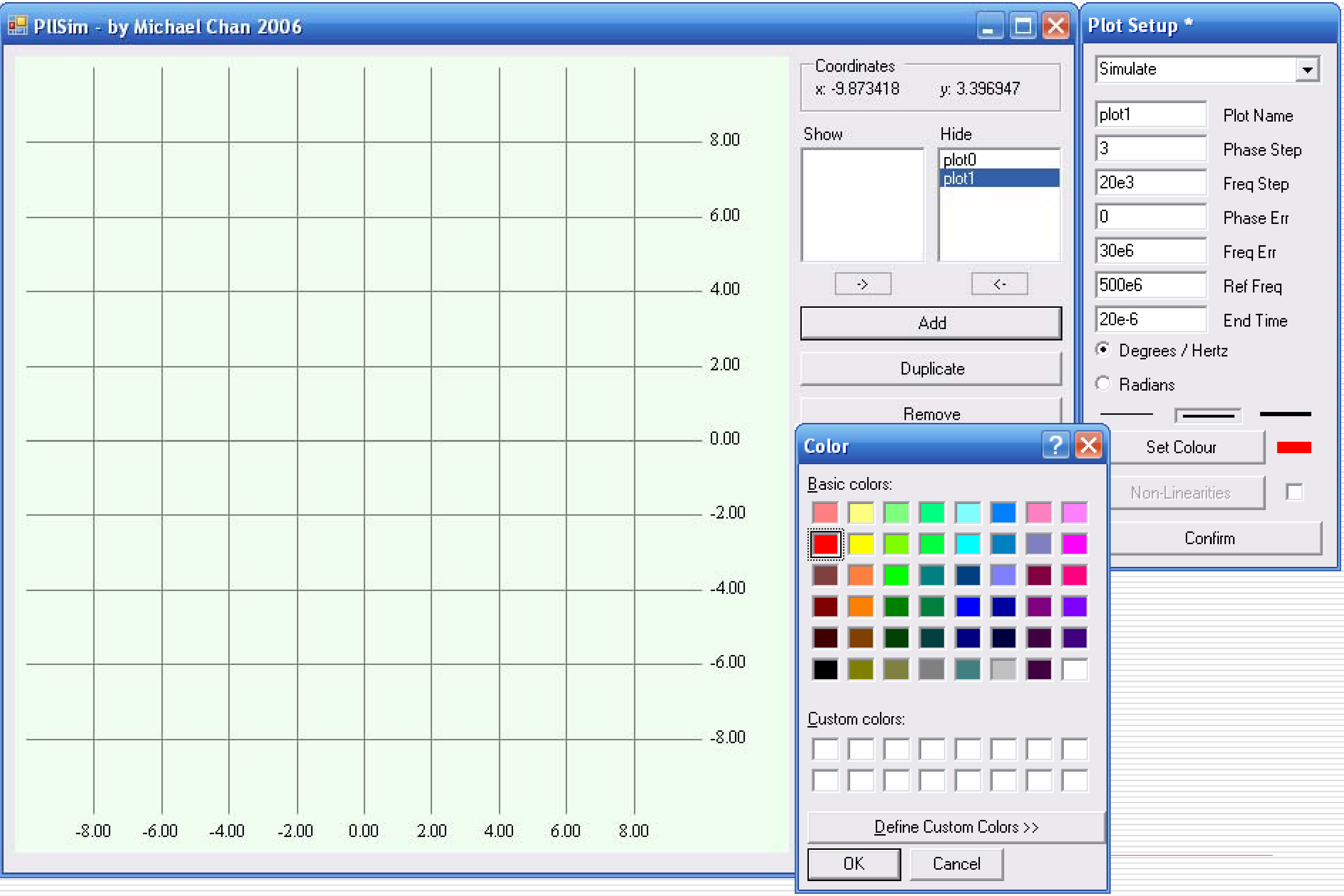
0
Degrees / Hertz
Radians
Set Colour
Non-Linearities
Confirm


PllSim - by Michael Chan 2006
Coordinates
x: -9.873418
y: 3.396947
Show
Hide
plot0
plot1
->
<-
Add
Duplicate
Remove
8.00
6.00
4.00
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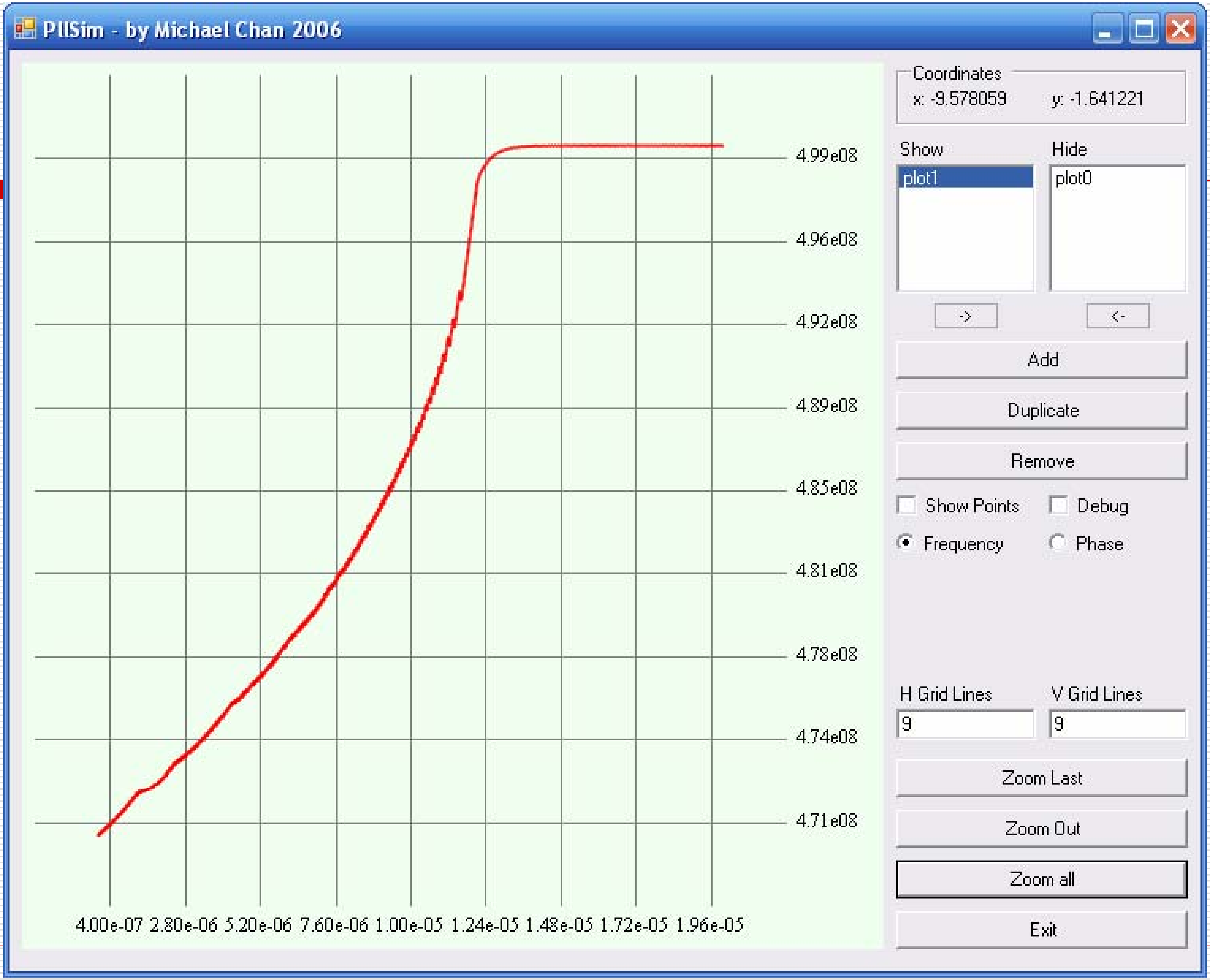
0.00
-2.00
-4.00
-6.00
-8.00
-8.00
-6.00
-4.00
-2.00
0.00
2.00
4.00
6.00
8.00
Plot Setup *
Simulate
plot1
Plot Name
3
Phase Step
20e3
Freq Step
0
Phase Err
30e6
Freq Err
500e6
Ref Freq
20e-6
End Time
Degrees / Hertz
Radians
Set Colour
Non-Linearities
Confirm
Color
Basic colors:
Custom colors:
Define Custom Colors >>
OK
Cancel



PllSim - by Michael Chan 2006
Coordinates
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Show
plot1
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plot0
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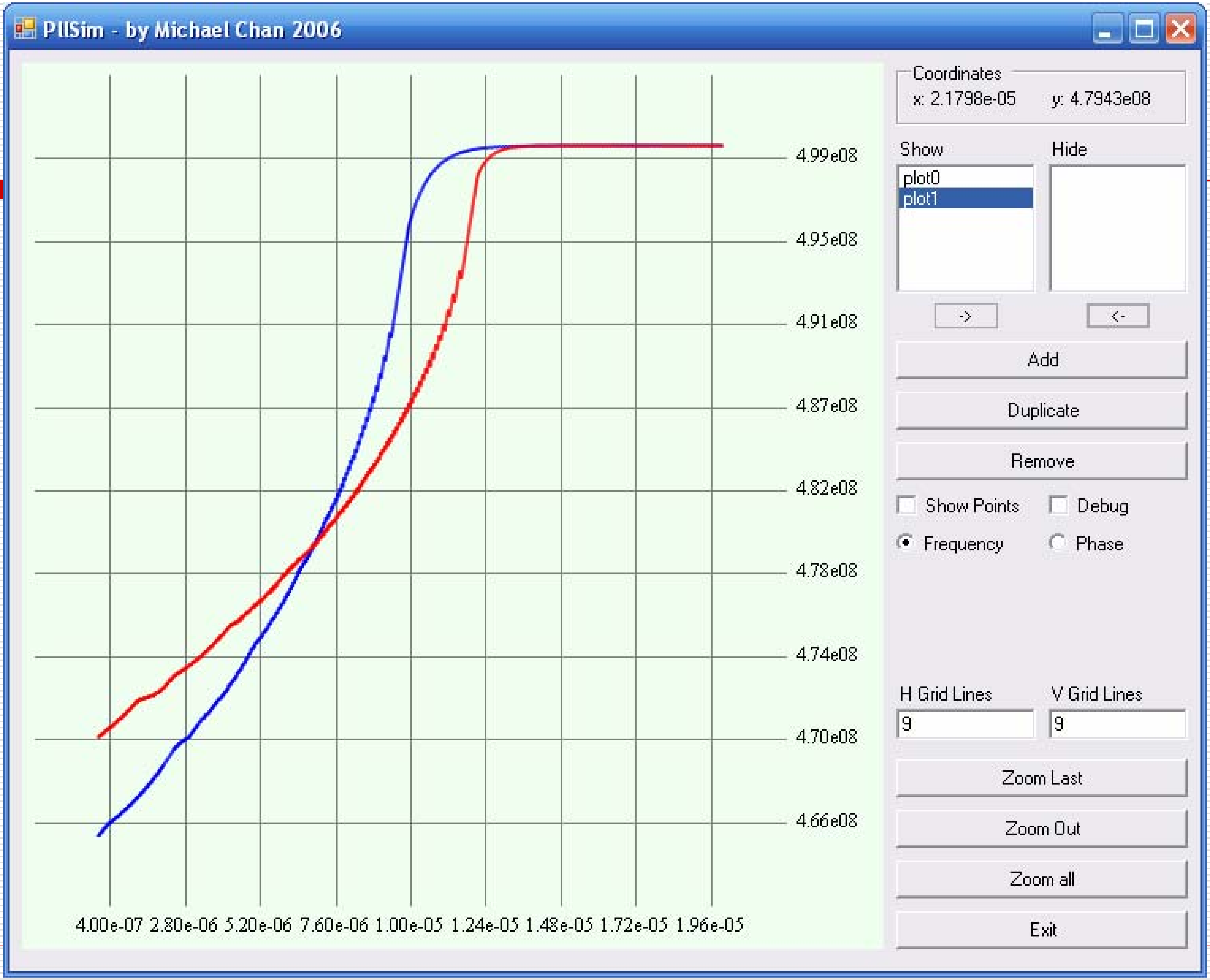
<-
Add
Duplicate
Remove
Show Points
Debug
Frequency
Phase
H Grid Lines
9
V Grid Lines
9
Zoom Last
Zoom Out
Zoom all
Exit
4.99e08
4.96e08
4.92e08
4.89e08
4.85e08
4.81e08
4.78e08
4.74e08
4.71e08
4.00e-07 2.80e-06 5.20e-06 7.60e-06 1.00e-05 1.24e-05 1.48e-05 1.72e-05 1.96e-05



PllSim - by Michael Chan 2006
Coordinates
x: 2.1798e-05
y: 4.7943e08
Show
Hide
plot0
plot1
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Add
Duplicate
Remove
Show Points
Debug
Frequency
Phase
H Grid Lines
V Grid Lines
9
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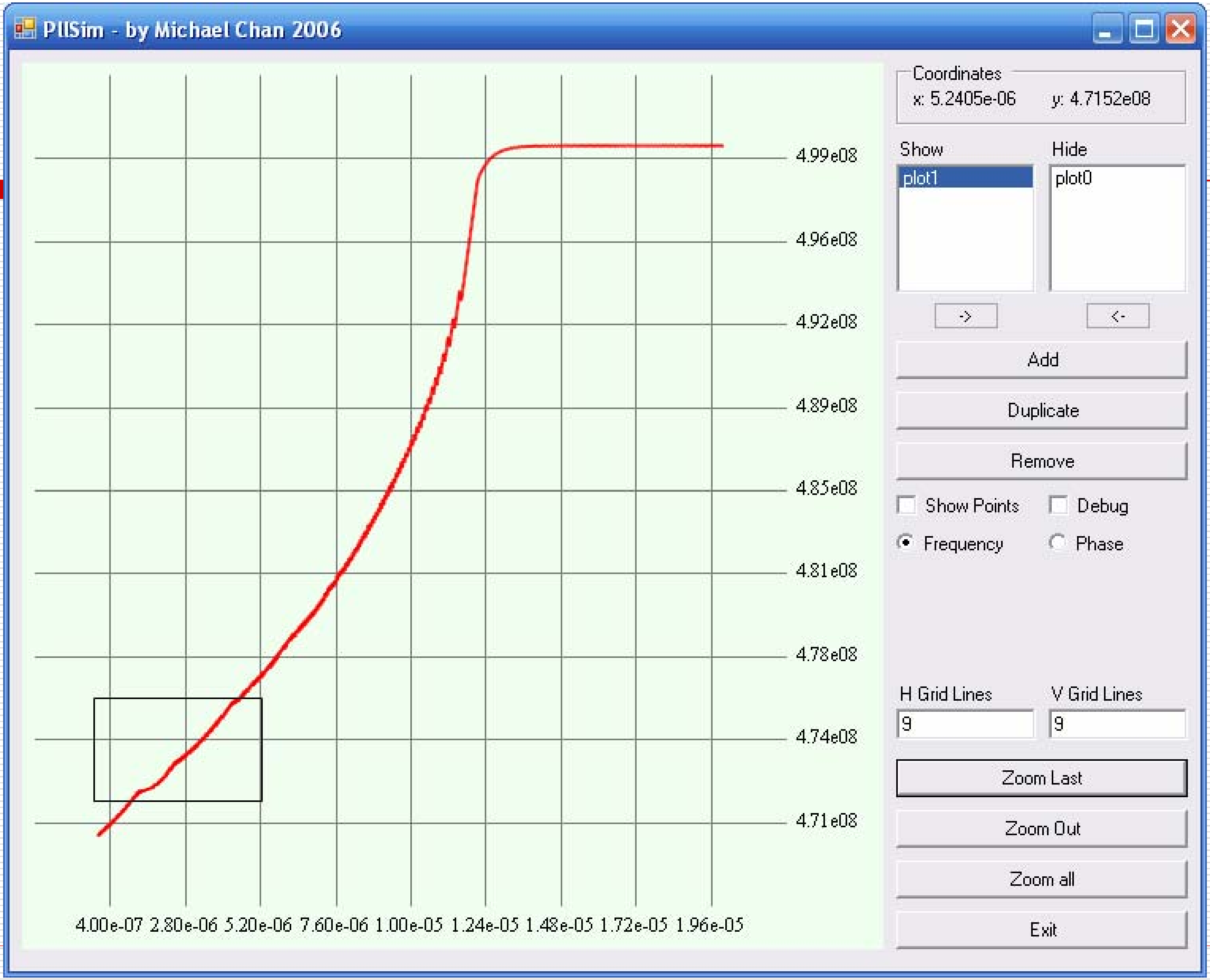
Zoom Last
Zoom Out
Zoom all
Exit
4.99e08
4.95e08
4.91e08
4.87e08
4.82e08
4.78e08
4.74e08
4.70e08
4.66e08
4.00e-07 2.80e-06 5.20e-06 7.60e-06 1.00e-05 1.24e-05 1.48e-05 1.72e-05 1.96e-05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Coordinates
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y: 4.7152e08
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plot1
plot0
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Add
Duplicate
Remove
Show Points
Debug
Frequency
Phase
H Grid Lines
V Grid Lines
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9
Zoom Last
Zoom Out
Zoom all
Exit
4.99e08
4.96e08
4.92e08
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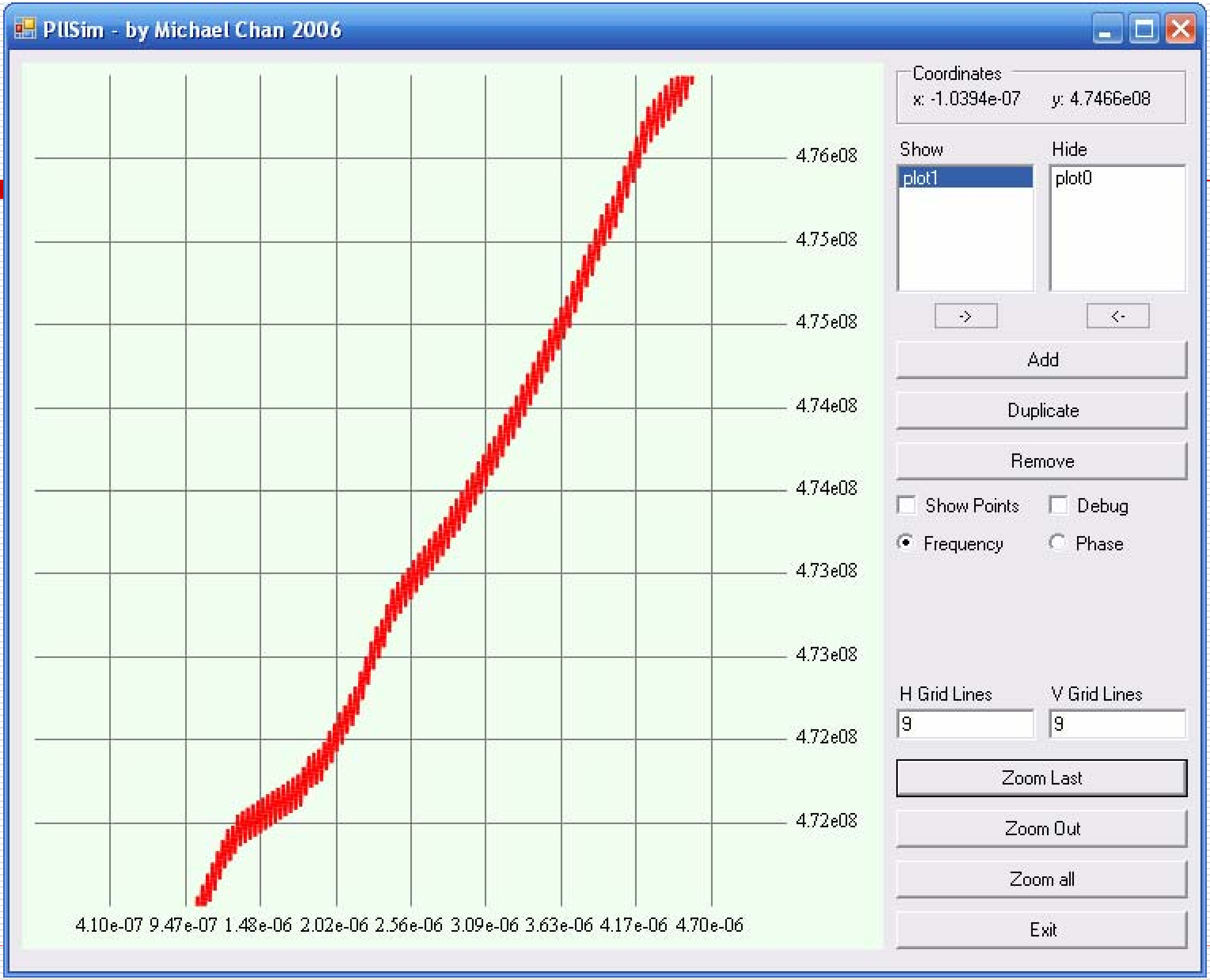
4.74e08
4.71e08
4.00e-07 2.80e-06 5.20e-06 7.60e-06 1.00e-05 1.24e-05 1.48e-05 1.72e-05 1.96e-05


PllSim - by Michael Chan 2006
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4.75e08
4.75e08
4.74e08
4.74e08
4.73e08
4.73e08
4.72e08
4.72e08
4.10e-07 9.47e-07 1.48e-06 2.02e-06 2.56e-06 3.09e-06 3.63e-06 4.17e-06 4.70e-06
Coordinates
x: -1.0394e-07 y: 4.7466e08
Show
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plot1
plot0
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Duplicate
Remove
Show Points
Debug
Frequency
Phase
H Grid Lines
V Grid Lines
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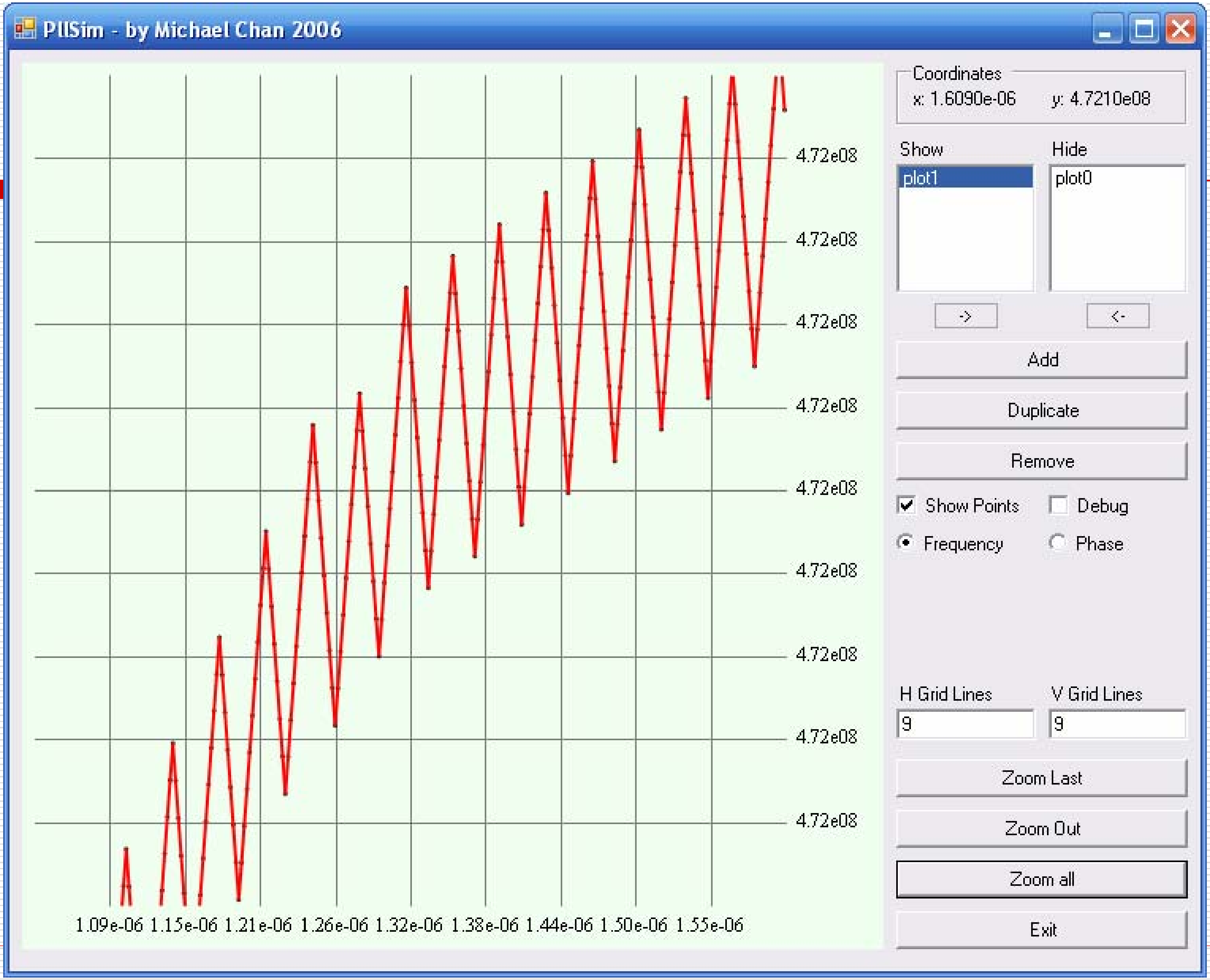
Zoom Last
Zoom Out
Zoom all
Exit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plot0
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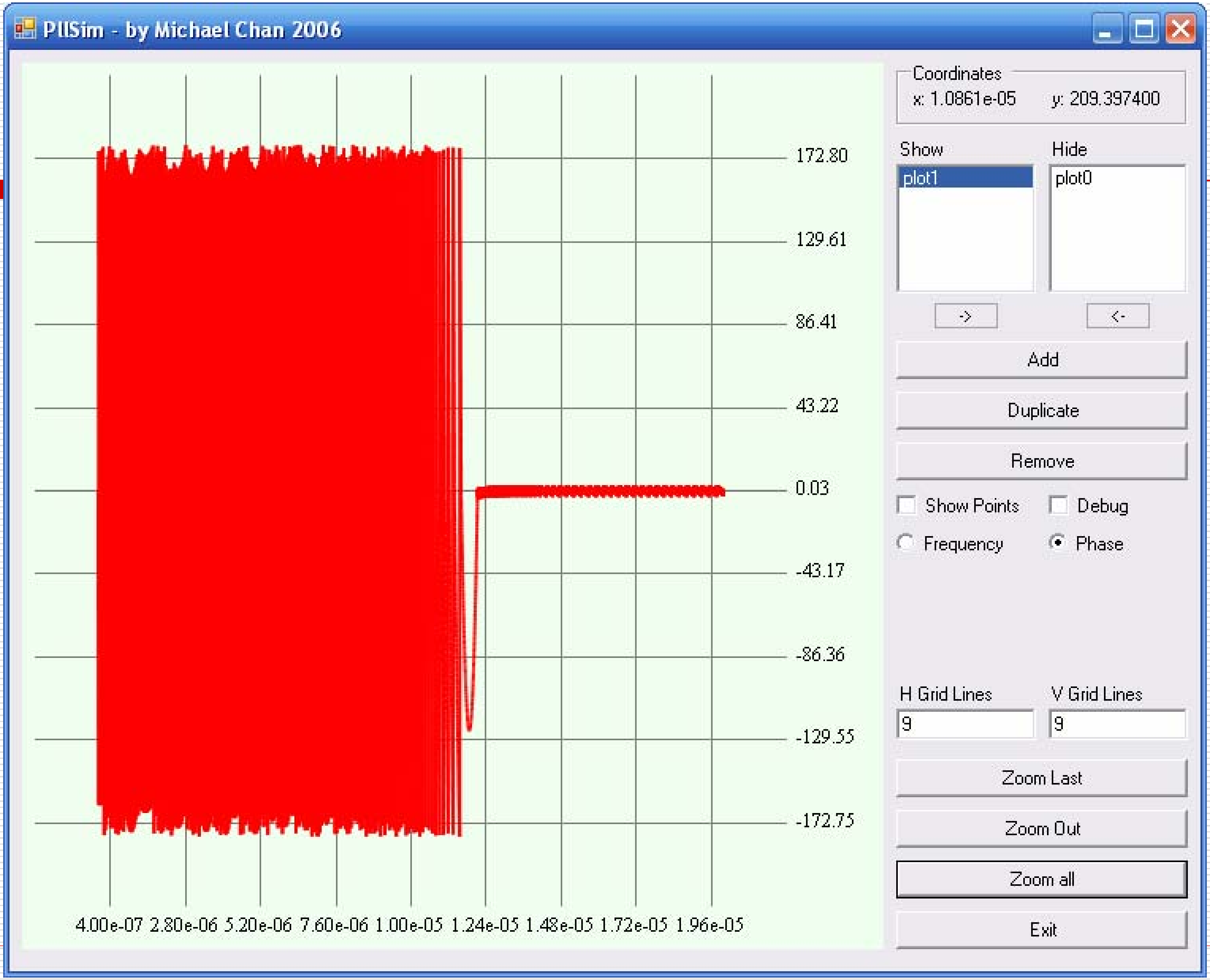
Add
Duplicate
Remove
Show Points
Debug
Frequency
Phase
H Grid Lines
V Grid Lines
9
9
Zoom Last
Zoom Out
Zoom all
Exit
4.72e08
1.09e-06 1.15e-06 1.21e-06 1.26e-06 1.32e-06 1.38e-06 1.44e-06 1.50e-06 1.55e-06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Coordinates
x: 1.0861e-05
y: 209.397400
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Hide
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plot0
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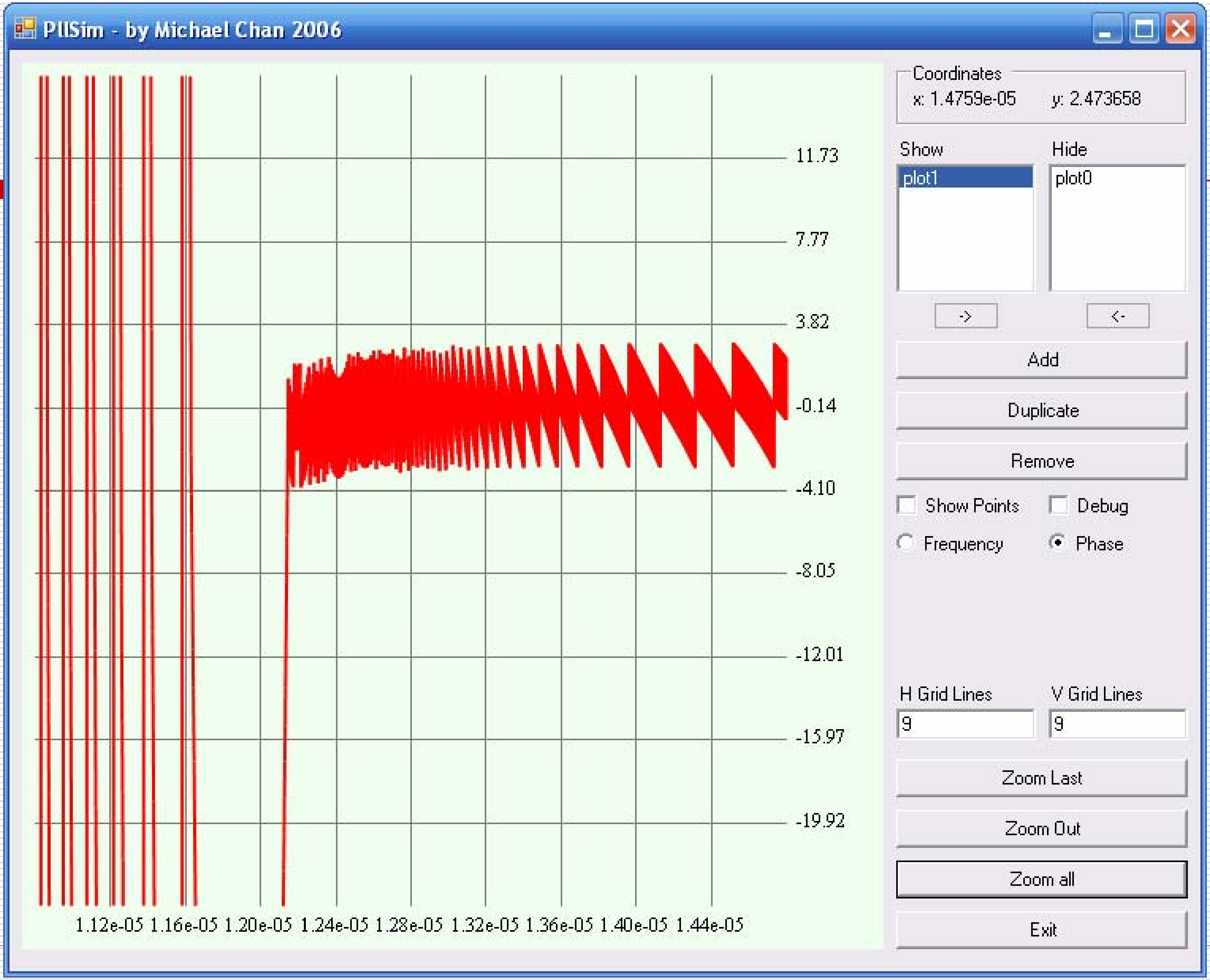
Add
Duplicate
Remove
Show Points
Debug
Frequency
Phase
H Grid Lines
V Grid Lines
9
9
Zoom Last
Zoom Out
Zoom all
Exit
172.80
129.61
86.41
43.22
0.03
-43.17
-86.36
-129.55
-172.75
4.00e-07 2.80e-06 5.20e-06 7.60e-06 1.00e-05 1.24e-05 1.48e-05 1.72e-05 1.96e-05


PllSim - by Michael Chan 2006
Coordinates
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y: 2.473658
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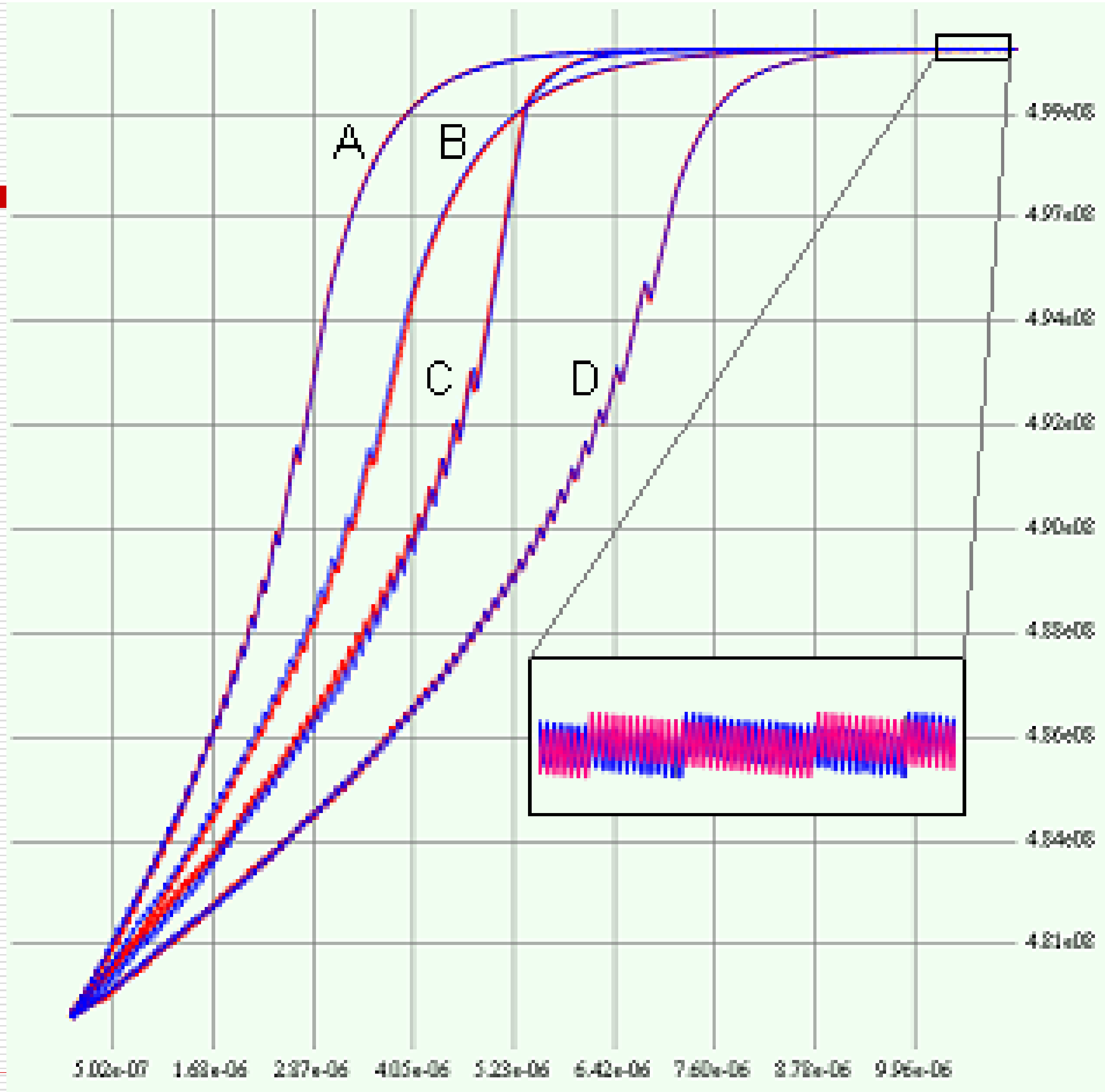
Hide
plot1
plot0
->
<-
Add
Duplicate
Remove
Show Points
Debug
Frequency
Phase
H Grid Lines
V Grid Lines
9
9
Zoom Last
Zoom Out
Zoom all
Exit
11.73
7.77
3.82
-0.14
-4.10
-8.05
-12.01
-15.97
-19.92
1.12e-05 1.16e-05 1.20e-05 1.24e-05 1.28e-05 1.32e-05 1.36e-05 1.40e-05 1.44e-05

Simulation Configurations

Plot	$\Delta\ \Phi`$	$\Delta\ \omega`$	ω_{ref}	$\omega_{err}(0)$	$\Phi_{err}(0)$
A	5°	20kHz	500MHz	20MHz	-90°
B	5°	15KHz	500MHz	20MHz	-90°
C	3°	20KHz	500MHz	20MHz	-90°
D	3°	15KHz	500MHz	20MHz	-90°

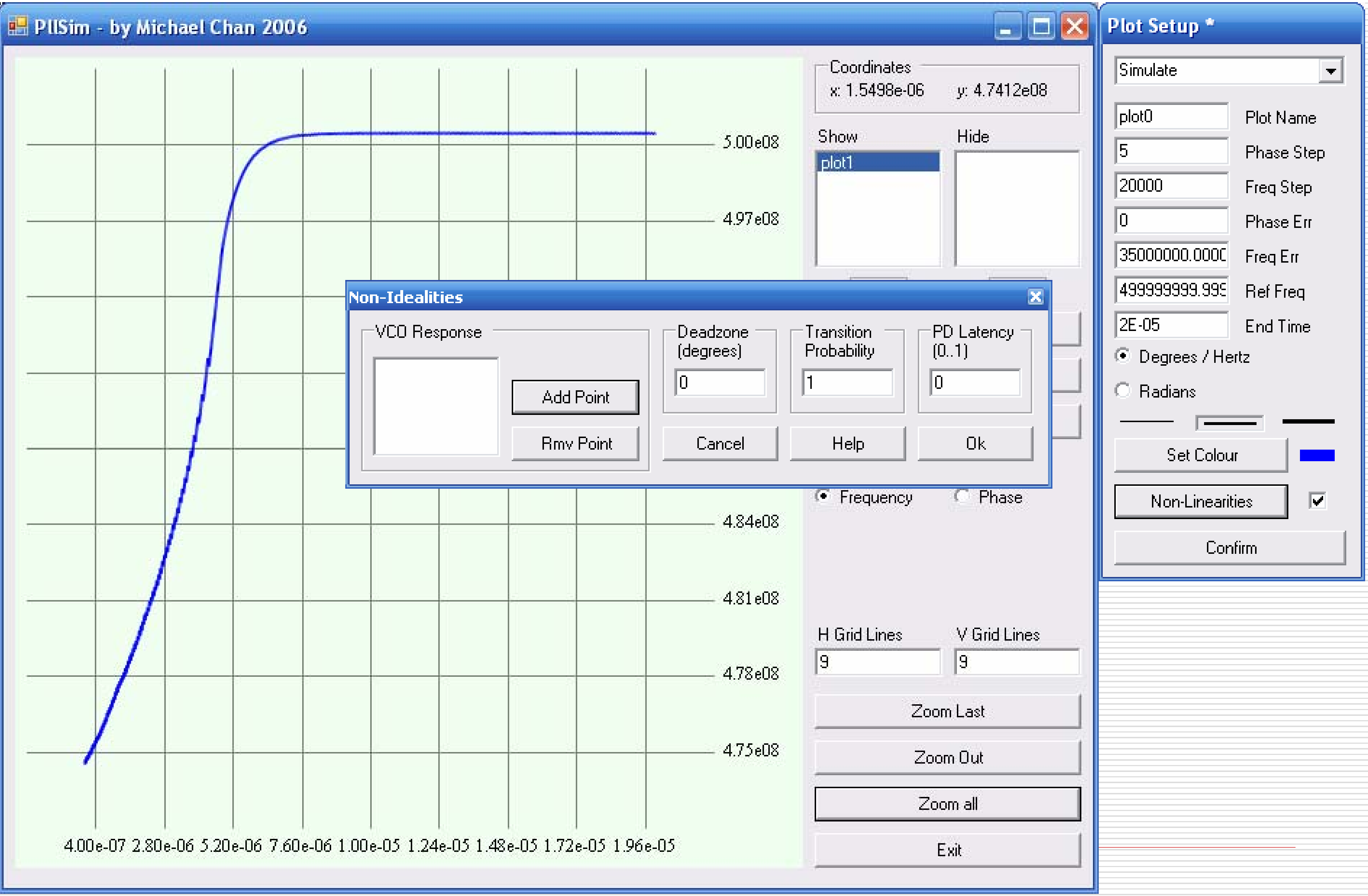
Performance Comparison

Simulation Configuration	Simulation Time	PLLSim Time	Simulink Time	Speedup
A	20 us	5.9 ms	389 s	6.95e04
B	30 us	8.8 ms	730 s	8.30e04
C	20 us	5.9 ms	403 s	6.83e04
D	30 us	8.7 ms	697 s	8.01e04

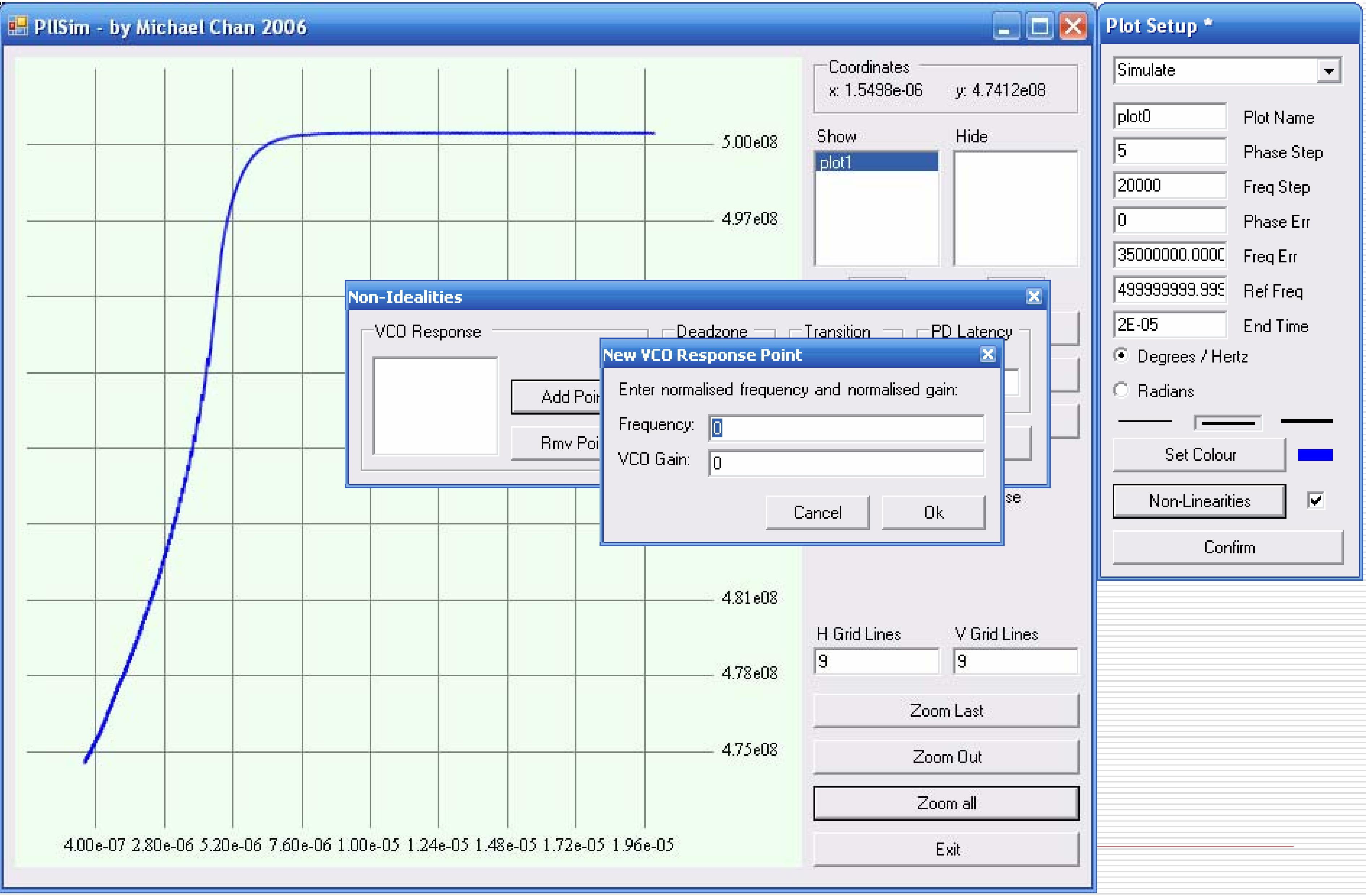

A
B
C
D
4.99e08
4.97e08
4.94e08
4.92e08
4.90e08
4.88e08
4.86e08
4.84e08
4.81e08
5.02e-07
1.68e-06
2.87e-06
4.05e-06
5.23e-06
6.42e-06
7.60e-06
8.78e-06
9.96e-06

Non Ideal Behavior

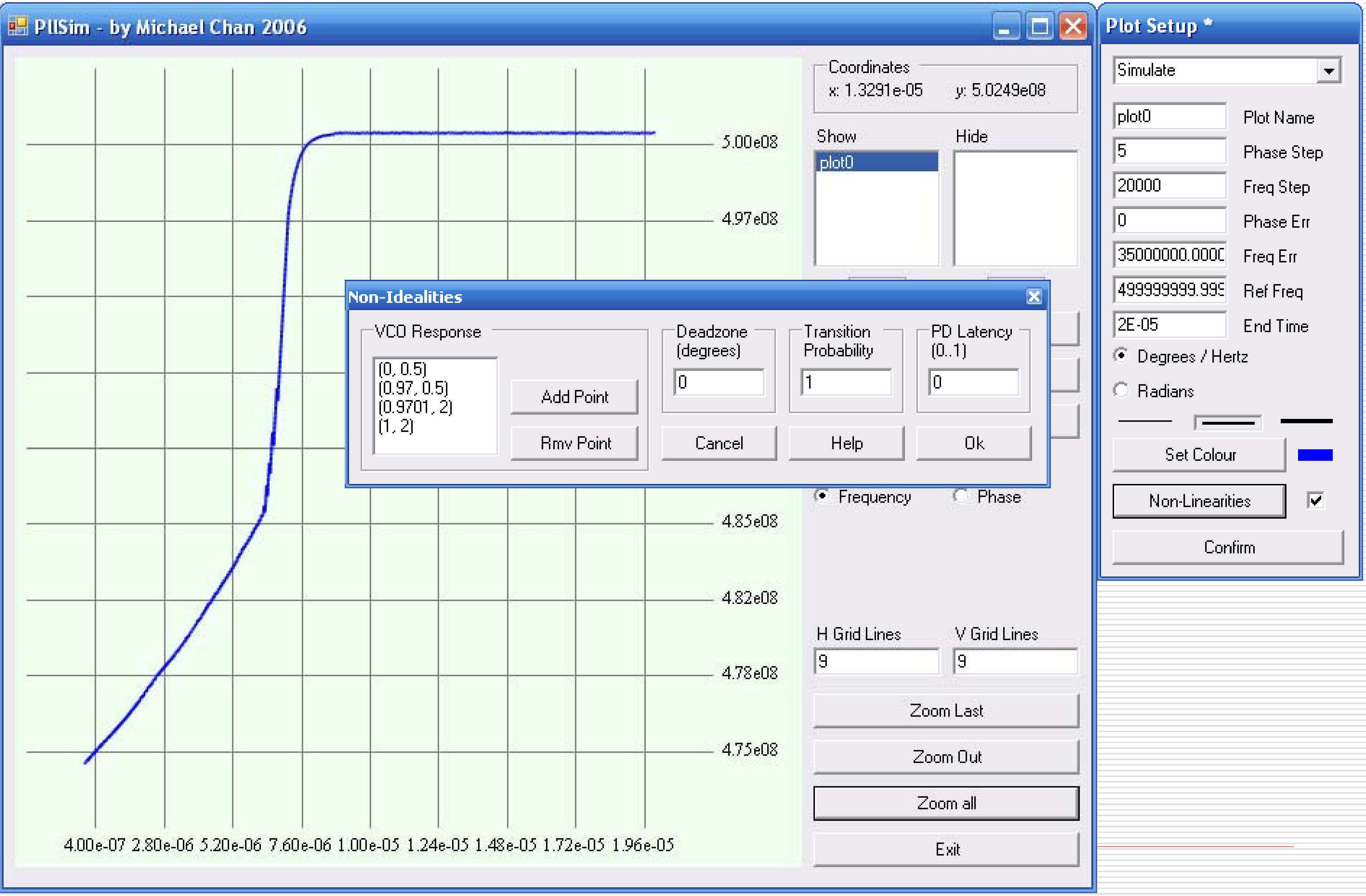
- Non-linear VCO response
- Phase detector deadzone
- Phase detector latency
- Also handle random reference data sources



PllSim - by Michael Chan 2006
Coordinates
x: 1.5498e-06 y: 4.7412e08
Show
Hide
plot1
5.00e08
4.97e08
4.84e08
4.81e08
4.78e08
4.75e08
4.00e-07 2.80e-06 5.20e-06 7.60e-06 1.00e-05 1.24e-05 1.48e-05 1.72e-05 1.96e-05
Non-Idealities
VCO Response
Add Point
Rmv Point
Deadzone (degrees)
0
Transition Probability
1
PD Latency (0..1)
0
Cancel
Help
Ok
Frequency
Phase
H Grid Lines
9
V Grid Lines
9
Zoom Last
Zoom Out
Zoom all
Exit
Plot Setup *
Simulate
plot0
Plot Name
5
Phase Step
20000
Freq Step
0
Phase Err
35000000.0000
Freq Err
499999999.999
Ref Freq
2E-05
End Time
Degrees / Hertz
Radians
Set Colour
Non-Linearities
Confirm



PllSim - by Michael Chan 2006
Coordinates
x: 1.5498e-06 y: 4.7412e08
Show
Hide
plot1
5.00e08
4.97e08
4.81e08
4.78e08
4.75e08
4.00e-07 2.80e-06 5.20e-06 7.60e-06 1.00e-05 1.24e-05 1.48e-05 1.72e-05 1.96e-05
Non-Idealities
VCO Response
Deadzone
Transition
PD Latency
Add Poi
Rmv Poi
New VCO Response Point
Enter normalised frequency and normalised gain:
Frequency: 0
VCO Gain: 0
Cancel
Ok
H Grid Lines
V Grid Lines
9
9
Zoom Last
Zoom Out
Zoom all
Exit
Plot Setup *
Simulate
plot0
Plot Name
5
Phase Step
20000
Freq Step
0
Phase Err
35000000.0000
Freq Err
499999999.999
Ref Freq
2E-05
End Time
Degrees / Hertz
Radians
Set Colour
Non-Linearities
Confirm



PllSim - by Michael Chan 2006
Coordinates
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Hide
plot0
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4.97e08
4.85e08
4.82e08
4.78e08
4.75e08
4.00e-07 2.80e-06 5.20e-06 7.60e-06 1.00e-05 1.24e-05 1.48e-05 1.72e-05 1.96e-05
Non-Idealities
VCO Response
(0, 0.5)
(0.97, 0.5)
(0.9701, 2)
(1, 2)
Add Point
Rmv Point
Deadzone (degrees)
0
Transition Probability
1
PD Latency (0..1)
0
Cancel
Help
Ok
Frequency
Phase
H Grid Lines
9
V Grid Lines
9
Zoom Last
Zoom Out
Zoom all
Exit
Plot Setup *
Simulate
plot0
Plot Name
5
Phase Step
20000
Freq Step
0
Phase Err
35000000.0000
Freq Err
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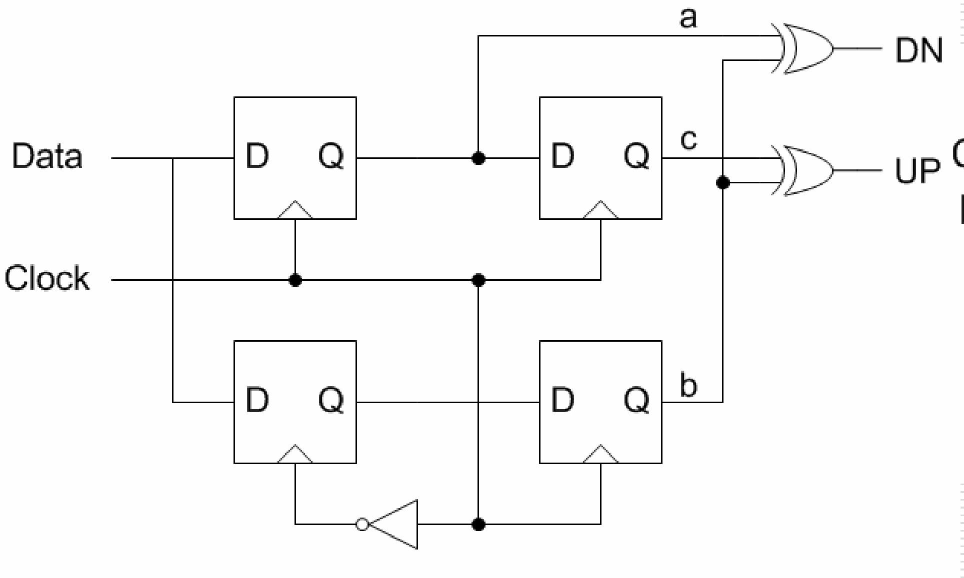
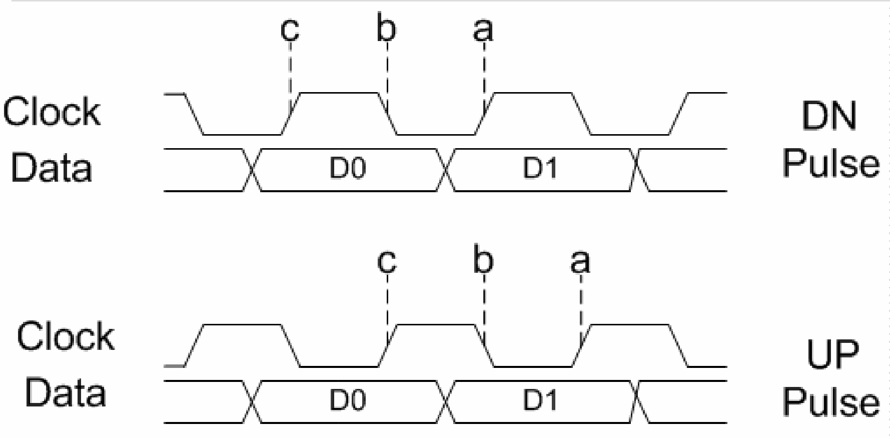
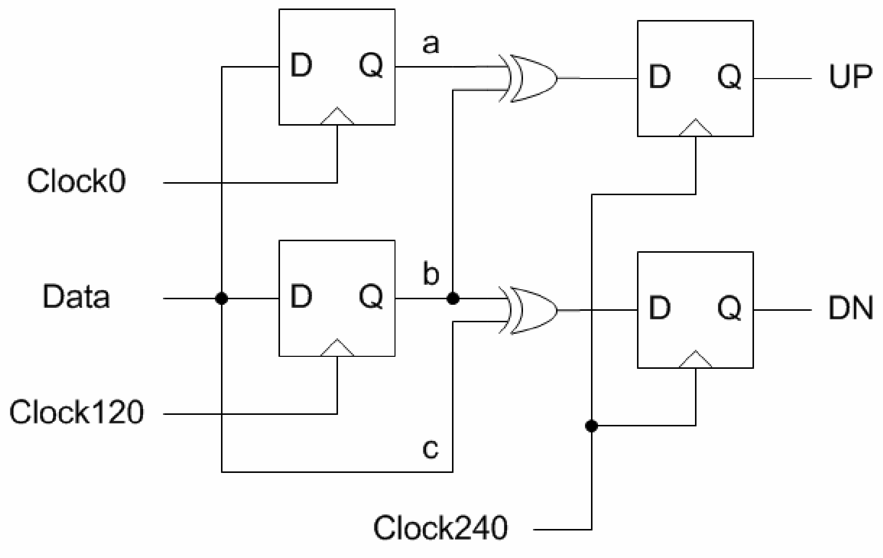
Ref Freq
2E-05
End Time
Degrees / Hertz
Radians
Set Colour
Non-Linearities
Confirm

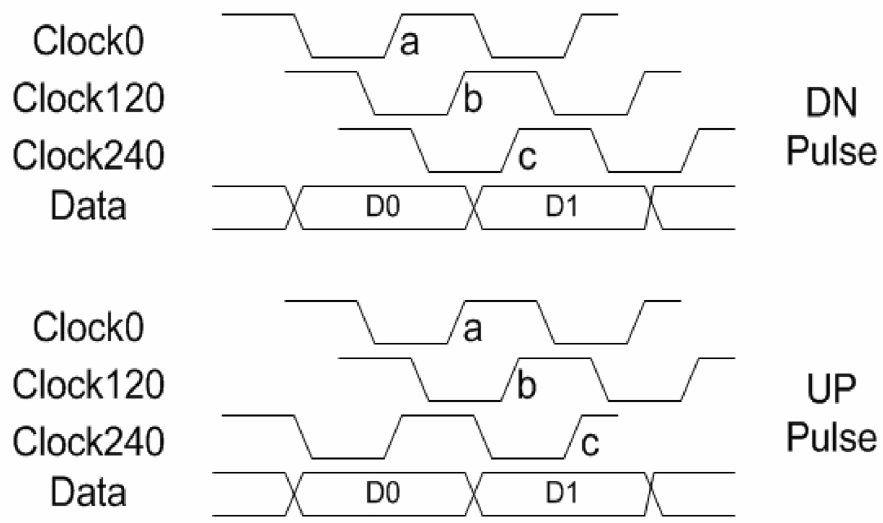
Latency in an Alexander PD

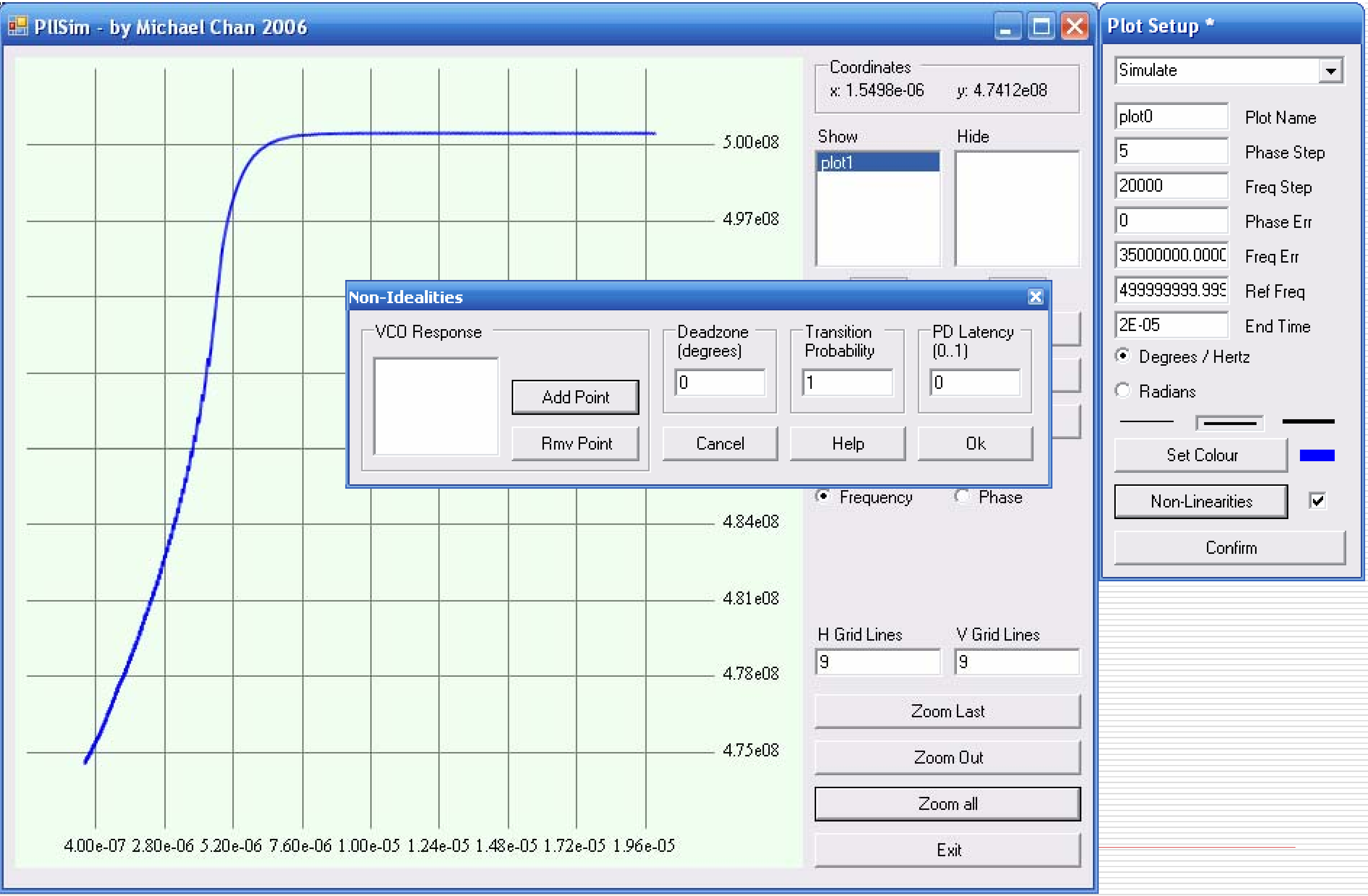


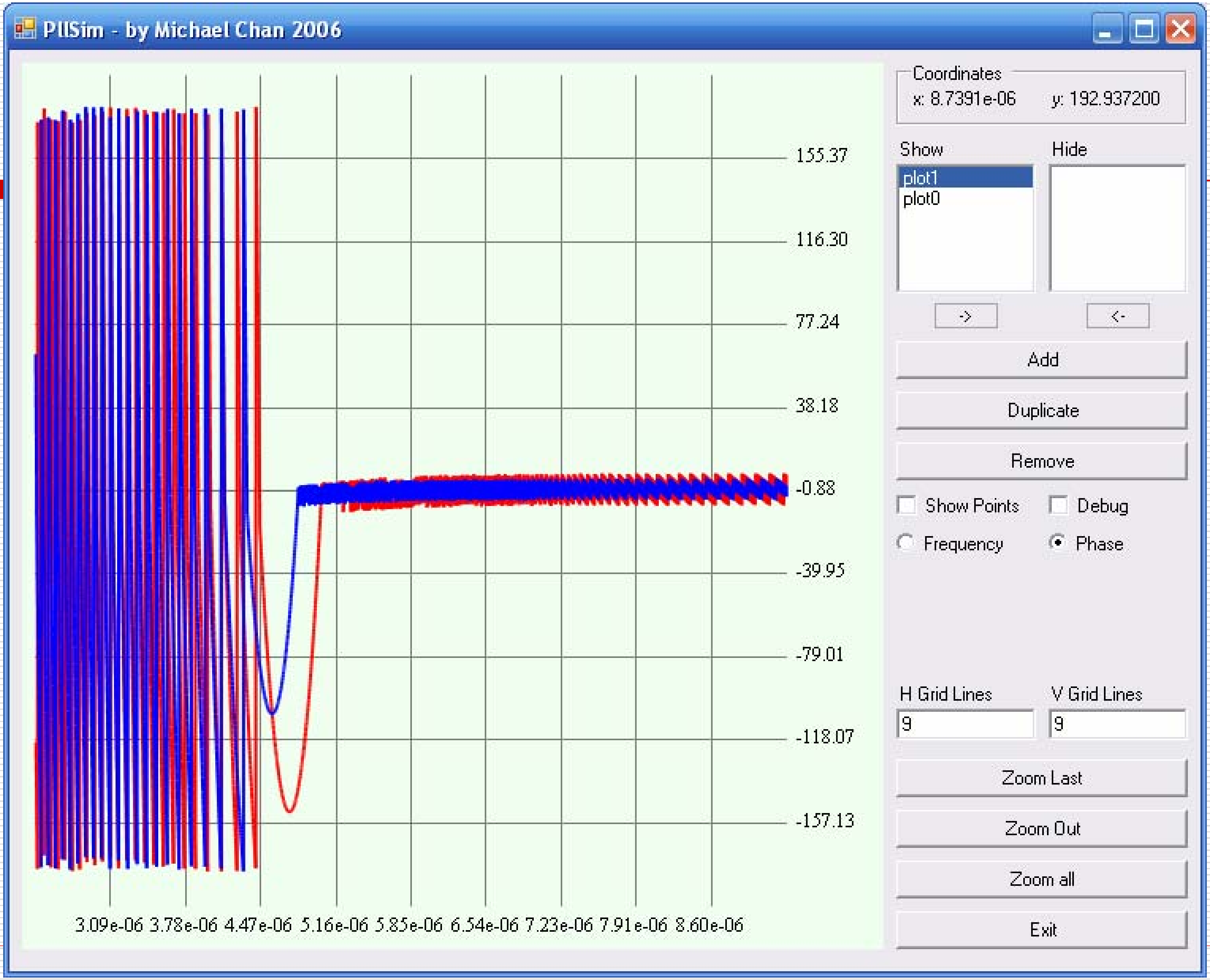


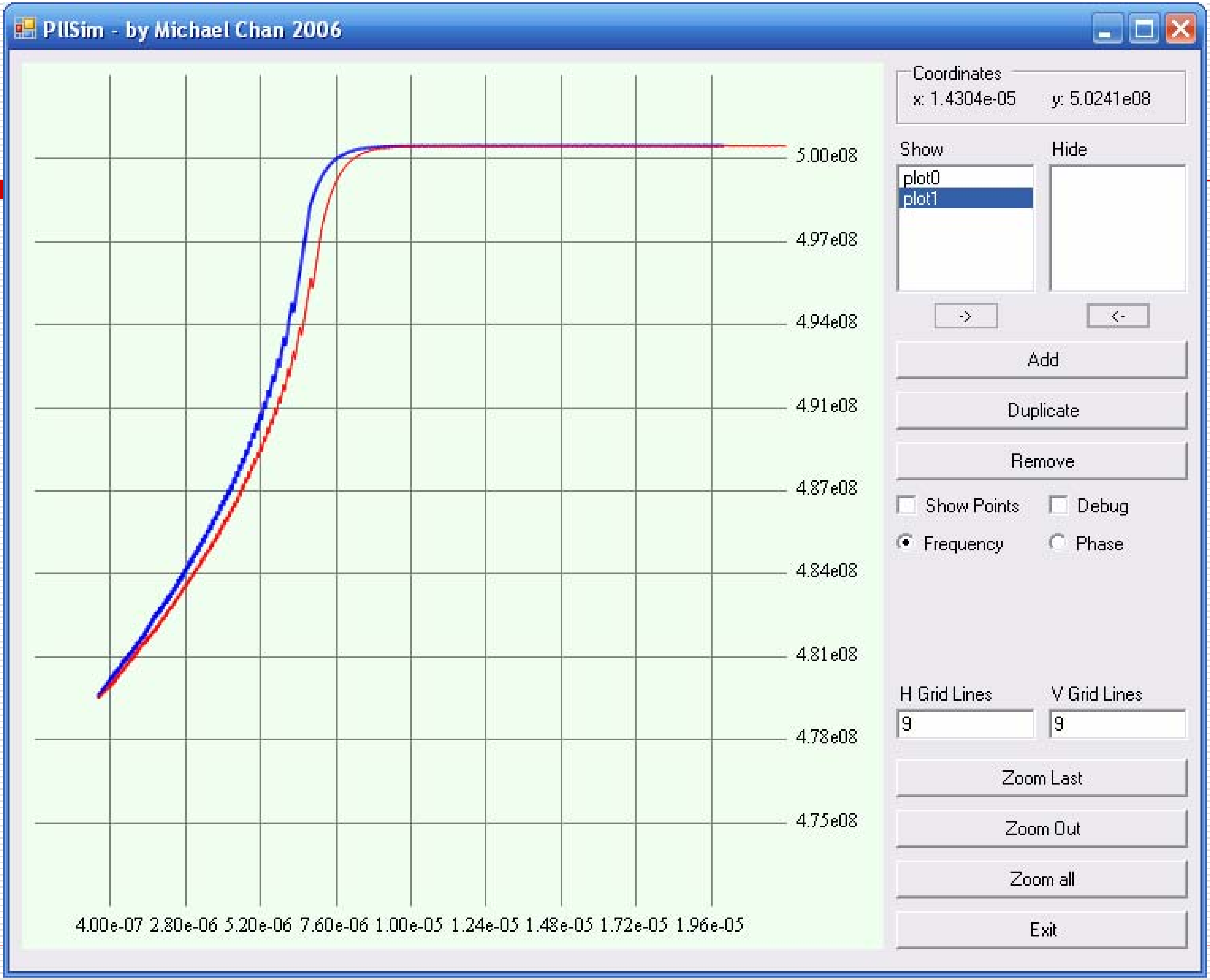
Latency in a 3 times Oversampling PD






PllSim - by Michael Chan 2006
Coordinates
x: 1.5498e-06
y: 4.7412e08
Show
Hide
plot1
5.00e08
4.97e08
4.84e08
4.81e08
4.78e08
4.75e08
4.00e-07 2.80e-06 5.20e-06 7.60e-06 1.00e-05 1.24e-05 1.48e-05 1.72e-05 1.96e-05
Non-Idealities
VCO Response
Add Point
Rmv Point
Deadzone (degrees)
0
Transition Probability
1
PD Latency (0..1)
0
Cancel
Help
Ok
Frequency
Phase
H Grid Lines
9
V Grid Lines
9
Zoom Last
Zoom Out
Zoom all
Exit
Plot Setup *
Simulate
plot0
Plot Name
5
Phase Step
20000
Freq Step
0
Phase Err
35000000.0000
Freq Err
499999999.999
Ref Freq
2E-05
End Time
Degrees / Hertz
Radians
Set Colour
Non-Linearities
Confirm

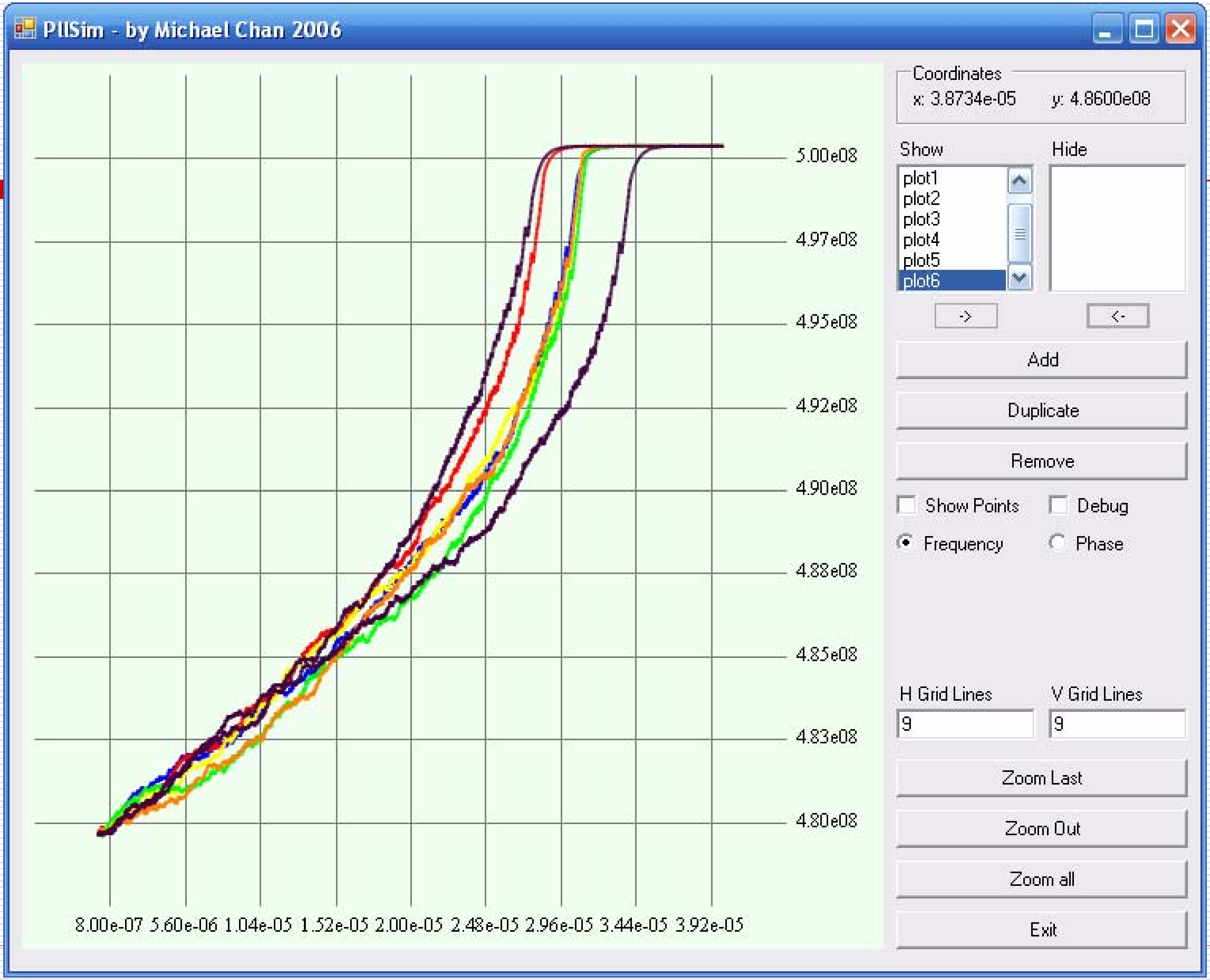

PllSim - by Michael Chan 2006
155.37
116.30
77.24
38.18
-0.88
-39.95
-79.01
-118.07
-157.13
3.09e-06 3.78e-06 4.47e-06 5.16e-06 5.85e-06 6.54e-06 7.23e-06 7.91e-06 8.60e-06
Coordinates
x: 8.7391e-06
y: 192.937200
Show
Hide
plot1
plot0
->
<-
Add
Duplicate
Remove
Show Points
Debug
Frequency
Phase
H Grid Lines
V Grid Lines
9
9
Zoom Last
Zoom Out
Zoom all
Exit



PllSim - by Michael Chan 2006
Coordinates
x: 1.4304e-05
y: 5.0241e08
Show
Hide
plot0
plot1
->
<-
Add
Duplicate
Remove
Show Points
Debug
Frequency
Phase
H Grid Lines
9
V Grid Lines
9
Zoom Last
Zoom Out
Zoom all
Exit
5.00e08
4.97e08
4.94e08
4.91e08
4.87e08
4.84e08
4.81e08
4.78e08
4.75e08
4.00e-07 2.80e-06 5.20e-06 7.60e-06 1.00e-05 1.24e-05 1.48e-05 1.72e-05 1.96e-05

Non Ideal Behavior

- Non-linear VCO response
- Phase detector deadzone
- Phase detector latency
- Also handle random reference data sources


PllSim - by Michael Chan 2006
Coordinates
x: 3.8734e-05
y: 4.8600e08
Show
Hide
plot1
plot2
plot3
plot4
plot5
plot6
->
<-
Add
Duplicate
Remove
Show Points
Debug
Frequency
Phase
H Grid Lines
V Grid Lines
9
9
Zoom Last
Zoom Out
Zoom all
Exit
5.00e08
4.97e08
4.95e08
4.92e08
4.90e08
4.88e08
4.85e08
4.83e08
4.80e08
8.00e-07 5.60e-06 1.04e-05 1.52e-05 2.00e-05 2.48e-05 2.96e-05 3.44e-05 3.92e-05

Summary

- Presented a model for bang-bang PLL behaviour
- Showed how this model could be applied to a simulation program
- Demonstrated remarkable speedup times for simulating bang-bang PLLs
- Extended the simulator to handle some common non-idealities
- You can download PLLSim at www.itee.uq.edu.au/~mchan