Laser Phase Locking to a LISA Arm: Experimental Approach

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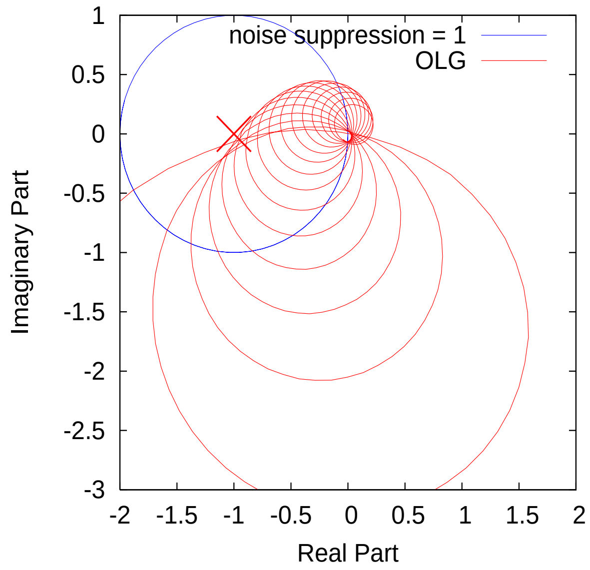
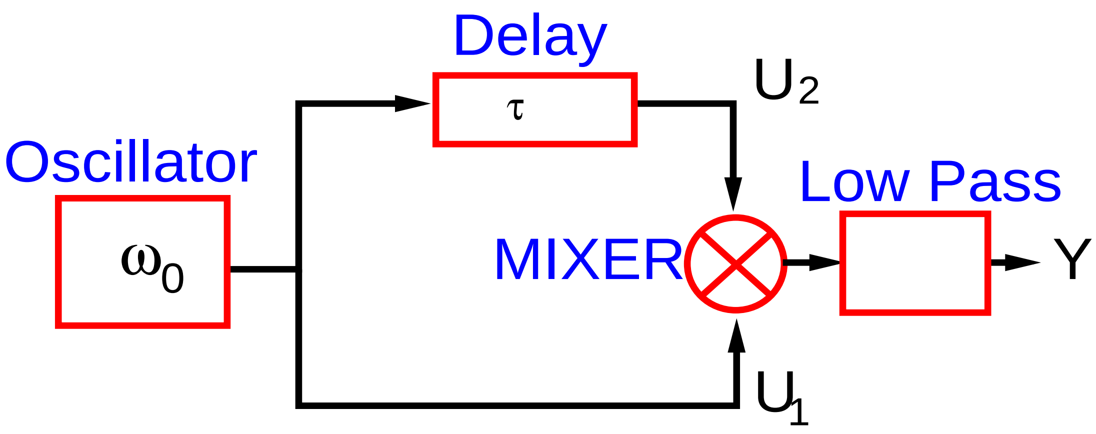


5th International LISA Symposium , July 12th-16th , ESTEC Noordwijk, The Netherlands

Delay line as a frequency noise detector(I)

Principle of function



Oscillator: ω_0

Frequency modulated at ω_m

Modulation depth: $\Delta\omega$

- $U_2(t) = U_1(t-\tau)$
- $Y(t) = (\Delta\omega\,\tau/2)\ \mathrm{Sinc}(\tau\,\omega_m/2)\ \mathrm{Sin}(\omega_m(t-\tau/2))$

$$\approx (\Delta\omega\,\tau/2)\ \mathrm{Sin}(\omega_m t)$$

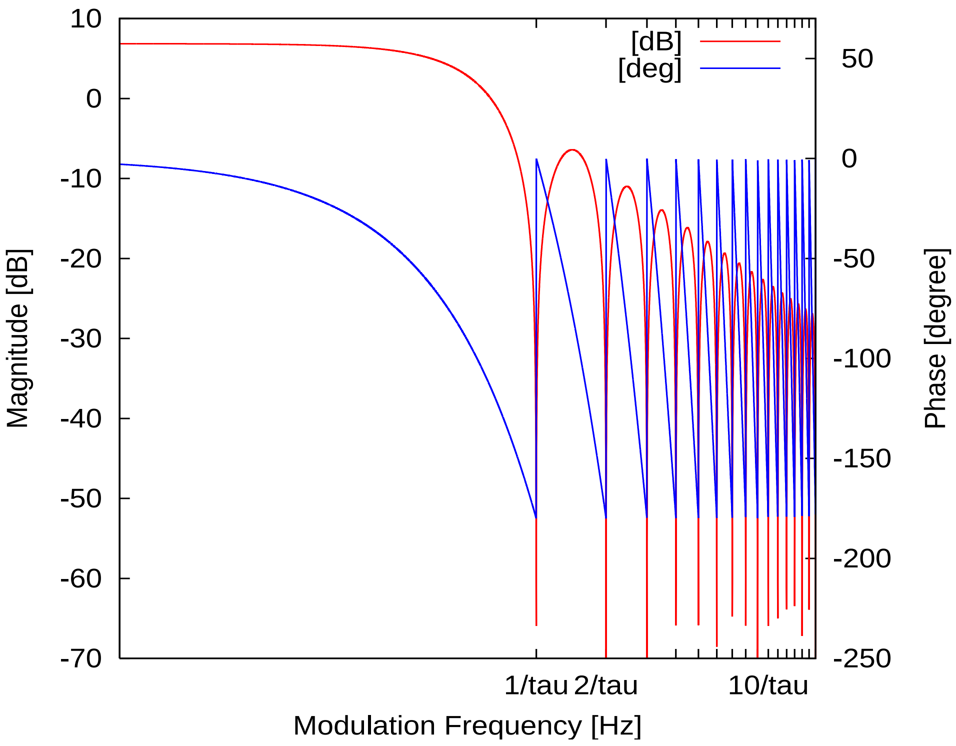
$(\omega_m \rightarrow 0)$

Delay line as a frequency noise detector (II)

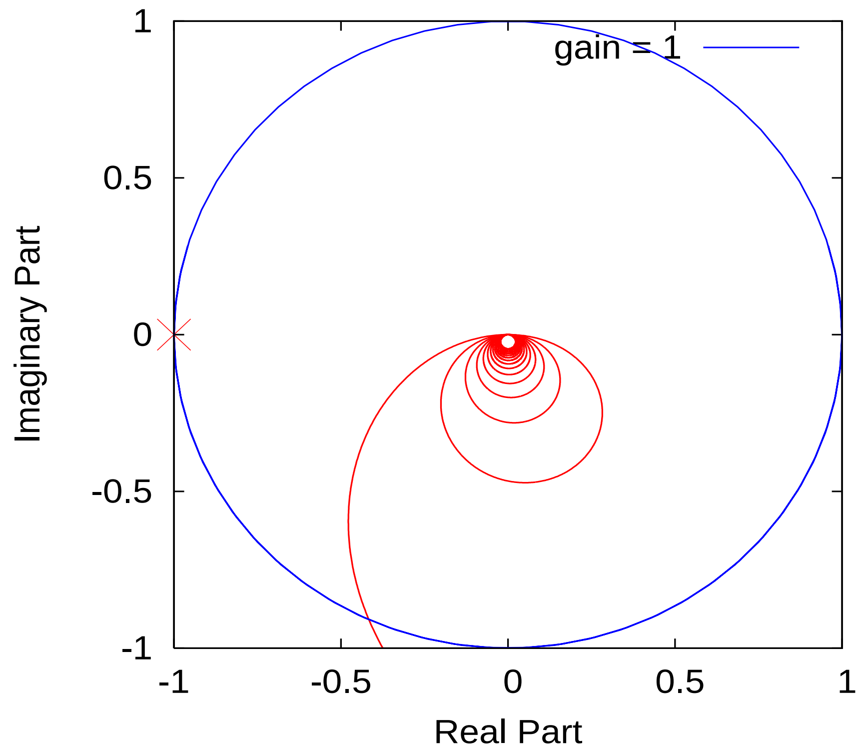
Ideal Transfer Function: Frequency Modulation to Phase Detection

- $Y(t) = (\Delta\omega\,\tau/2)\ \mathrm{Sinc}(\tau\,\omega_m/2)\ \mathrm{Sin}(\omega_m(t-\tau/2))$

Bode Representation



Nyquist Representation

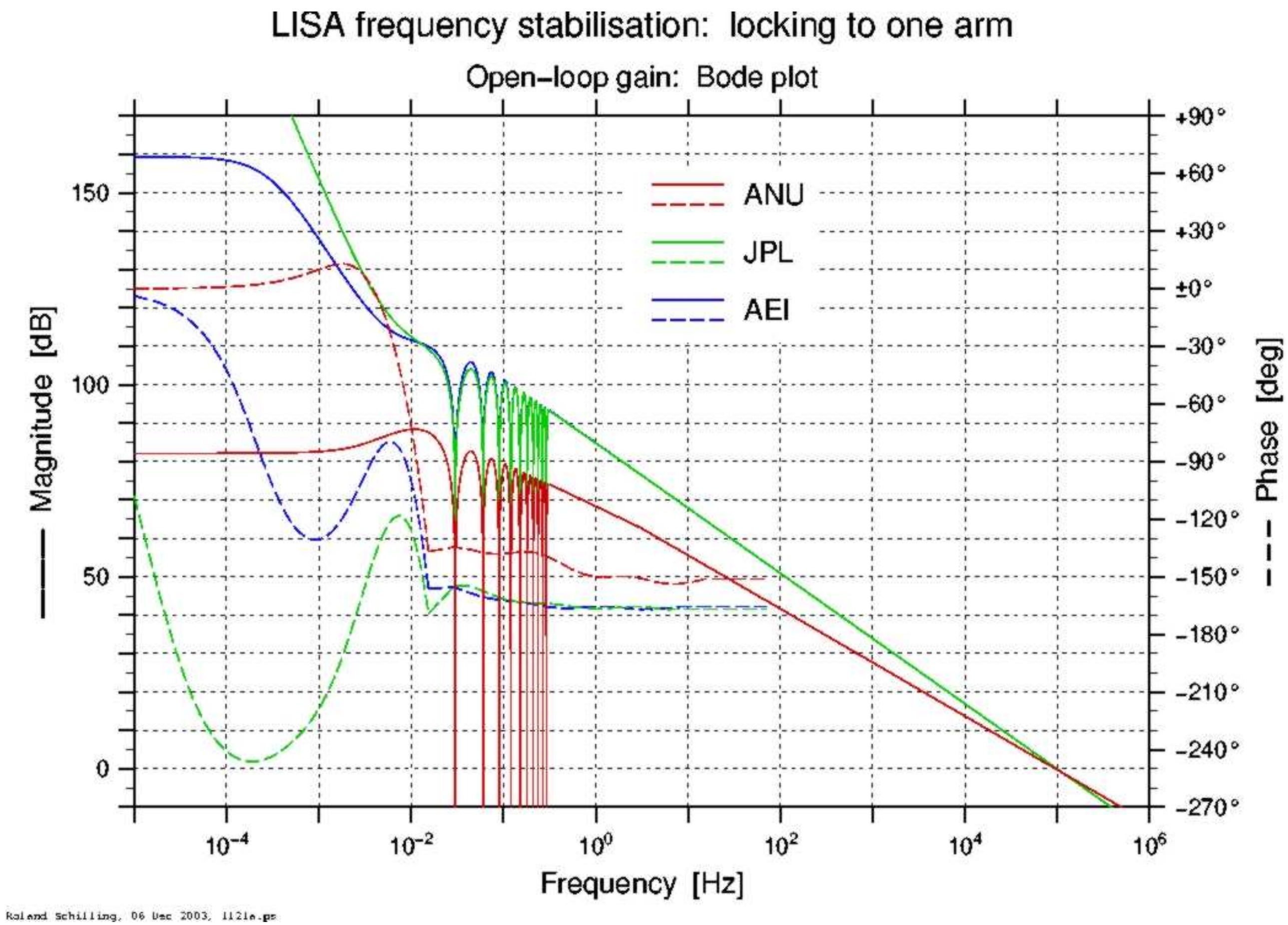


Please note the difference with a "Phase to Phase" transfer function!!

We have an **extra 1/f** here instead of in the servo

Servo Proposals for LISA

Theoretical Open Loop Gain (Roland Schilling)

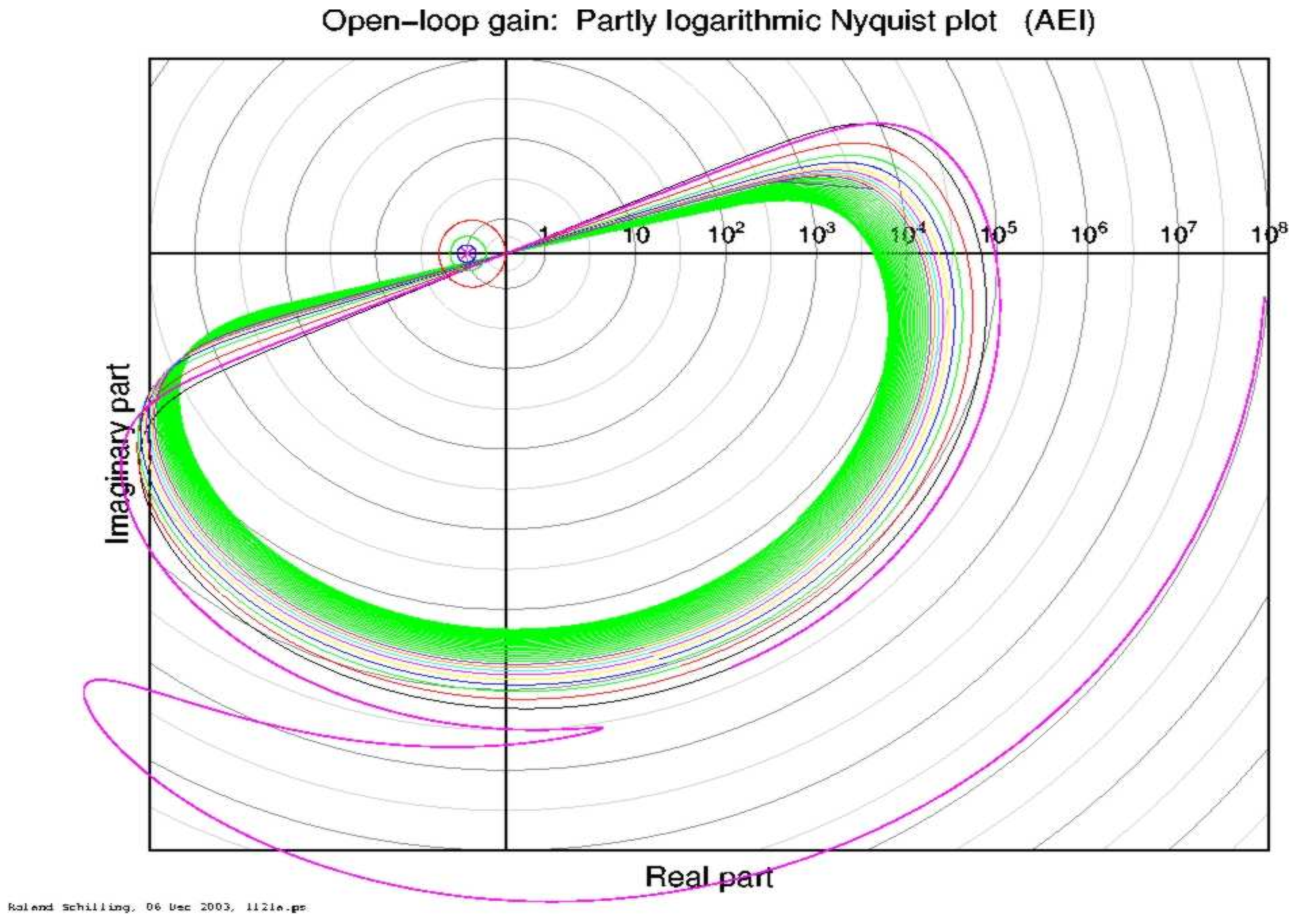


Bode Representation

Simulations achieve Unity Gain Frequency (**UGF**) far above **1**/τ

Servo Proposals for LISA

Theoretical Open Loop Gain (Roland Schilling)



Nyquist Representation

Scale is **logarithmic** outside from circle of radius 1 (gain 1)

Servo Proposals for LISA

Our Motivation

- It is a non-standard control Loop: Unity Gain Frequency above $1/\tau$.

- Initial noise during Lock Acquisiton replicates itself with period τ . Time-evolution of this replication is subject of analytical investigations (Tinto, Rüdiger, Shaddock,...)

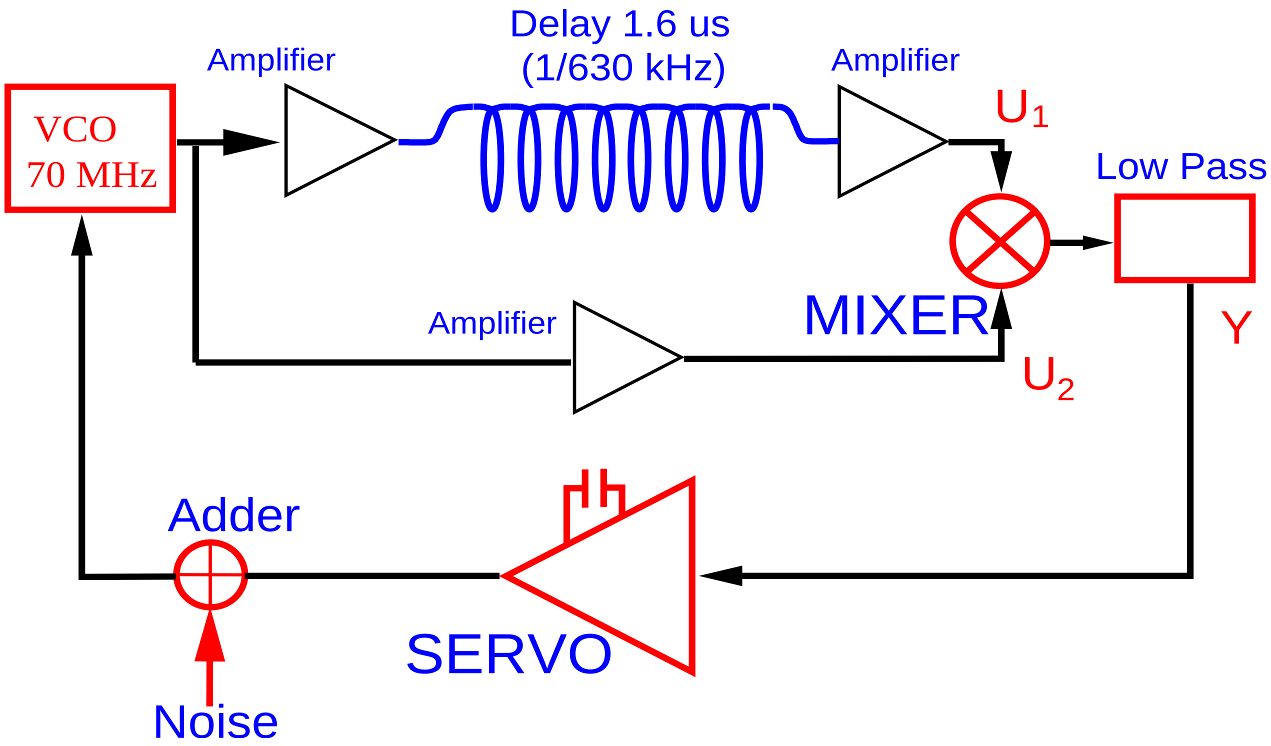
- Simulations ([Sheard et al.], AEI, JPL...) predict a very effective frequency noise suppression for LISA .

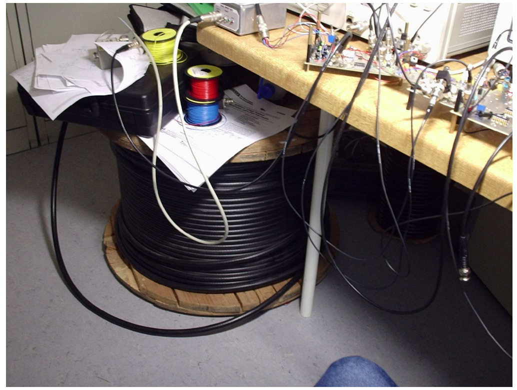
- **Experimental verification essential!**

  frequency stabilization system (Delay-line)

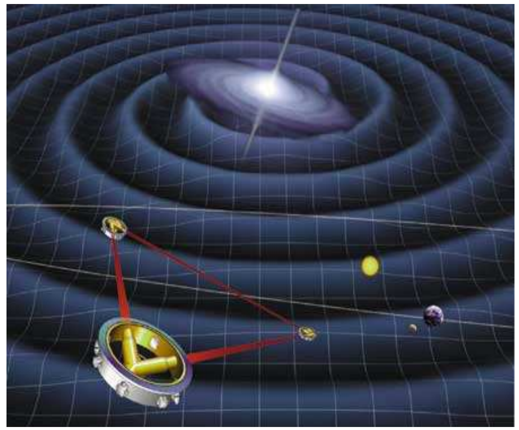
  noise reduction above $1/\tau$

Experimental Demonstration in Hannover (I)





Hannover

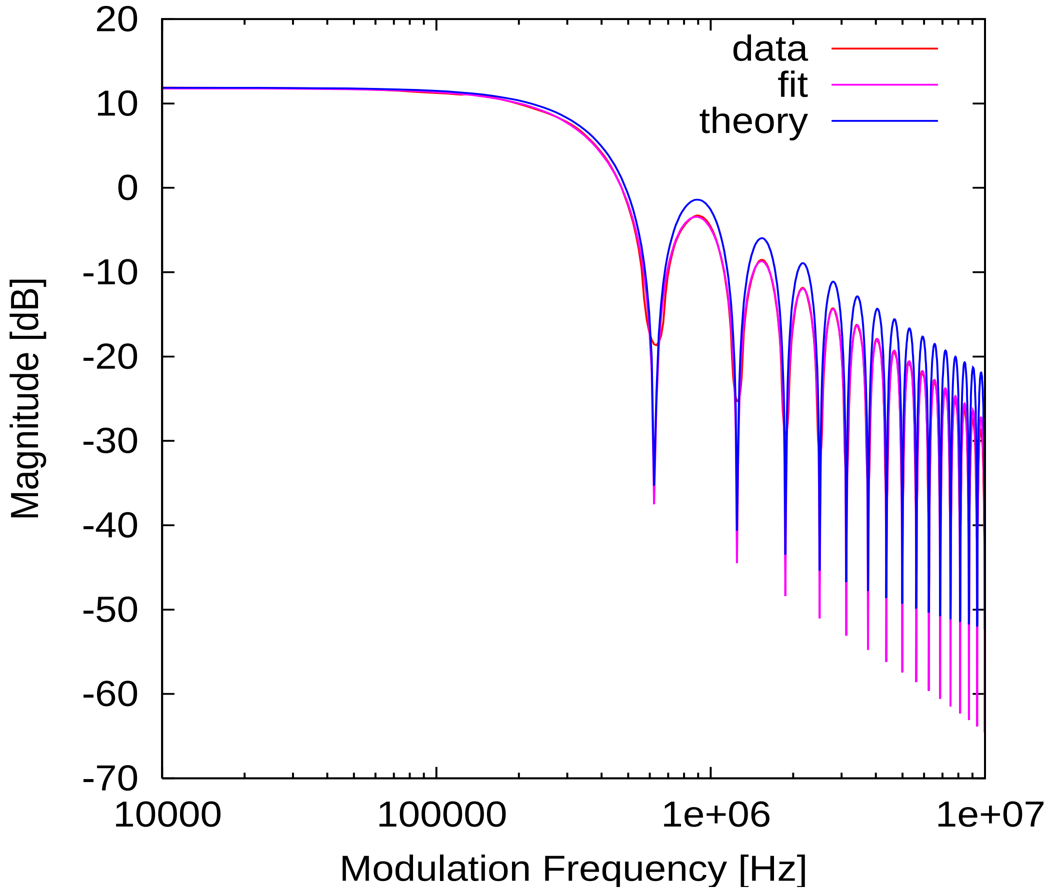


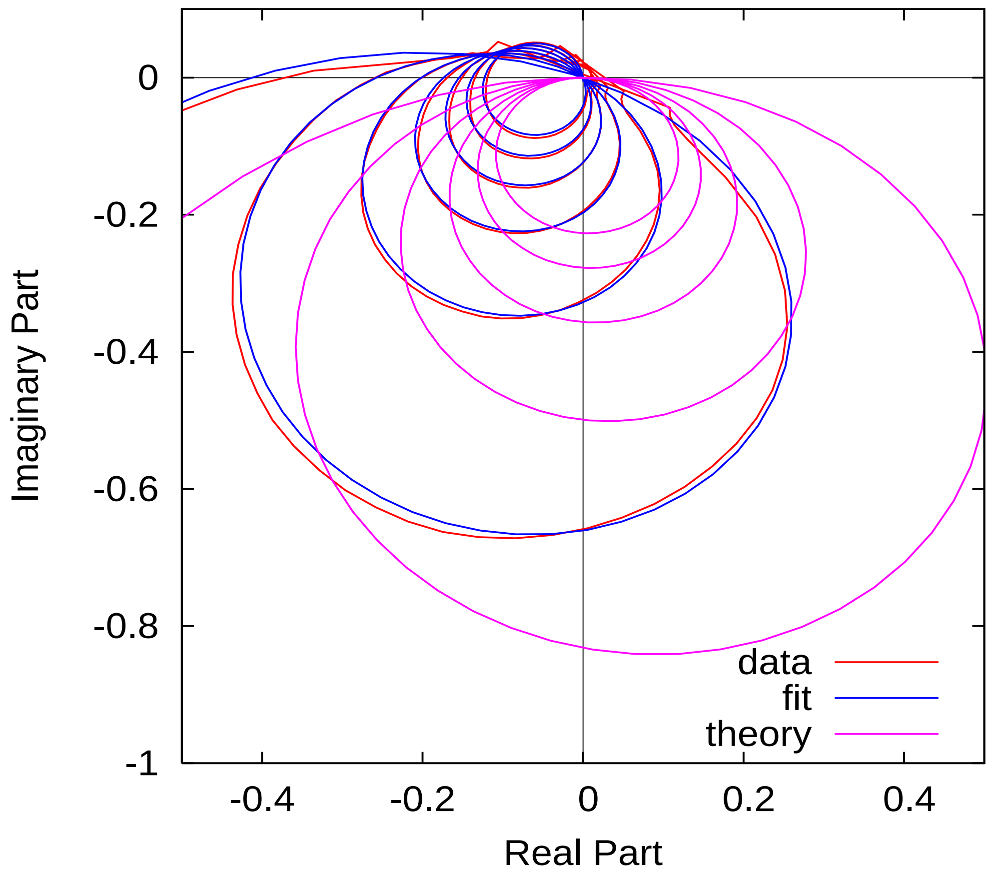
LISA

	Hannover	LISA
Signal	VCO Signal	Laser
τ	1.601 us	33 s
n/τ	n*625 kHz	n*30 mHz
freq. range	2 kHz to 20 MHz	0.1 mHz to 1 Hz

Experimental Demonstration in Hannover (II)

Measured Transfer Function

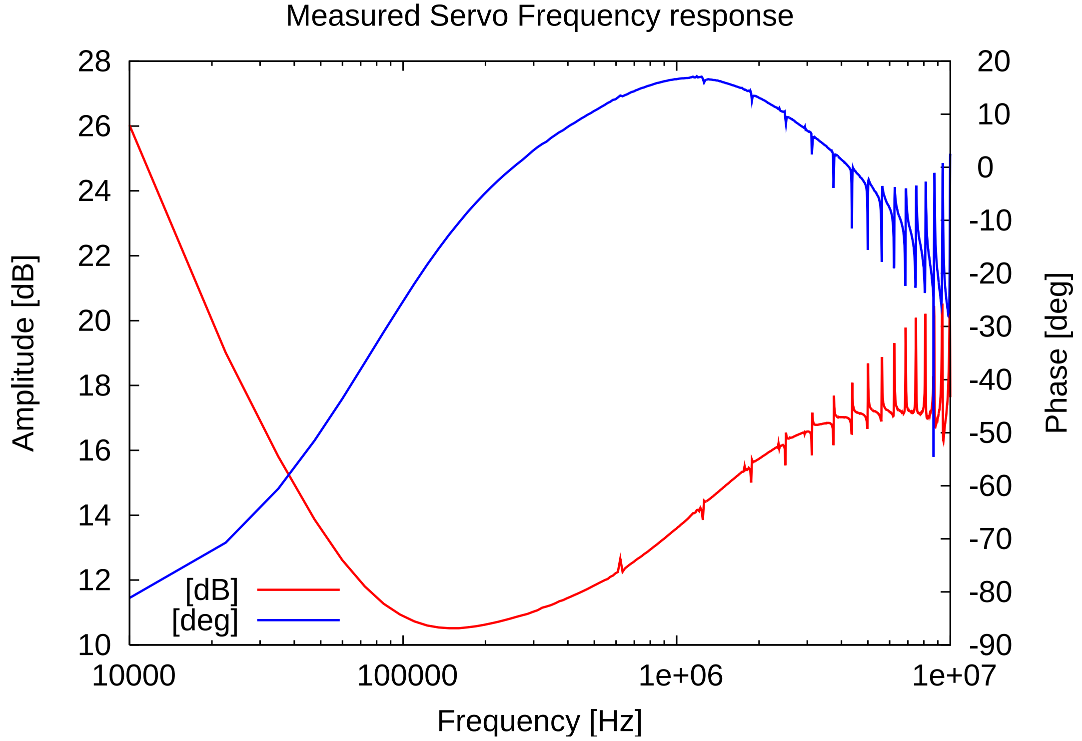




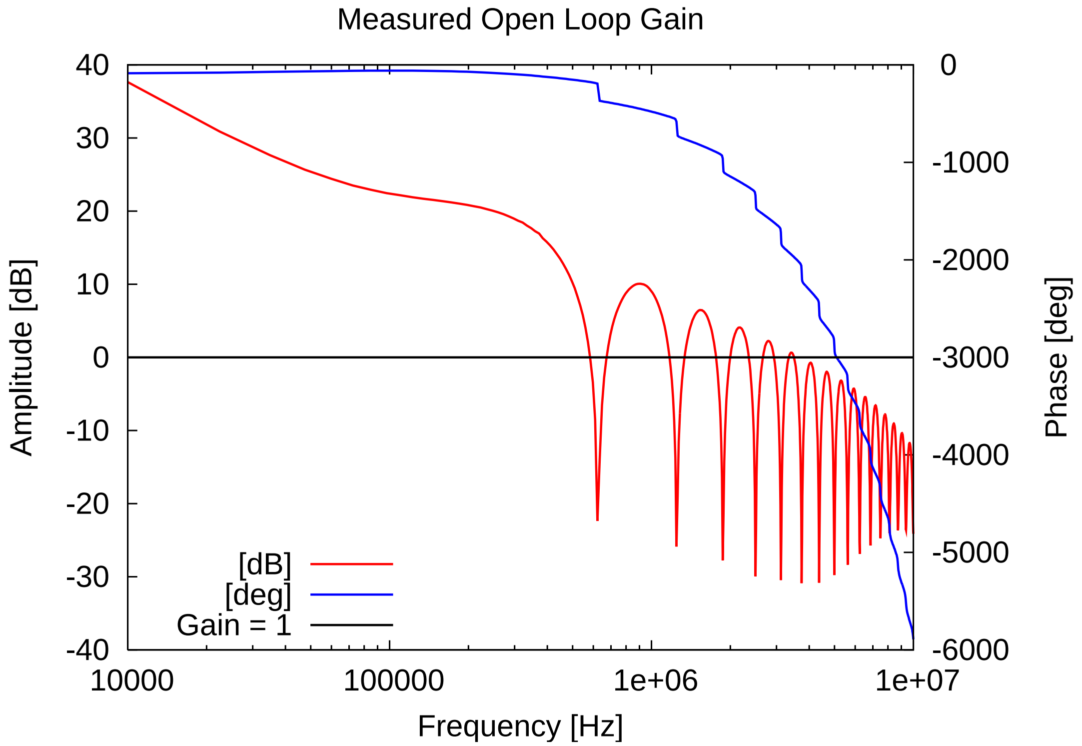
- FIT: Y(t) = $(\Delta\omega\tau/2)$ Sinc$(\tau\omega_m/2)$ Sin$(\omega_m(t-\tau/2-\tau^*))$*pole(f1)*zero(f2)*pole(f3)
  - $\tau^* = 75$ **ns** (fix value)
  - f1 = 530 kHz   f2 = 830 kHz   f3 =12 MHz (non flat f-response)

Experimental Demonstration in Hannover(III)

Servo frequency response (Bode)



Open Loop Gain (Bode)



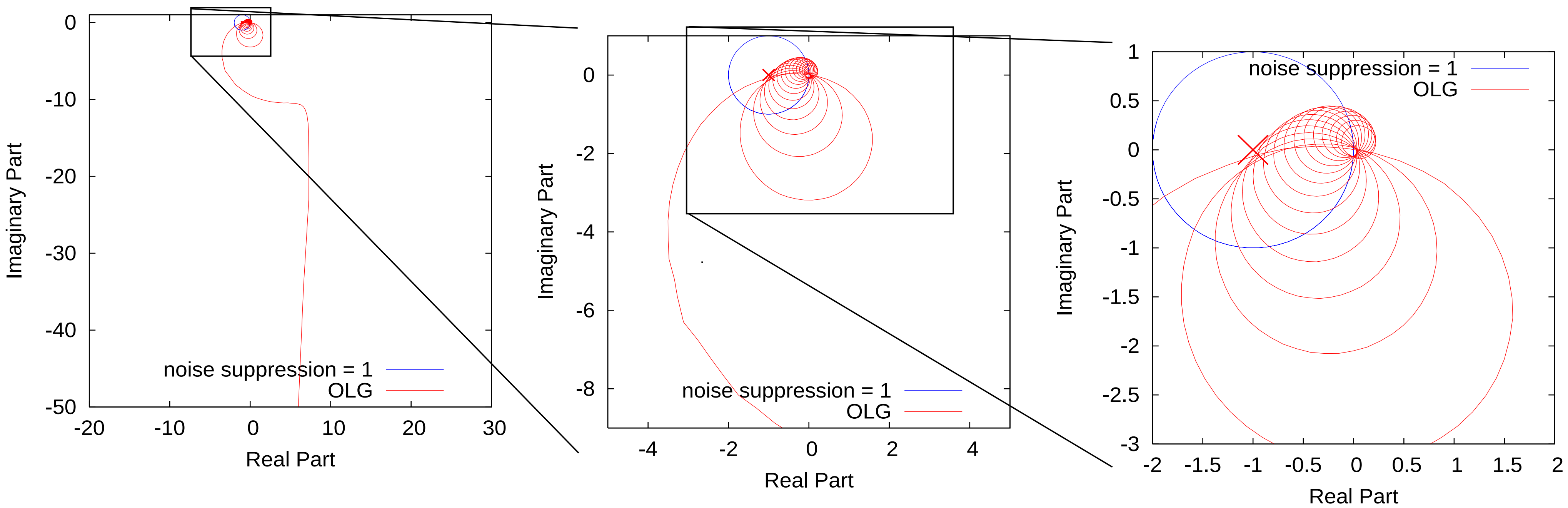
- Integrator from 100kHz down to DC
- $f^{0.3}$ equivalent to $f^{-0.7}$ roll off in Simulations
- spikes due to closed Loop measurement

Well behaved closed Loop

UGF > 1/τ !!

Experimental Demonstration in Hannover (IV)

Open Loop Gain (Nyquist)



- Instability shows up when OLG encloses (-1,0)
- Limiting factor is shown deviation of transfer function:

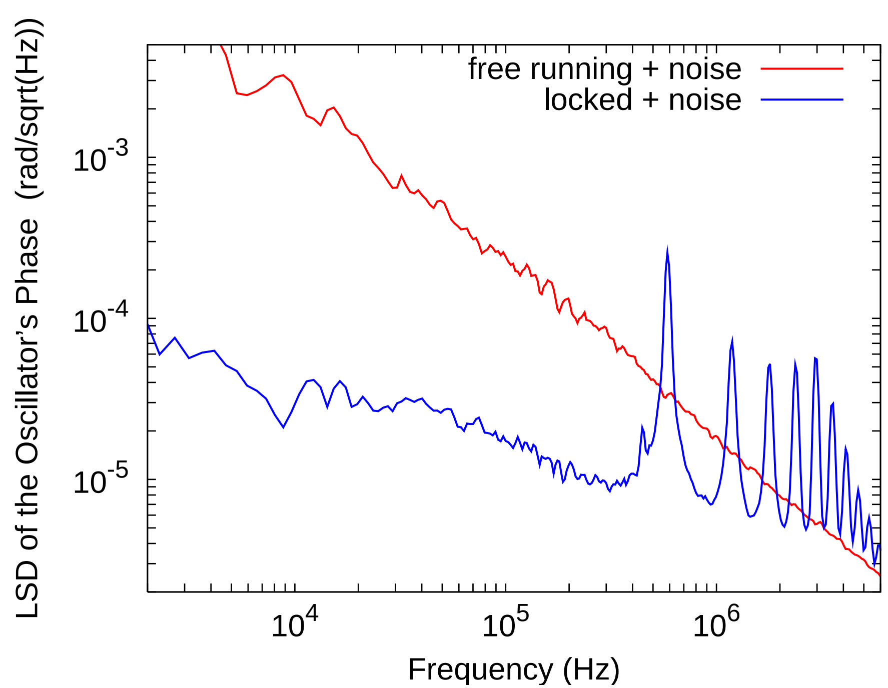
extra delay $\tau *$ (75 ns)

$$Y(t) = (\Delta\omega \tau/2)\, \mathrm{Sinc}(\tau \omega_m/2)\, \mathrm{Sin}(\omega_m(t-\tau/2 - \underline{\tau *}))^{*}\underline{pole(f1)*zero(f2)*pole(f3)}$$

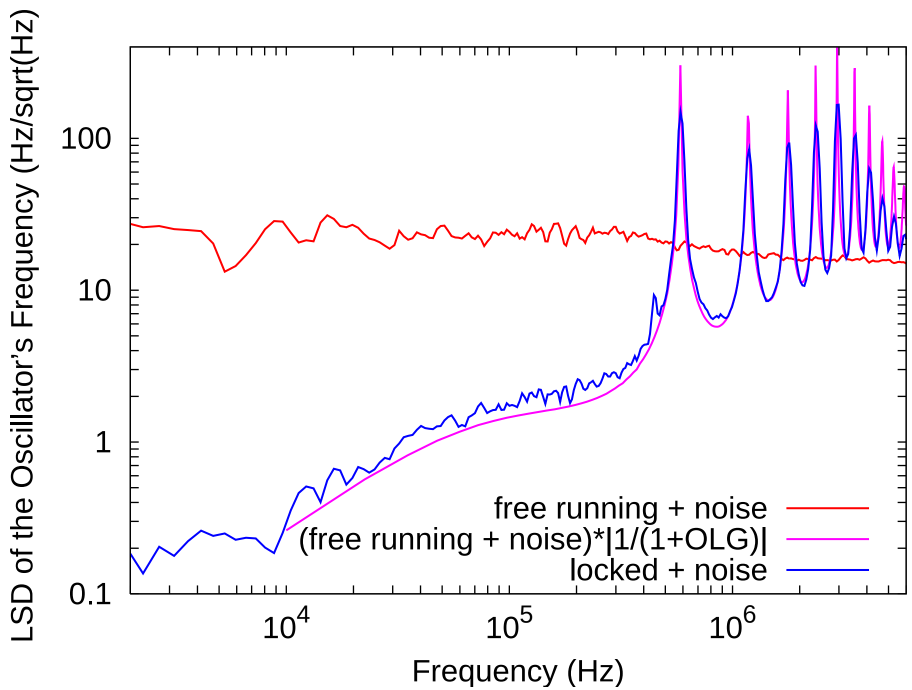
Experimental Demonstration in Hannover (V)

Out of Loop measurement of the Noise Suppression:

Oscillator's Phase Noise (LSD)



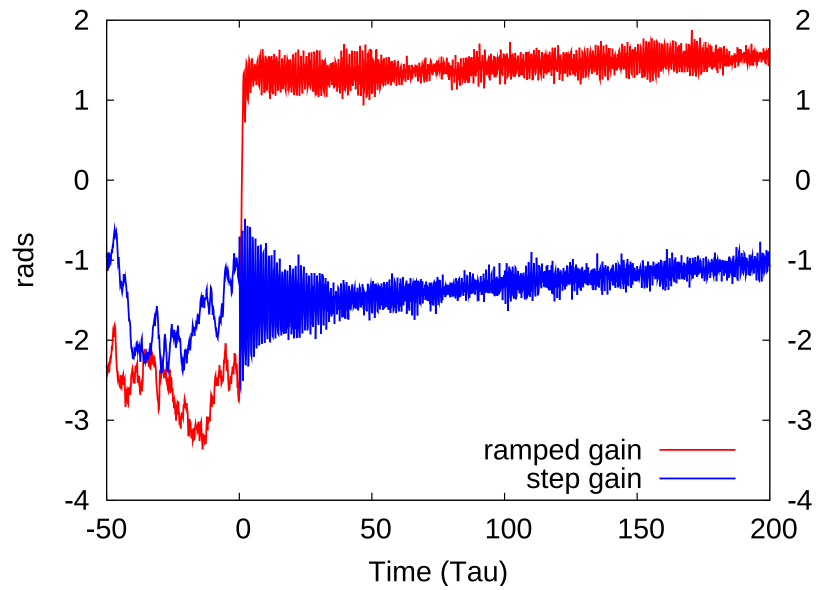
Oscillator's Frequency Noise (LSD)

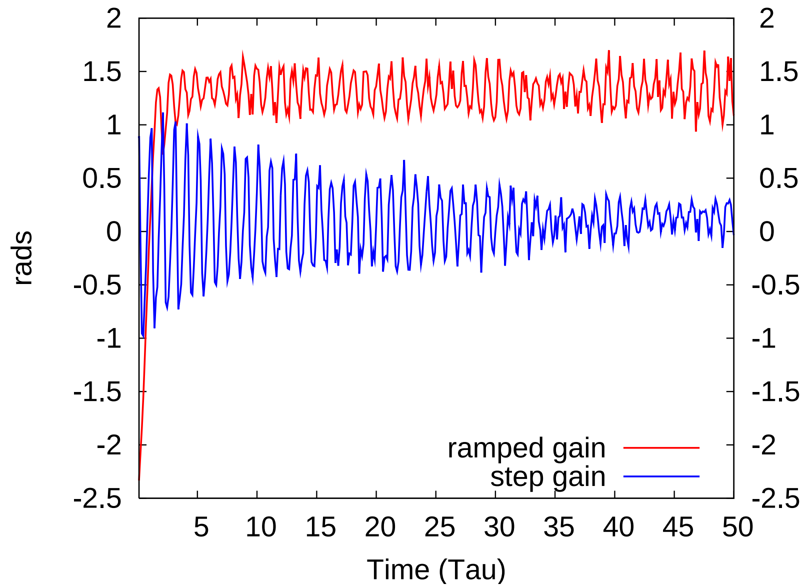


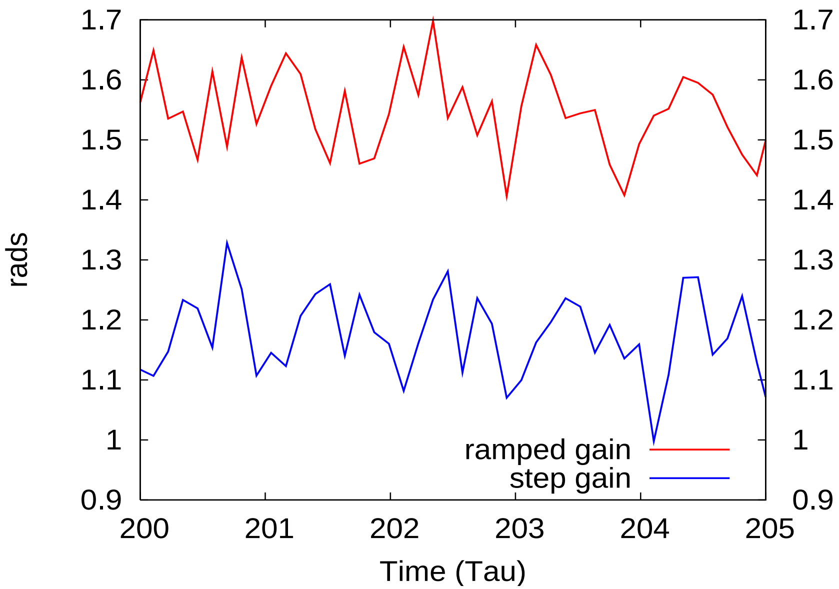
Noise measurement agrees with measured Open Loop Gain

Time Evolution Investigation (I): white noise

Oscillator's phase during and after lock acquisition



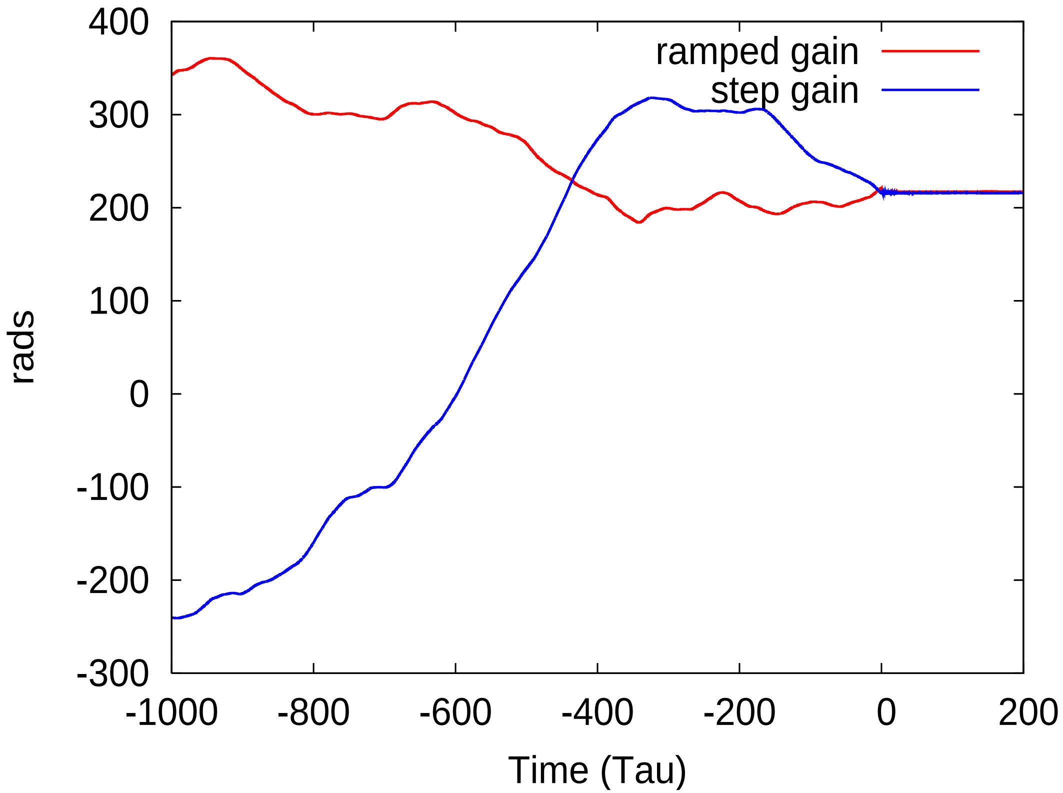


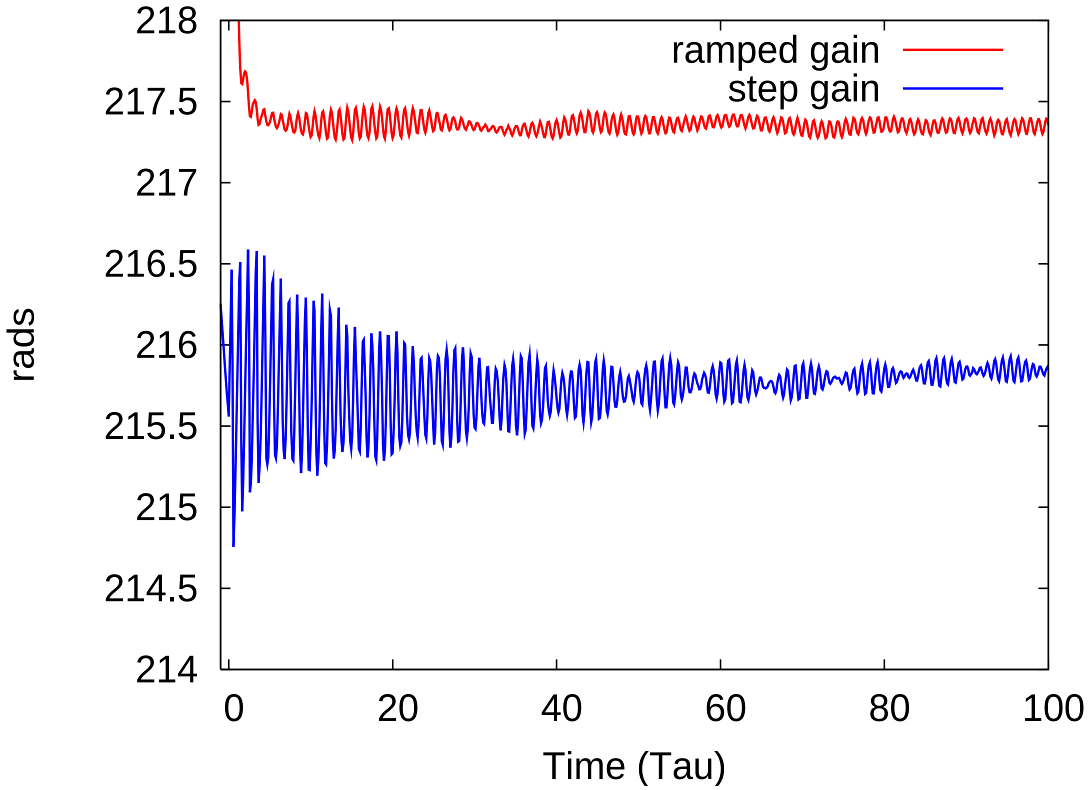


- **When gain is linearly time dependent ringing decays faster. Agreement with theoretical analysis (Tinto, Rakhmanov)**
- **Remaining noise level shows no exact repetition of initial pattern (see animation)**

Time Evolution Investigation (II): 1/f noise

Oscillator's phase during and after lock acquisition





- **1/f simulates Laser noise**
- **System locks despite high amplitude perturbations**

Summary

- We have built a frequency stabilization system based on a delay line $\Rightarrow$

  Well behaved Loop with UGF > $1/\tau$

  Noise measurements confirm In-Loop measured performance

- Time domain investigations in agreement with analytical results (ramping gain up)

- Proposal for future investigation:

  Identification and minimization of real limiting factors for LISA

  Take them into account for servo design (acquired know-how)

Does the 1/f noise really drive the oscillator over several hundreds of rads? **Yes!**