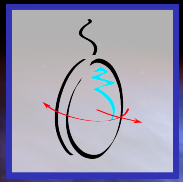
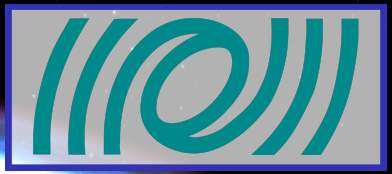
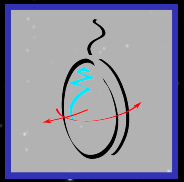






Feed-Forward Noise Cancellation in Virgo

—

Diego Bersanetti

INFN - Sezione di Genova

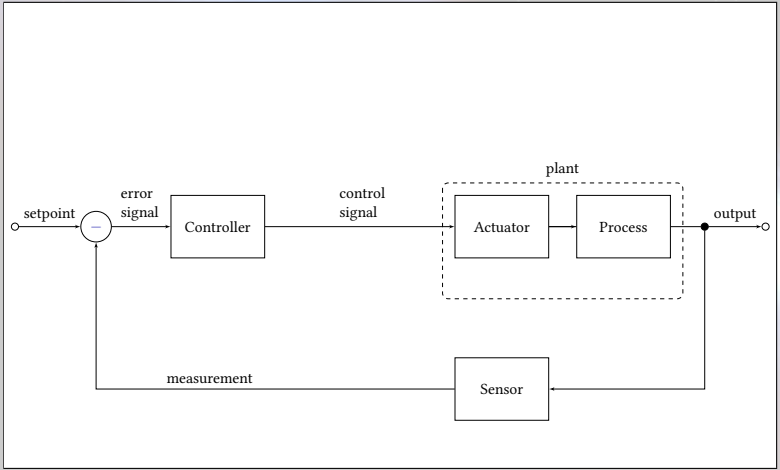
VIR-0015A-19

1st CA17137 Conference

Jan 14th, 2019

1. Introduction on Feed-Forward Techniques
2. Feed-Forward in Virgo #1: 50 Hz Noise Subtraction
3. Feed-Forward in Virgo #2: The Alpha Subtraction

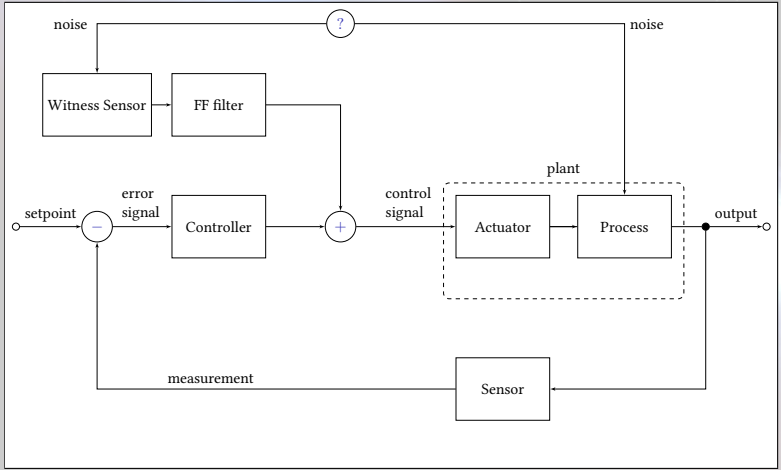
Feed-Back and Feed-Forward (1)



Feed-Back System:

- It is used to control an input variable
- It tracks the changes of the input variable
- It defines the working point of the system
- It has strict constraints (stability, tracking, regulation, etc...)

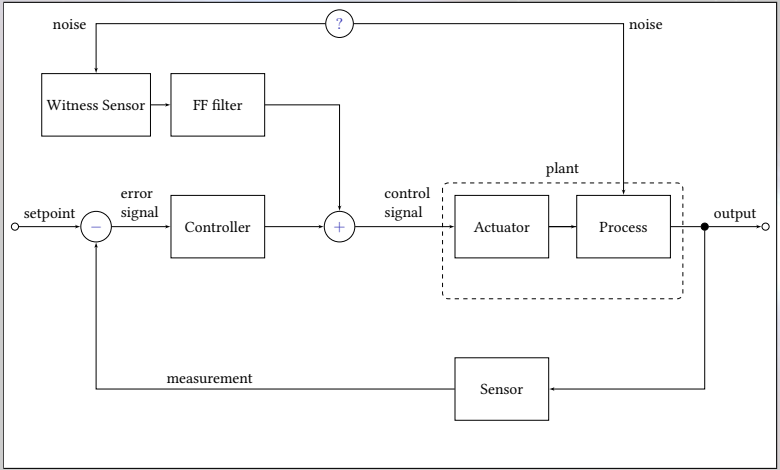
Feed-Back and Feed-Forward (2)



Feed-Forward System:

- It reduces a noise
- It needs a *witness*
- The input is not kept *under control*
- The correction is *static* over time
- It is less constrained than feedback
- It needs very accurate modeling

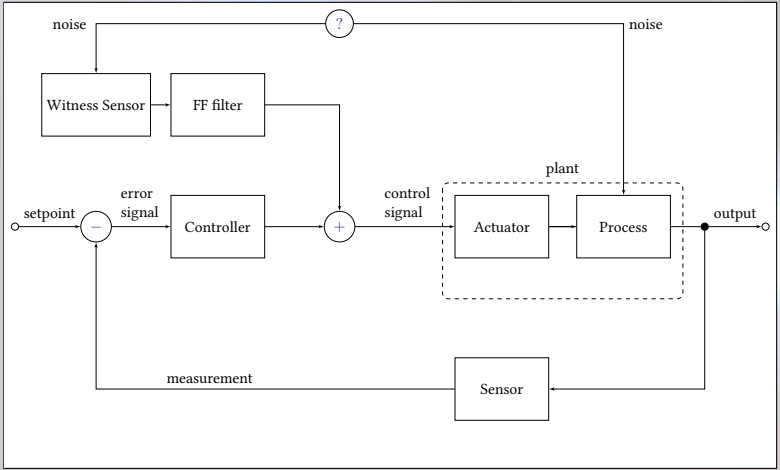
What is a Feed-Forward System? (1)



It needs a *witness* of the noise we want to reduce:

- Our system must be set up in a way to be able to read the external disturbance *independently*
- Such witness must possibly have no other information
- The witness must be reliable over time

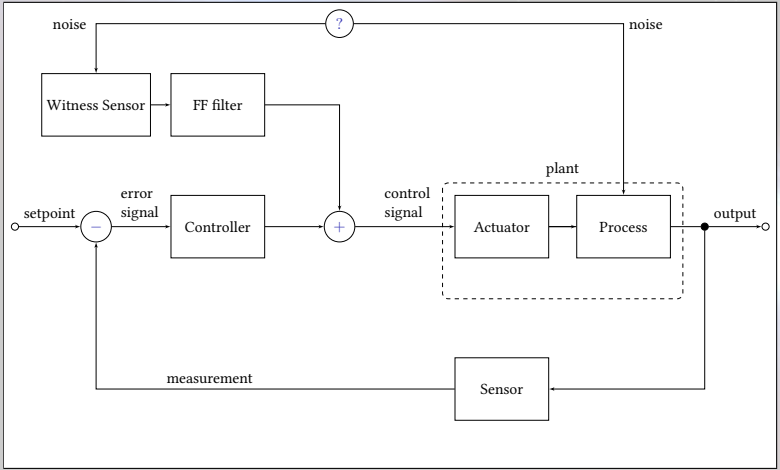
What is a Feed-Forward System? (2)



Input is not kept *under control*:

- There is no feedback
- There is no measurement of the input variable
- The input variable is an external disturbance, not the physical quantity we are interested in

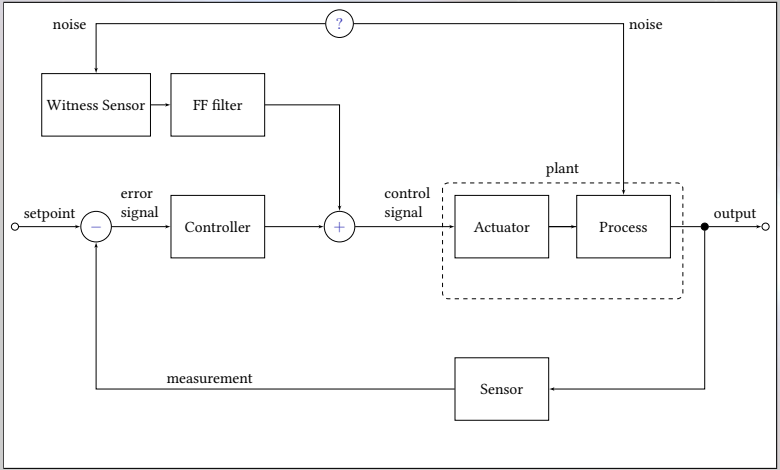
What is a Feed-Forward System? (3)



Correction is *static* over time:

- We have a static filter (as in the feedback case)
- The witness is out of loop by definition
- The effect is not a *control*, but rather a *subtraction*

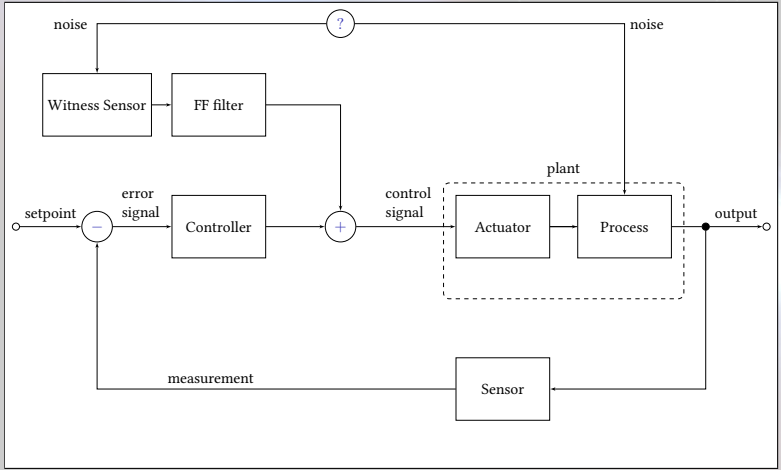
What is a Feed-Forward System? (4)



Less constrained than feedback:

- There are no requirements (phase margin, etc...)
- A feed-forward is not "stable" or "unstable"
- The witness and the model define the performance
- The effect is the *reduction* or *amplification* of noise

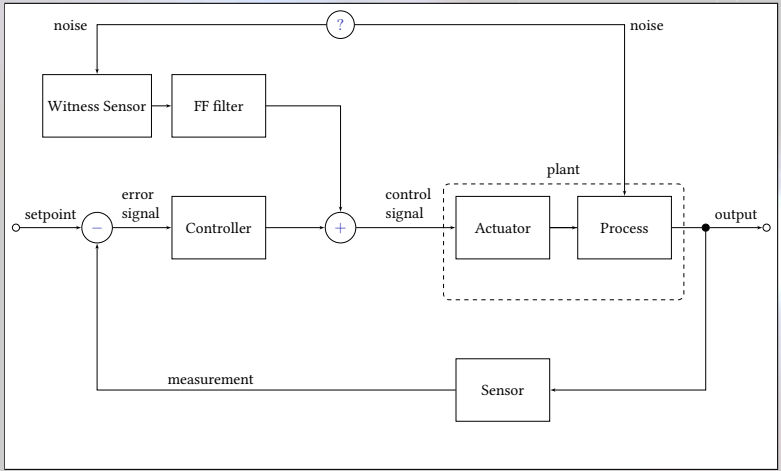
What is a Feed-Forward System? (5)



It needs a very accurate modeling:

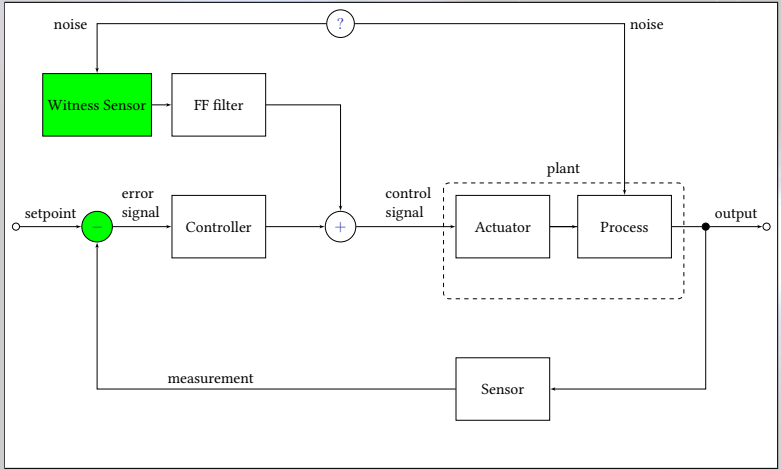
- The relationship between noise and witness must be well known
- The relationship between noise and target must be well known
- A precise model is needed in order to build a performing filter
- Both *amplitude* and *phase* are very important

How to Measure a Feed-Forward Path?



Procedure:

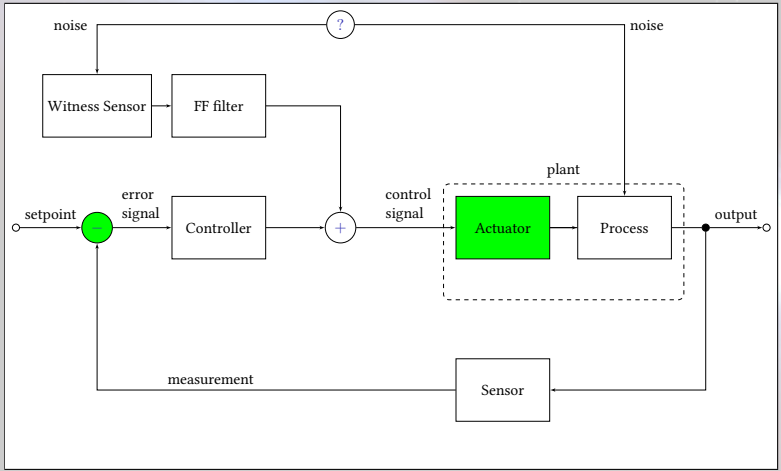
How to Measure a Feed-Forward Path?



Procedure:

- Measure the *transfer function* TF_A between witness and target

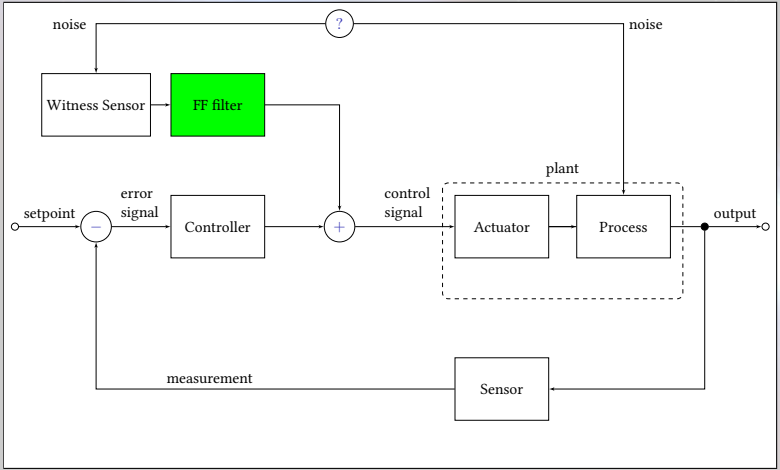
How to Measure a Feed-Forward Path?



Procedure:

- Measure the *transfer function* TF_A between witness and target
- Measure the *transfer function* TF_B between target and actuation (*closed loop transfer function*)

How to Measure a Feed-Forward Path?

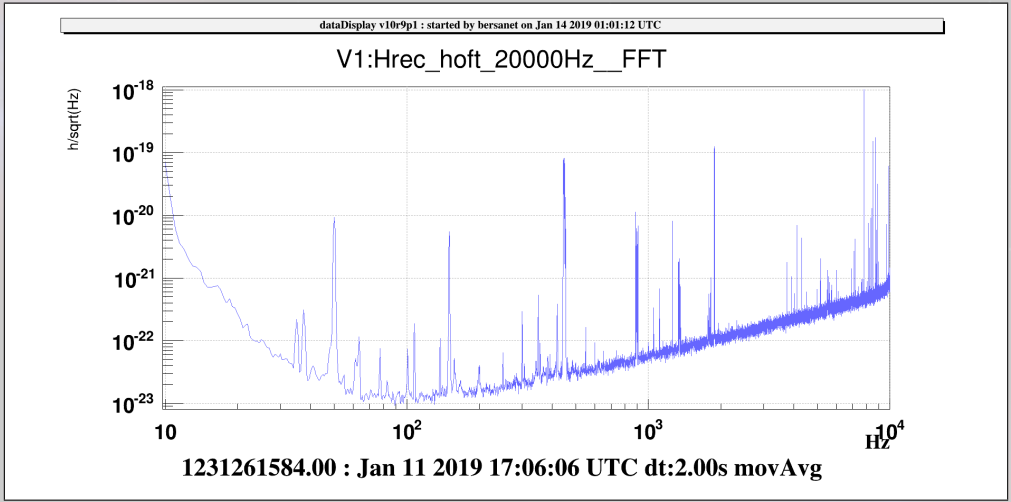


Procedure:

- Measure the *transfer function* $\mathrm{TF_A}$ between witness and target
- Measure the *transfer function* $\mathrm{TF_B}$ between target and actuation (*closed loop transfer function*)

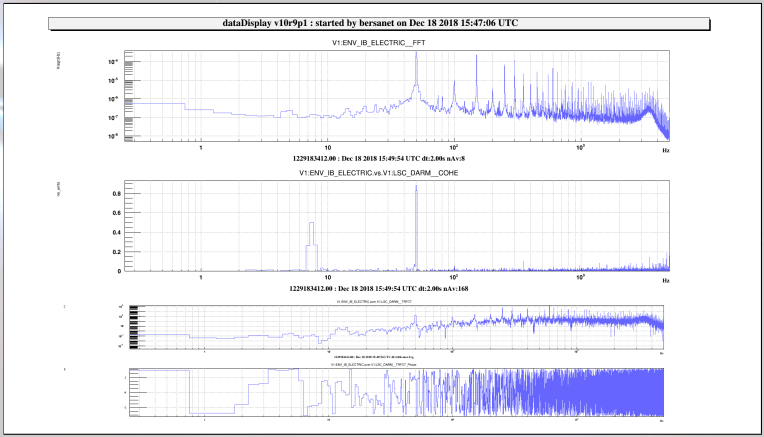
$$\mathrm{TF_{FF}} = -\frac{\mathrm{TF_A}}{\mathrm{TF_B}}$$

50 Hz Noise in Virgo (1)



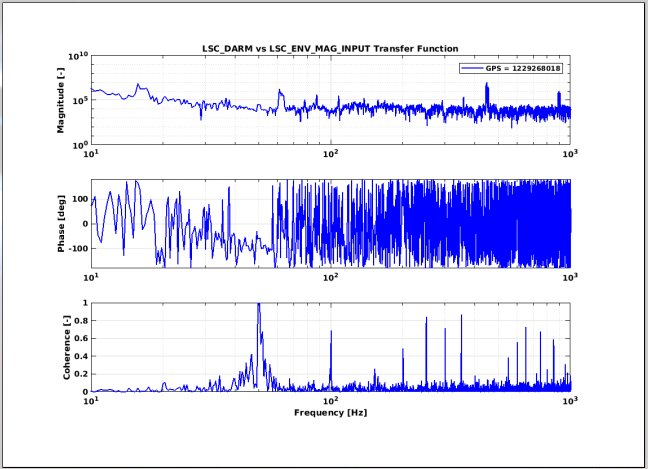
50 Hz Noise in Virgo (2)

- Known source of noise
- Source is the mains lines
- Source can not be removed
- Effect can be subtracted



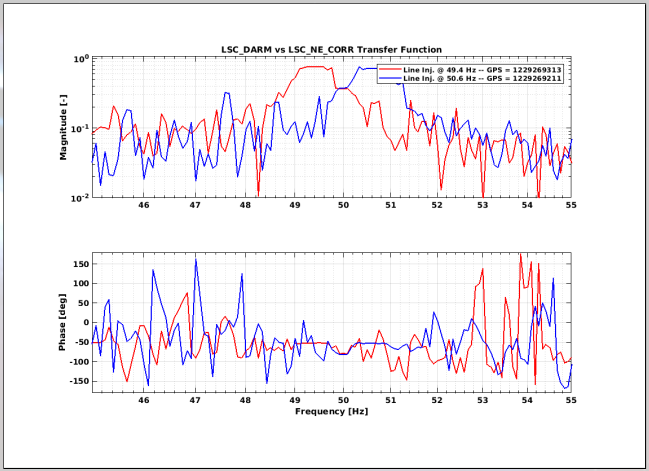
50 Hz Feed-Forward: TF between Witness and Target

- The first step is the measurement of TF_A between witness and target
- The relationship must be stable over time
- A constant phase between the two *in the band of interest* is a key ingredient



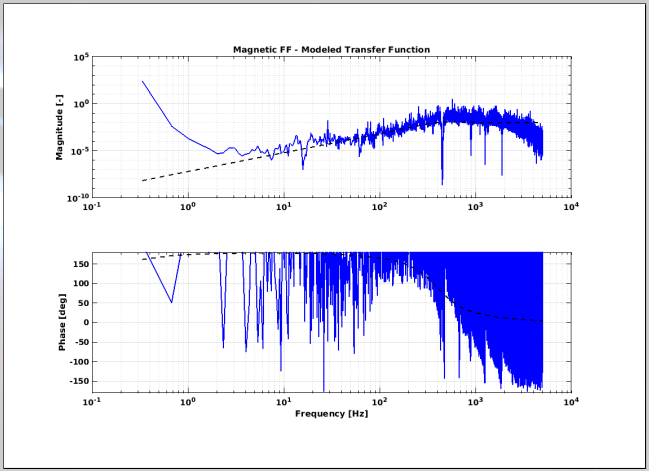
50 Hz Feed-Forward: Closed-Loop Transfer Function

- The second step is the measurement of TF_B between target and actuation
- This is the Closed Loop Transfer Function of DARM
- Noise must be *injected* in the loop to do a good measurement
- This also determines the inherent phase delay of the loop



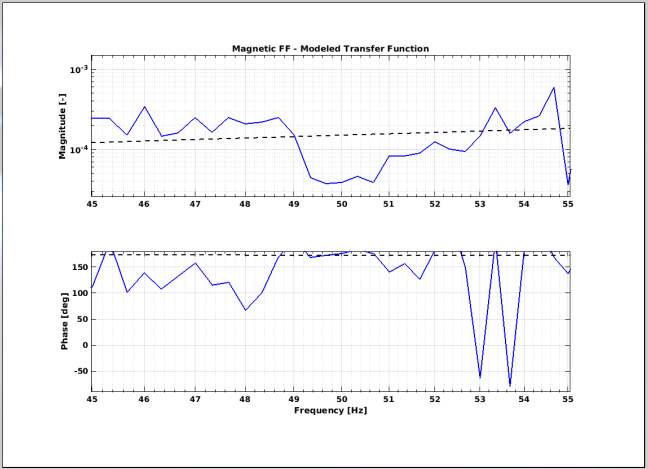
50 Hz Feed-Forward: Computation of the Feed-Forward Filter

- $\mathrm{TF_{FF}} = -\frac{\mathrm{TF_A}}{\mathrm{TF_B}}$
- The Feed-Forward filter can now be computed
- In simple cases (this one) it can be done by hand (phase-tuning needed only in a narrow band)
- In complicated cases (the next one) frequency-domain fitting (e.g., vectfit) is needed

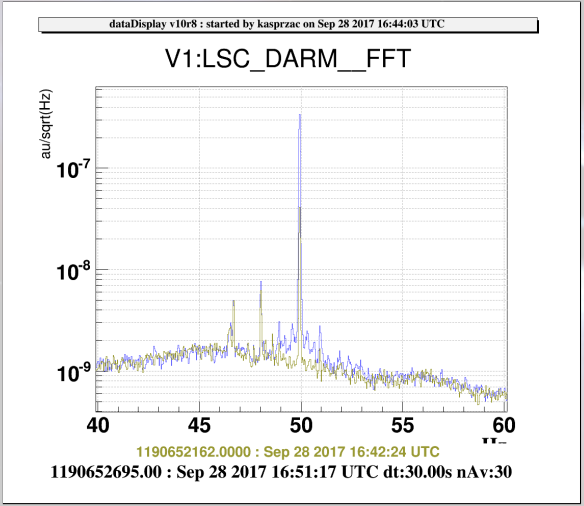


50 Hz Feed-Forward: Computation of the Feed-Forward Filter

- $\mathrm{TF_{FF}} = -\frac{\mathrm{TF_A}}{\mathrm{TF_B}}$
- The Feed-Forward filter can now be computed
- In simple cases (this one) it can be done by hand (phase-tuning needed only in a narrow band)
- In complicated cases (the next one) frequency-domain fitting (e.g., vectfit) is needed



50 Hz Feed-Forward Running Online



- Online subtraction proven successful in the Post-O2 Commissioning
- Reduction of the 50 Hz line of a factor $\simeq 10$
- Sidebands also decreased
- Re-implementation (different witness/actuation path) currently ongoing for O3

Longitudinal Degrees of Freedom (1)

$$\text{DARM} = L_N - L_W \text{ (differential arm length)}$$

$$\text{CARM} = \frac{L_N + L_W}{2} \text{ (average arm length)}$$

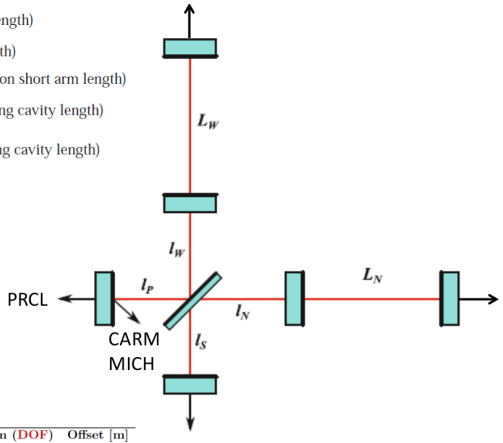
$$\text{MICH} = l_N - l_W \text{ (differential Michelson short arm length)}$$

$$\text{PRCL} = l_P + \frac{l_N + l_W}{2} \text{ (power recycling cavity length)}$$

$$\text{SRCL} = l_S + \frac{l_N + l_W}{2} \text{ (signal recycling cavity length)}$$

Advanced Virgo parameters

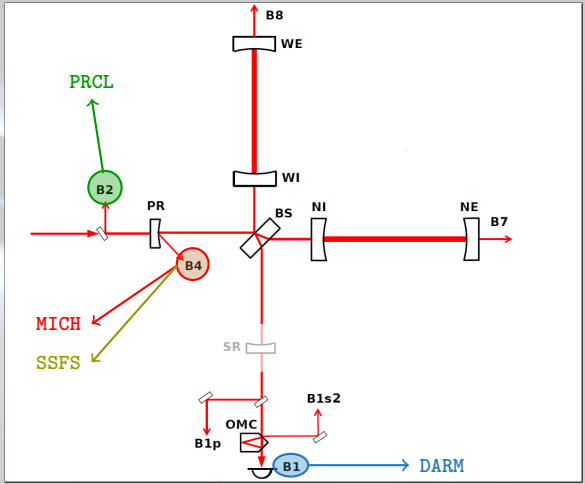
Parameter	Value
Power recycling mirror transmission	0.05
Input mirror transmission	0.014
End mirror transmission	1 ppm
Signal recycling mirror transmission	0.2
Losses per mirror	32.5 ppm
Arm cavity mirror mass	42 kg
Power recycling cavity length	11.952 m
Signal recycling cavity length	11.952 m
Schnupp asymmetry	0.23 m
Arm cavity length	2999.8 m
Modulation frequencies	$f_1 = 6270777$ Hz $f_2 = 56436993$ Hz $f_3 = 8361036$ Hz
Suspension last stage resonant frequency	600 mHz
DC readout offset	see Tab. 8.3
Signal recycling cavity detuning	3.022×10^{-7} m



Configuration	Degree(s) of Freedom (DOF)	Offset [m]
Power recycled 25W	MICH	$1.6 \cdot 10^{-9}$
Dual recycled 25W	DARM	$2.3 \cdot 10^{-11}$
Dual recycled 125W	DARM	$1.0 \cdot 10^{-11}$

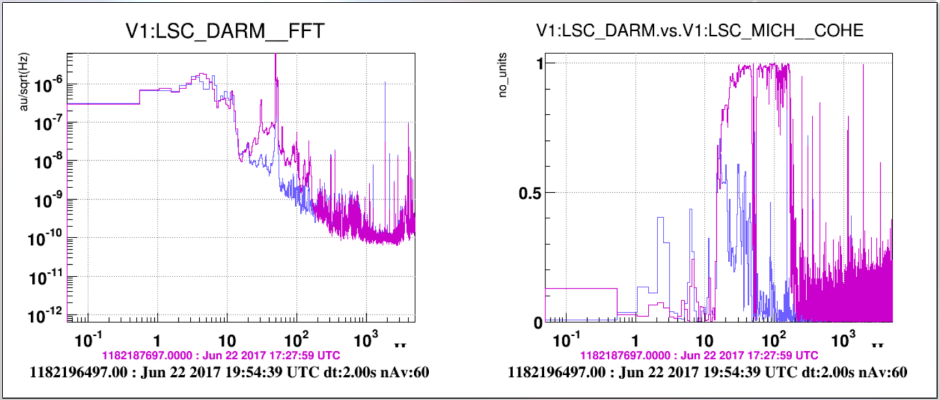
Longitudinal Degrees of Freedom (2)

- **Four longitudinal Degrees-Of-Freedom controlled:**
  - DARM controlled with `B1_DC`
  - MICH controlled with `B4_56MHz_Q`
  - SSFS controlled with `B4_56MHz_I`
  - PRCL controlled with `B2_8MHz`
- **Problem: the interferometer is not a diagonal system!**

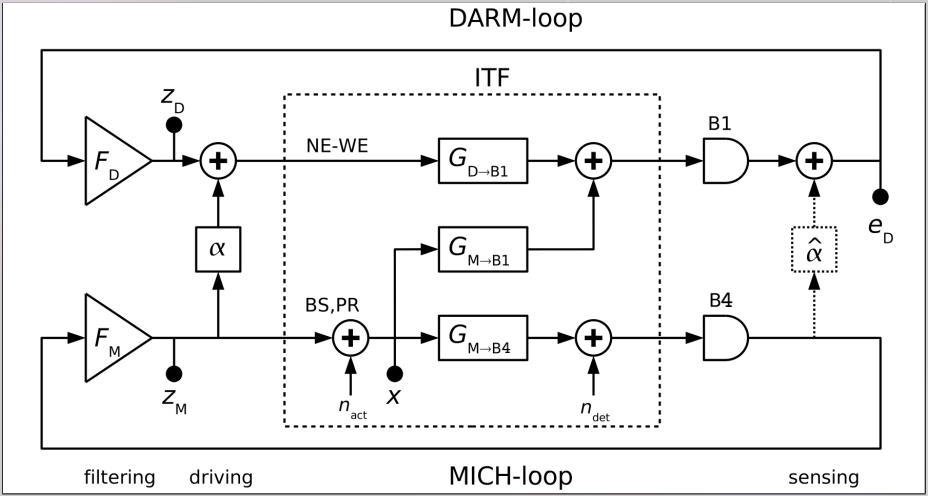


MICH → DARM Coupling

- Strong effect on DARM
- Frequency-dependent behaviour
- Most of the coupling is *linear*
- Online subtraction is possible



Alpha Technique: Mechanism



Alpha Technique: Definitions

- In principle the coupling factor is simply

$$\alpha = -\frac{G_{\mathrm{M}\to\mathrm{B1}}}{G_{\mathrm{D}\to\mathrm{B1}}}$$

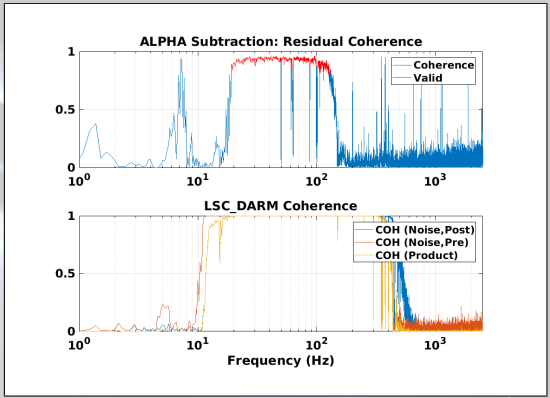
- But we cannot measure $G_{\mathrm{M}\to\mathrm{B1}}$ directly
- In the real ITF, we have instead:

$$\alpha_{\mathrm{new}} = \alpha_{\mathrm{old}} - \frac{\mathrm{TF}_{\mathrm{M}\to\mathrm{B1}}}{G_{\mathrm{Dcl}} \cdot \mathrm{TF}_{\mathrm{D}\to\mathrm{B1}}} = \alpha_{\mathrm{old}} - \frac{\mathrm{TF}_{\mathrm{M}\to\mathrm{B1}} \left(1 - \mathrm{TF}_{\mathrm{Dpost}\to\mathrm{Dpre}}\right)}{\mathrm{TF}_{\mathrm{D}\to\mathrm{B1}}}$$

Alpha Technique: Procedure

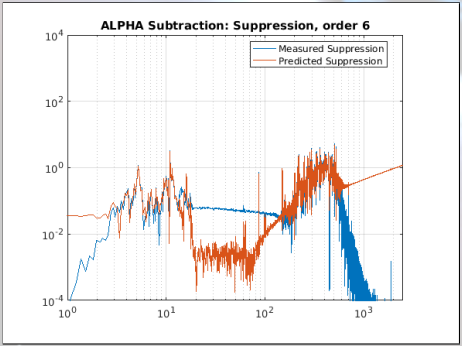
Procedure:

- Noise injections on both DARM and MICH
- Important: the DARM/MICH coherence should be high enough, but *without* saturating any of the actuators
- Calculate *offline* the new Alpha, by computing the TFs and fitting the new filter
- Important: Alpha is frequency dependent, so the frequency window and the frequency dependence of the weights are impacting
- Upload the new Alpha filter in the online software

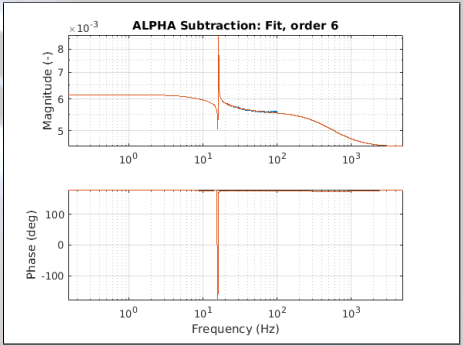


Alpha Technique: Evaluation

- Several fits are made for different orders
- The predicted new suppression is computed and compared to the current one

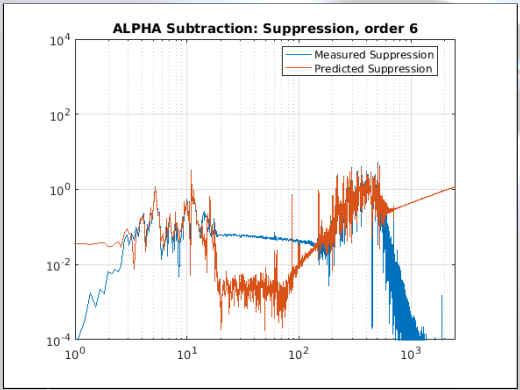


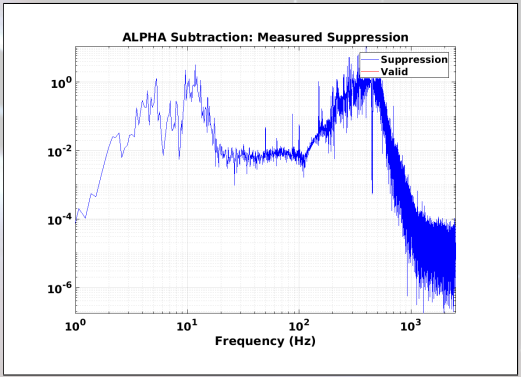
- Example of filter update after a change in the MICH loop made the subtraction under-performing



Alpha Technique: Validation

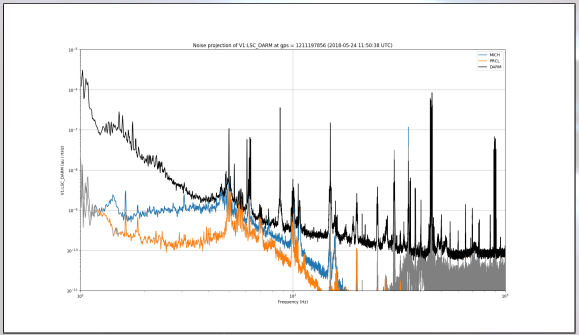
- With the new filter, another set of noise injections will validate the performance
- Comparison between the predicted suppression and the measured one



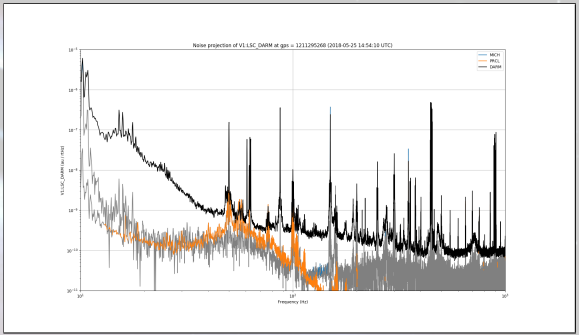


Alpha Technique: Longitudinal Noise Budget

- Contribution from MICH gets lower
- Coherence drops as well

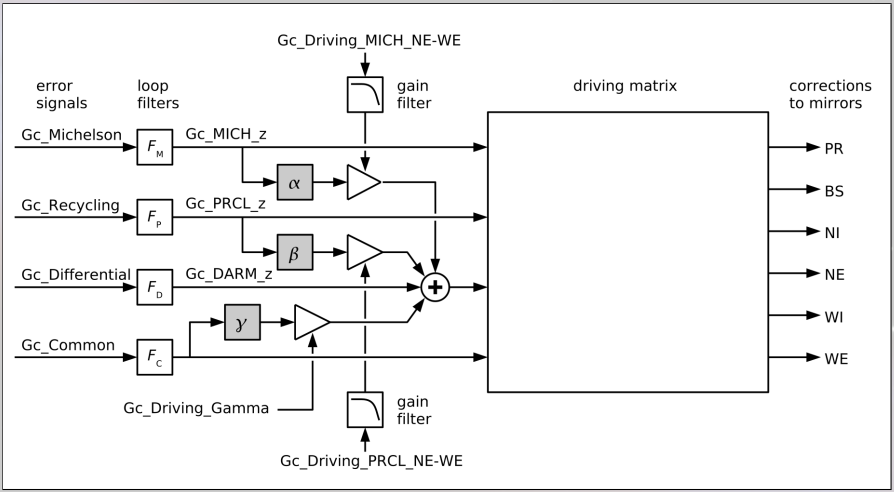


Old Alpha filter



New Alpha filter

Alpha, Beta & Gamma




Thank You!