h(t) reconstruction and validation

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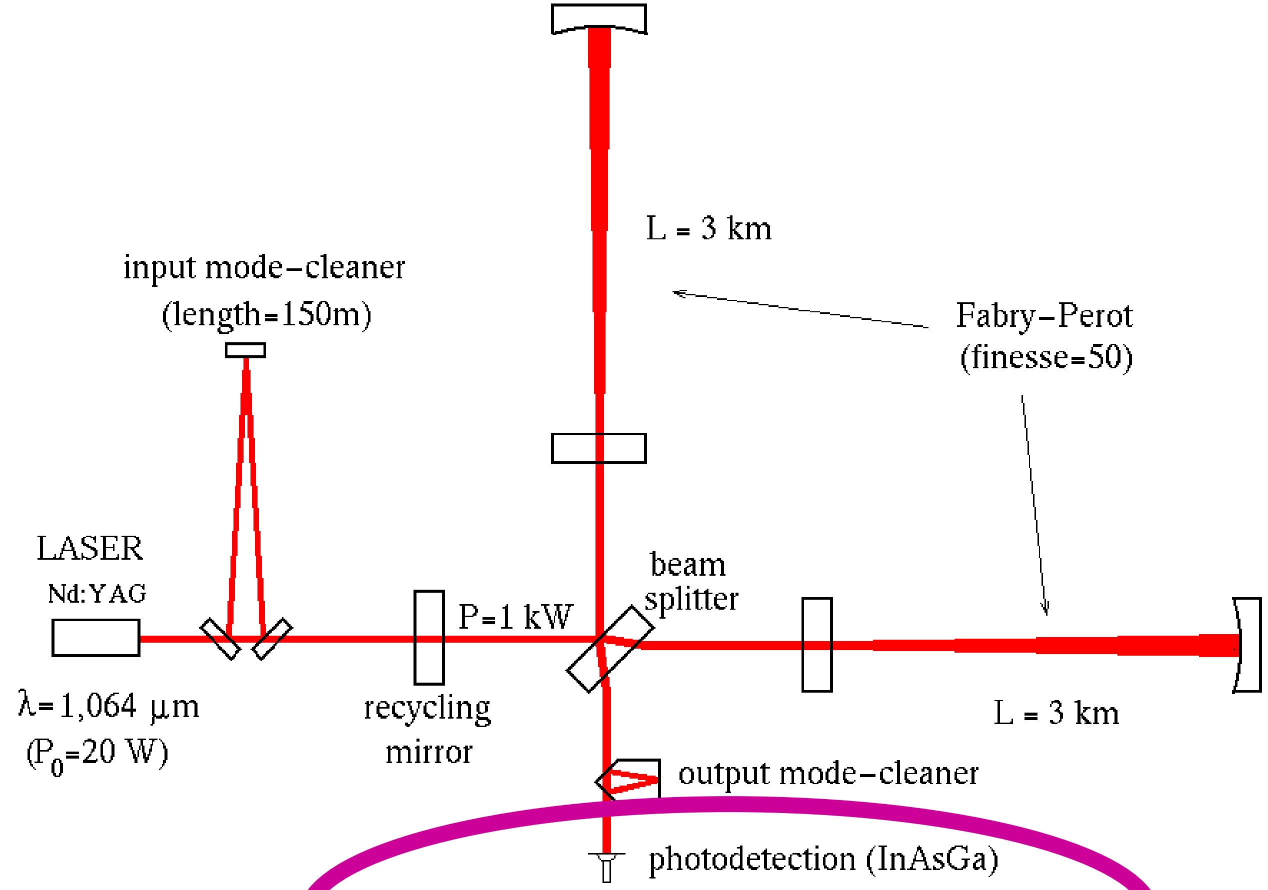
Gravitational Wave Data Analysis Workshop
IHP Paris

Outline

- Why do we need an h(t) reconstruction?
  - The controls
  - The time domain approach vs frequency domain
- Measuring the basic calibration factors
  - The actuators gain
  - The transfer function
- Building h(t)
  - Frequency dependence effect
  - Noise subtraction
- Validation
  - Comparing the sensitivity curves
  - The shot noise level
  - The photon calibrator
  - Hardware injection

Remark: use Virgo examples; work in progress: not final results

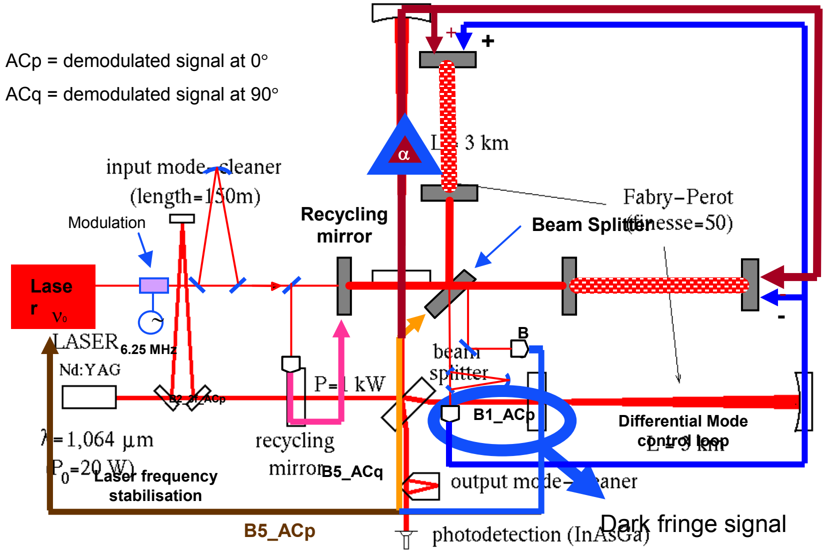
Virgo Optical Configuration



First calibration task: **Volts → meters?**

The control challenge

- Mirrors must be free test masses
  - ◆ The free mirror motions is of several μ
- The ITF needs
  - ◆ The mirrors at the right place
    - » BS on the dark fringe
    - » Locked F.P. and recycling cavities



- Contradiction solved by the Locking strategy
  - ◆ Control the mirror at low frequency
  - ◆ Mirrors are free at high frequency

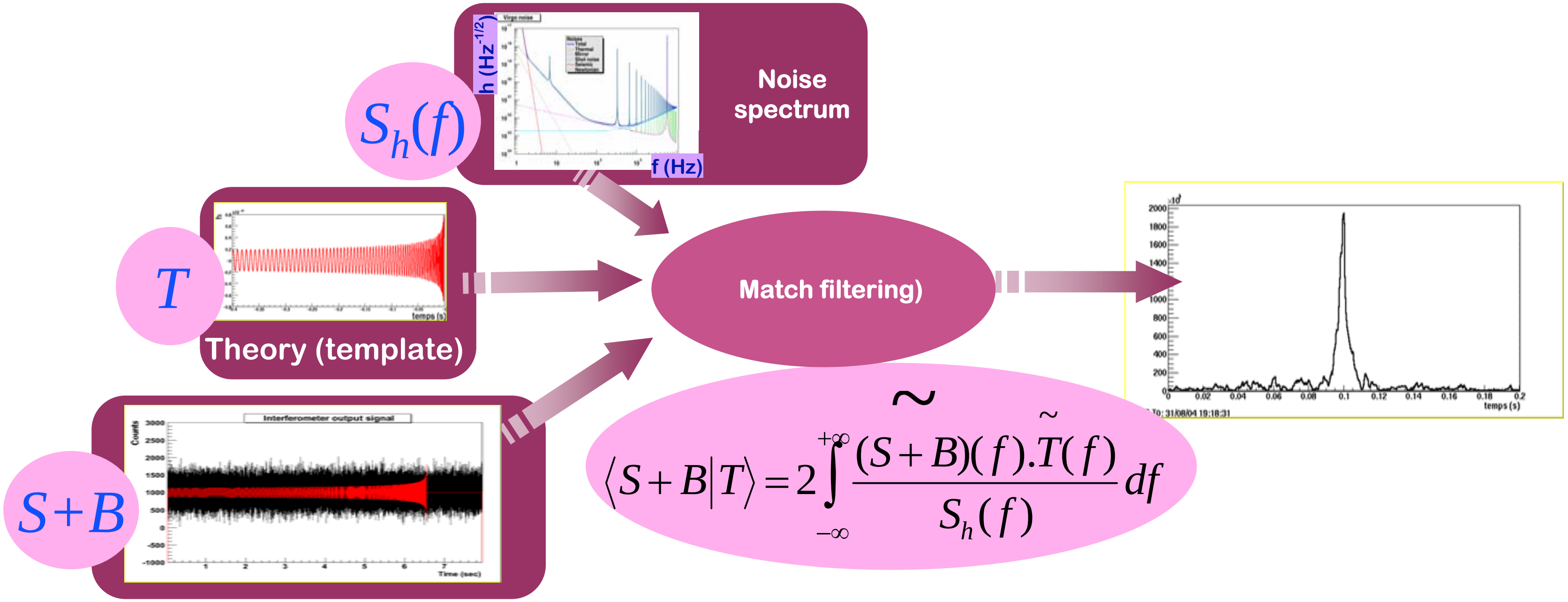
→ Distortion of the dark fringe signal

→ Transfer Function (TF): **Shape and Scale**

Second Calibration task: correct the control effects

Handling the TF: Frequency domain approach

- A lot of analysis works in the frequency domain
  - Example: Match Filtering for Binaries



- Some others analysis use a narrow or high frequency band:
  - require a simple procedure
- Need to get the right TF: time dependant
  - Data base required…

Handling the TF: time domain approach

- Correct the error signal and produce a time series: h(t)
- No more need of a data base from the user
  - Use only one channel: h(t)
- Will allow a additional bonus:
  - Some noise subtraction is possible

- But before: needs to get all inputs for the corrections

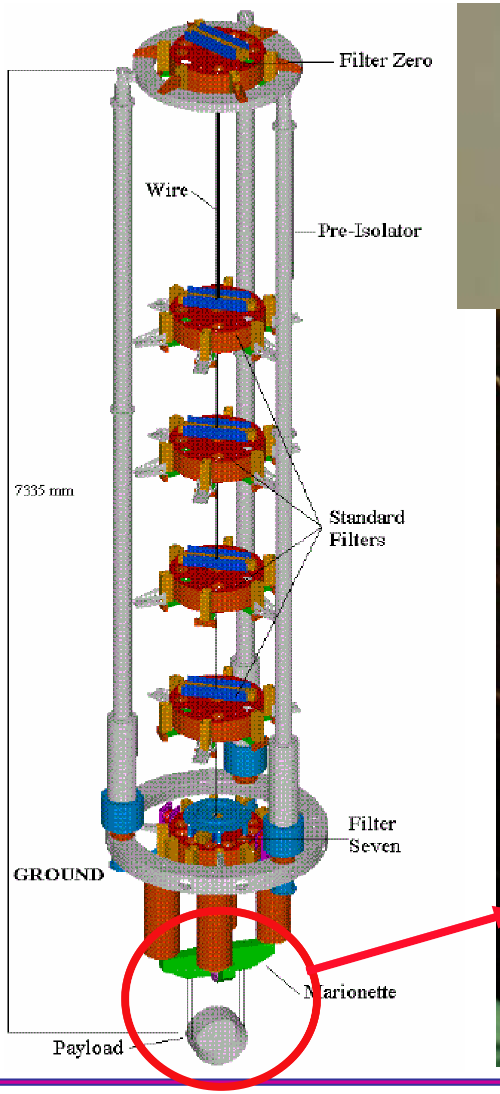
Extracting the calibration parameters

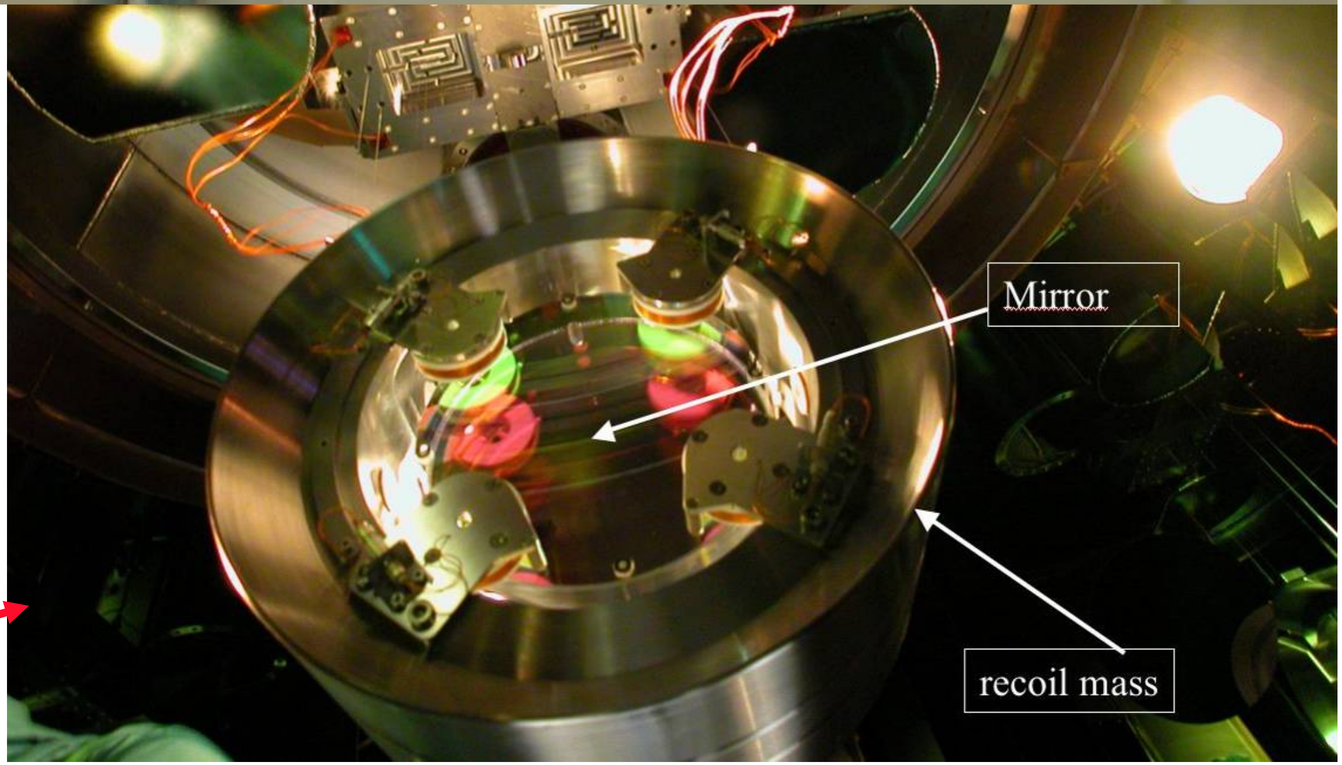
1)The scale

Need to push to mirror in a known way:

Actuator gain: 1V $\rightarrow$ X meters?

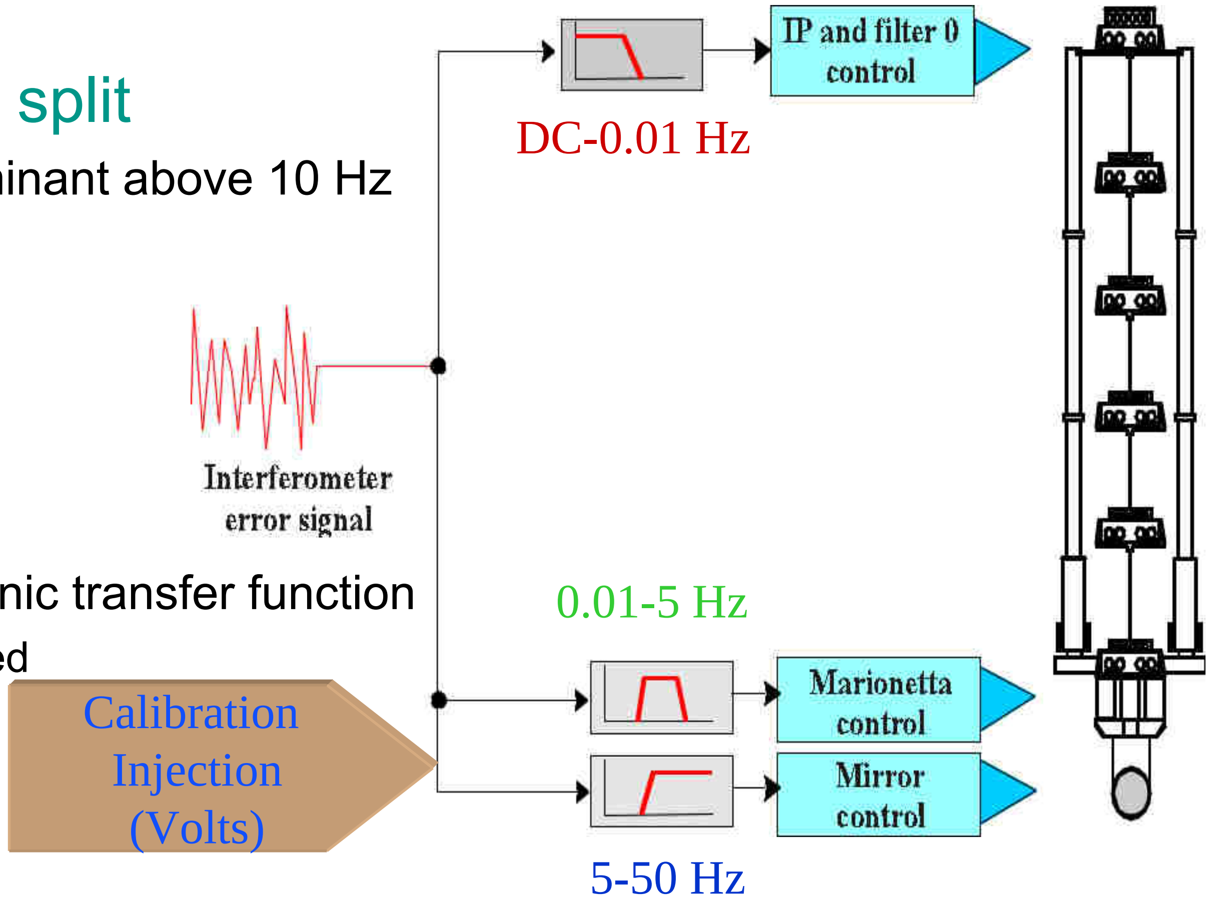
Mirror actuators





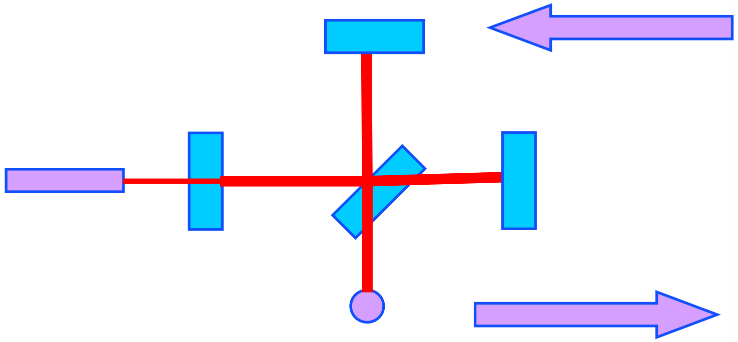
Virgo mirror controls

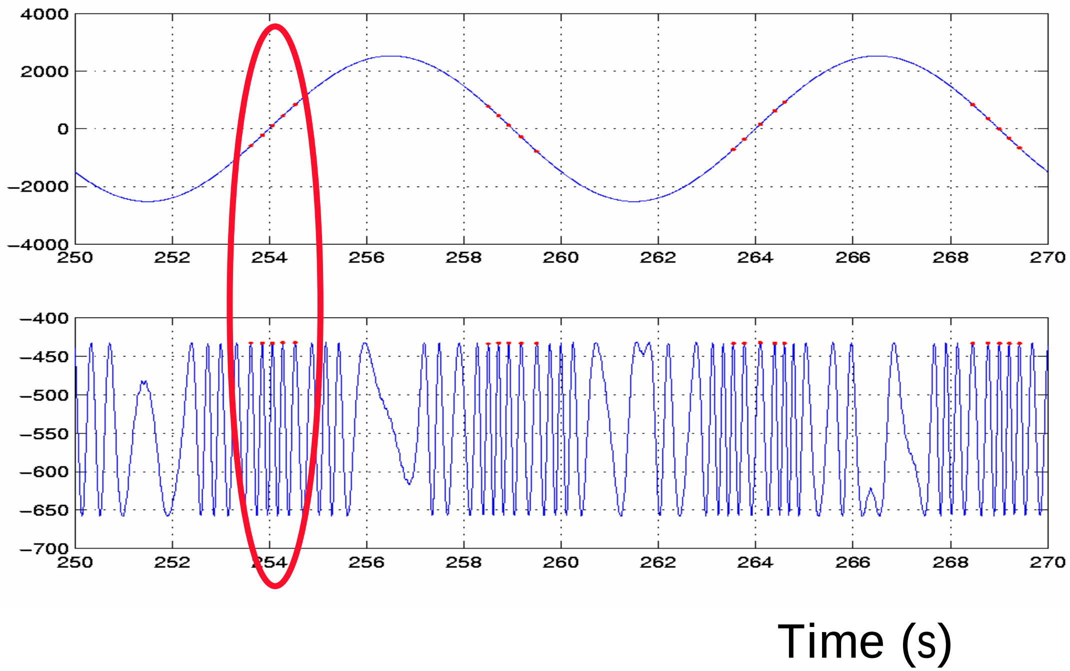
- Control signals are split
  - ◆ Reference mass dominant above 10 Hz
- Last stage model:
  - ◆ Simple pendulum
  - ◆ Assume a flat electronic transfer function
    - » More checks needed



Actuator gain measurement: fringe counting

- Simple Michelson:
  - Push the mirror over several fringes
  - Extract gain from the DC power



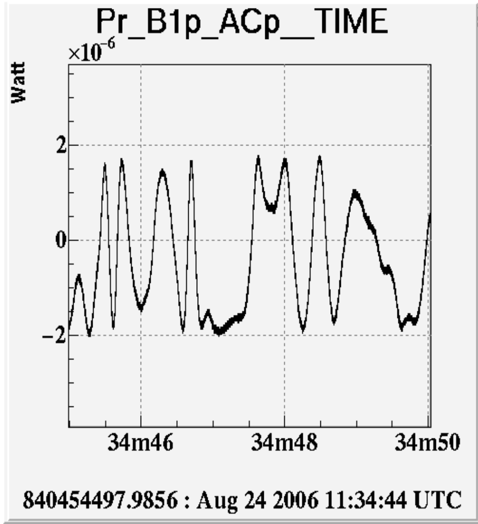


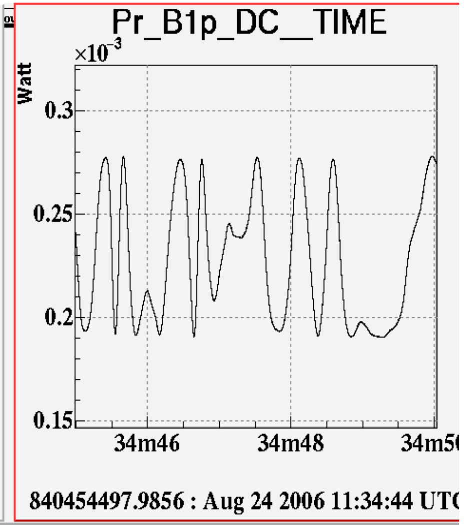
  - $P = P_0/2(1+C.\cos(2\pi\Delta L/\lambda))$

- Remark:
  - need large displacement and a quite site
  - Measure at low frequency

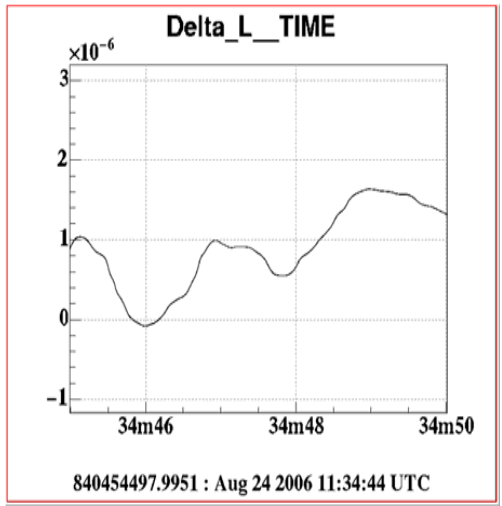
Open loop Michelson Reconstruction

- Monitor the DC and AC signals
  - AC signal is shifted by 90° from DC
  - Get the Power and the ITF contrast
    - » $P_{DC} = P_{0DC}/2(1+C.\cos(2\pi\Delta L/\lambda))$



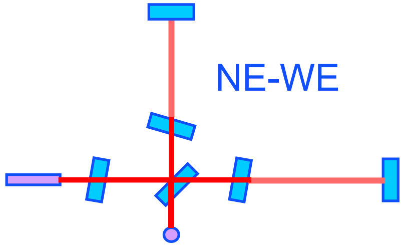


- Invert the Michelson equation
  - non linear process
  - Get $\Delta L(t)$

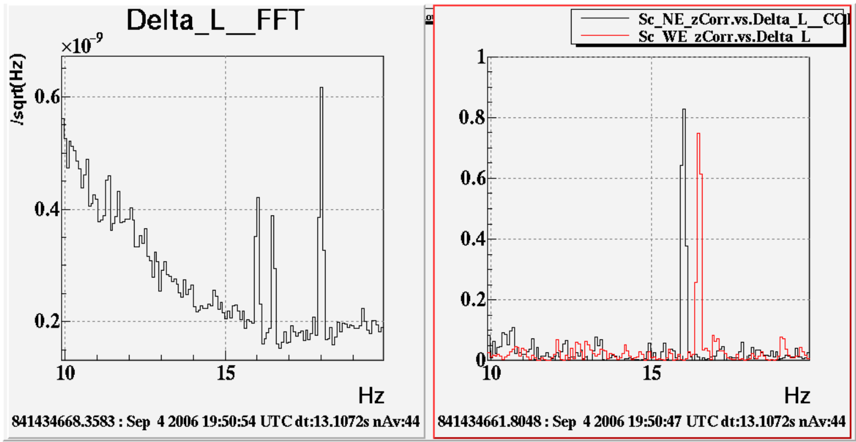


- Absolute scale given by laser wavelength

Using the Open loop Michelson



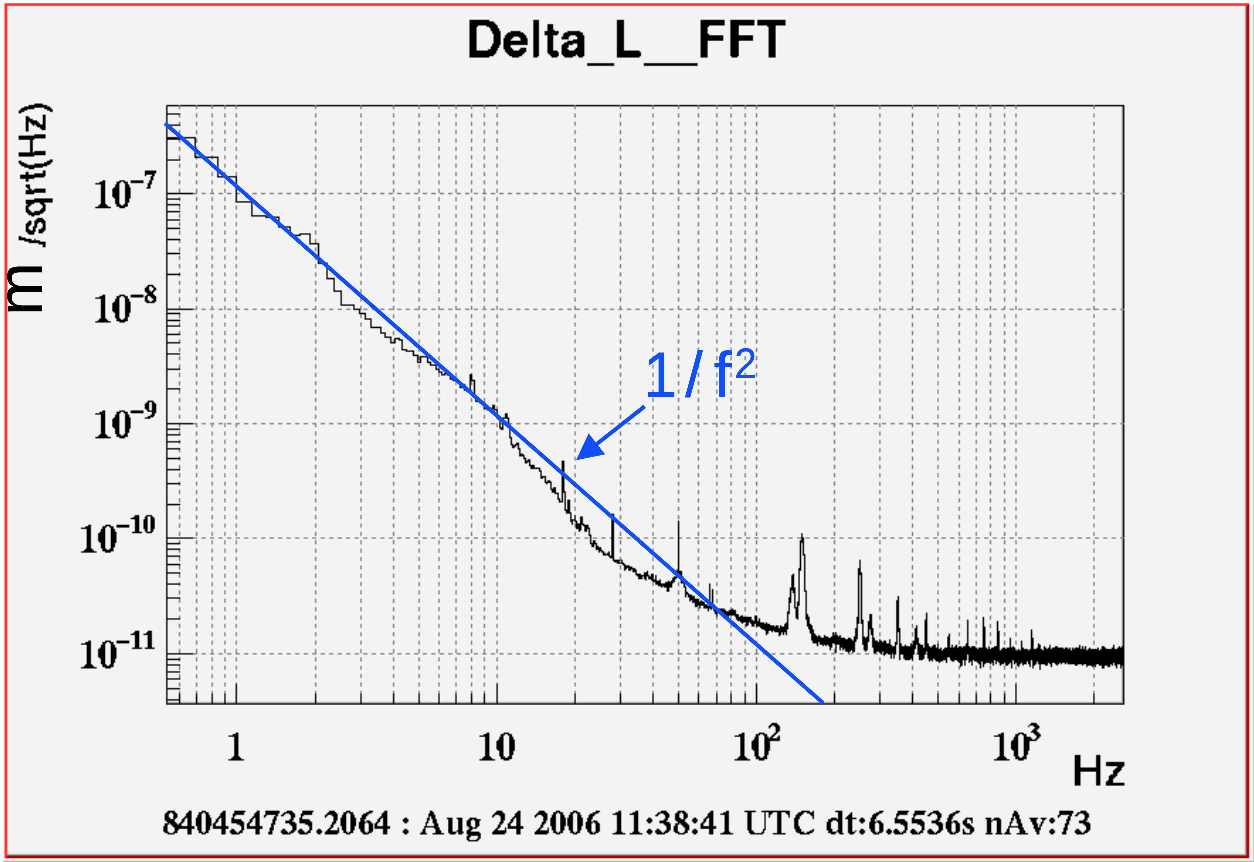
- ITF Configurations
  - Asymmetric (NE-WI;NI-WE) or long (NE-WE) Michelson
- Measurements:
  - Inject “calibration lines”
  - Take the transfer function (dL/zCorr)
  - Rescaled by (frequency/.6)^2
- Typical Results (Sep 4):



f [Hz]	ITF	Ampl.*601 [V]	WE Gain μ/V
26.5	Asym	3	11.6 ± 1.1
26.5	Asym	4	12.3 ± 1.7
26.5	Asym	6	11.9 ± 1.3
26.5	Long	6	12.8 ± 1.1
26.5	Asym	8	11.7 ± 0.9
16.5	Asym	6	12.2 ± 0.4
16.5	Long	6	12.5 ± 1.0
116.5	Asym	6	7.9 ±3.6
Mean	Value	-	12.14 ± 0.30

Only statistical errors

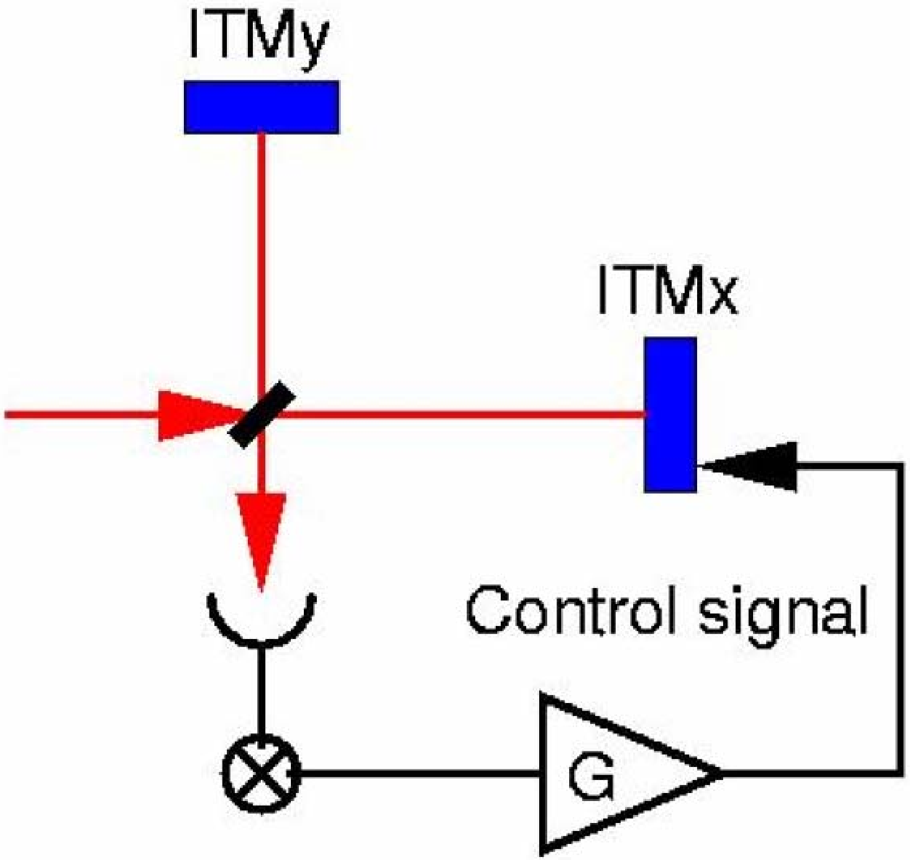
Typical Noise spectrum (WI-NE)



- Best sensitivity around 20-30Hz
  - ◆ No measurement above ~ 100 Hz

Another method: ITM fringe toggling

Used by LIGO
(slide from M. Landry)



1. Lock Michelson on dark/bright fringe
2. Wait N seconds
3. G->-G, Michelson transitions to bright/dark fringe
4. Goto step 2

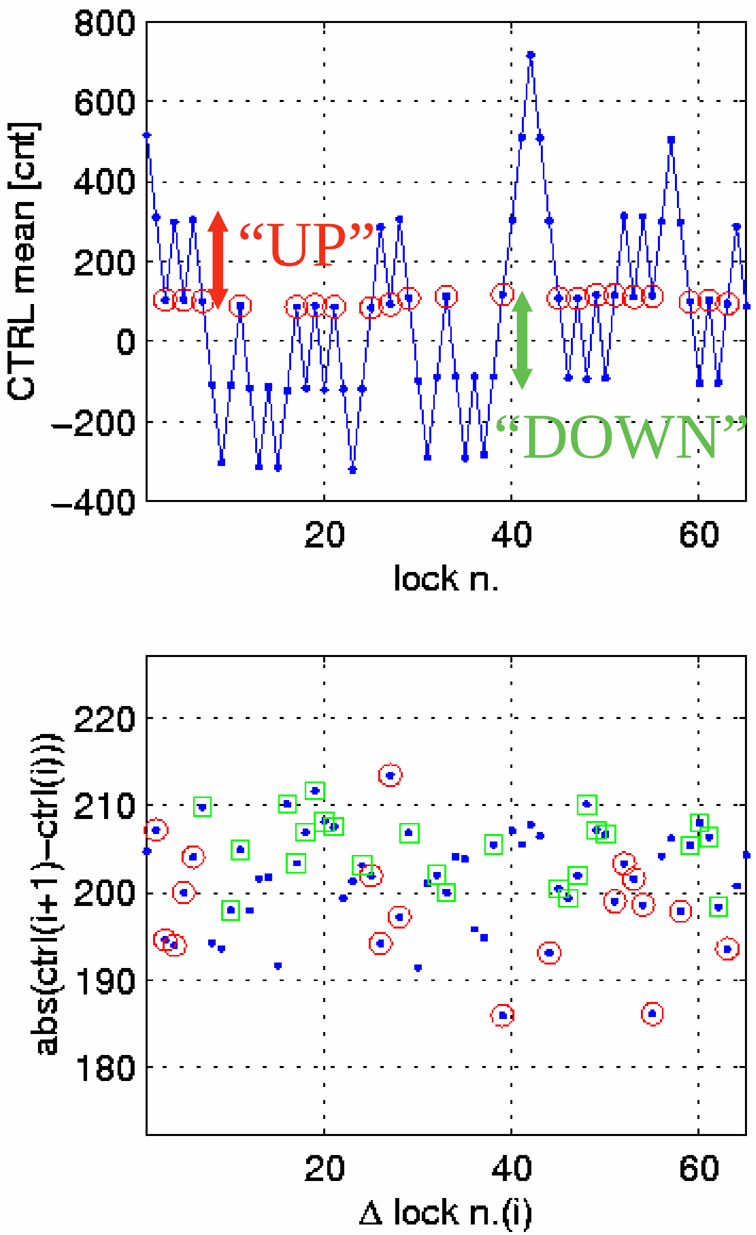
$\lambda/4$ **transition**

Calibration of control signal

Fringe toggling analysis

Mean of MICH control signal for a given time stretch

Difference of control signal between two successive locked stretches



Used by LIGO (slide from M. Landry)

Mean (cnt) = 201.6607 +− 5.9289

−−−> (1.319e−09 +− 3.878e−11) [m/cnt]

Mean UP(cnt) = 198.1013 +− 6.8505

Mean DOWN(cnt) = 205.0896 +− 3.9418

Mean SUM(cnt) = 403.1908 +− 7.9036

−−−> (1.3195e−09 +− 2.5865e−11) [m/cnt]

H1:LSC-ITMY
1.32×10^{-9} m/count,

Sigma:
0.03×10^{-9}

Actuators gain: some challenges

- The actuators gains are measured:
  - At low frequencies ("DC")
    - » But used in a wider frequencies band
  - With large amplitude
    - » But used with lower signal (problem of the injected noise)
    - » Coil drivers have variable gain or frequency dependant responses ("whitening")
- Need to cross check the electronic
  - Measure to know the coil driver Transfer Function
- Need to pay attention to the mirror mechanical model
  - near the pendulum resonance (0.6Hz for Virgo)
  - mirror internal mode (kHz band)
- Not all mirror actuators directly measured
  - Some optical configuration makes the life more complicate
    - » signal recycling, high finesse
  - Need to transfer measurements from one mirror to another mirror
    - » Use for instance locked cavities with closed calibration lines on all mirrors

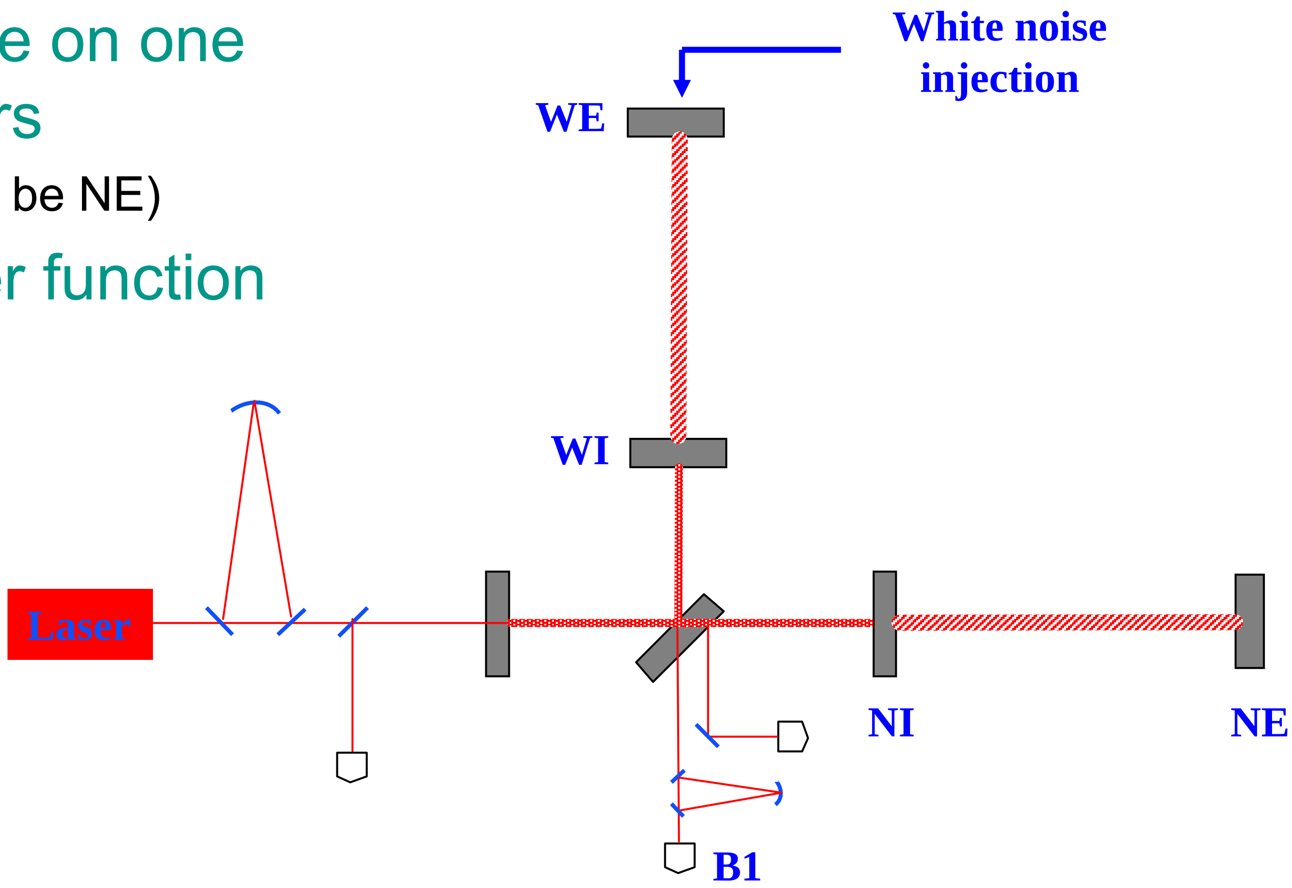
Extracting the calibration parameters

2)The shape

Measuring the Transfer function

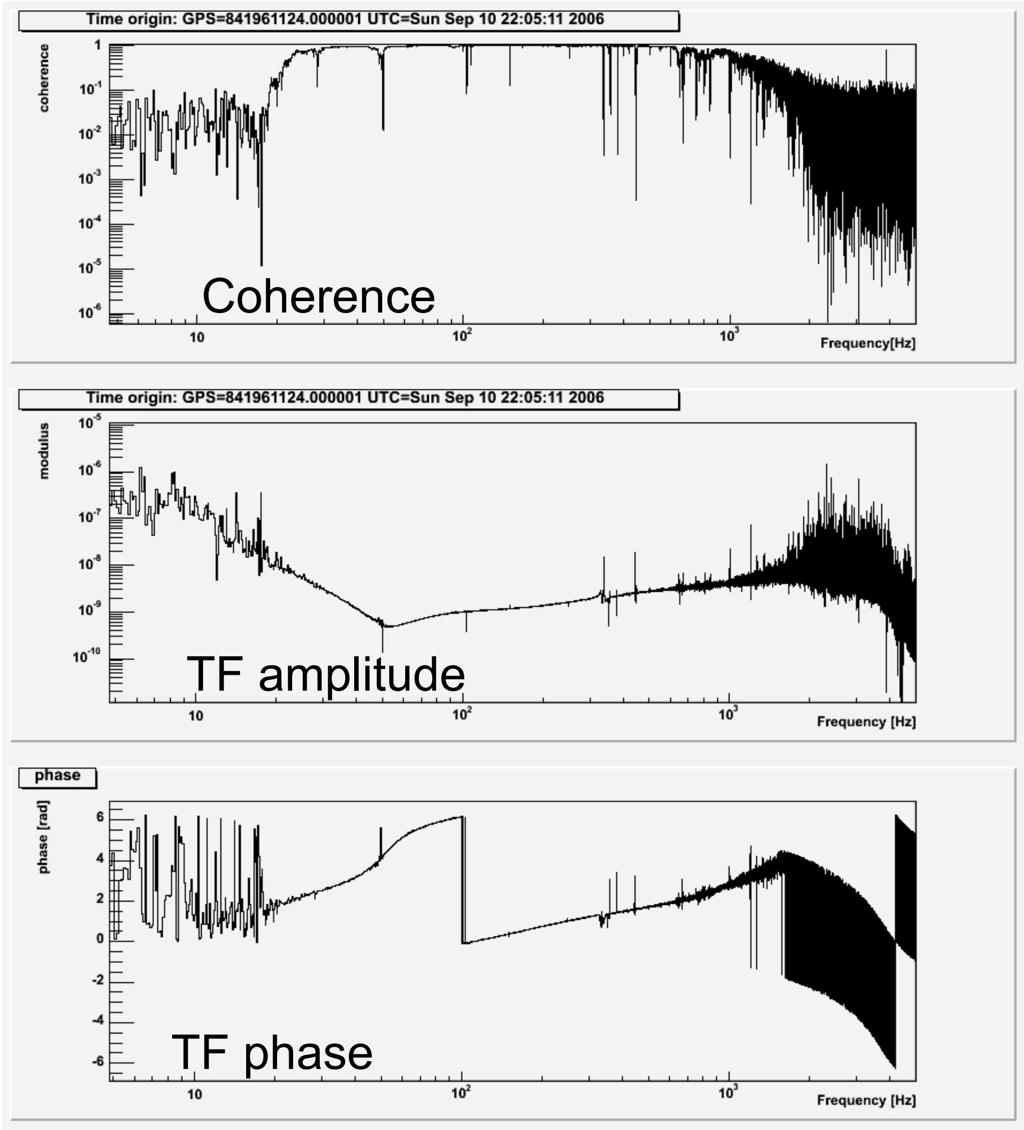
TF Measurement

- Inject white noise on one of the end mirrors
  - Now WE (used to be NE)
- Measure transfer function to B1_ACp



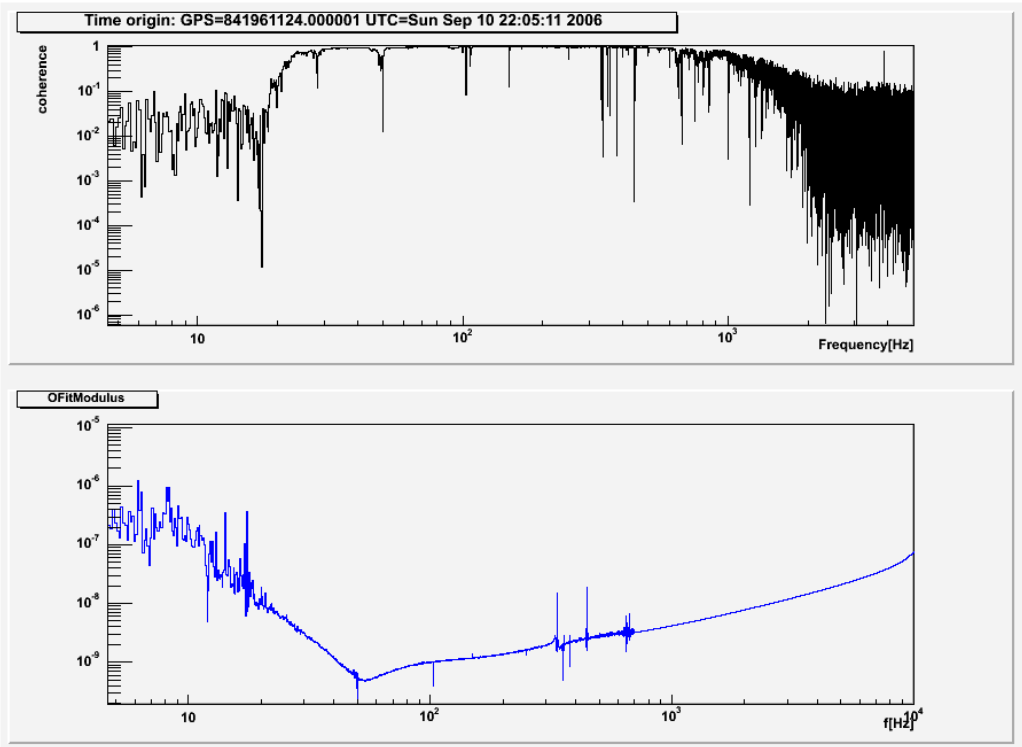
Example of measured TF

- White noise applied on mirror
  - ⇒ Coherence typically between 30 and 700 Hz



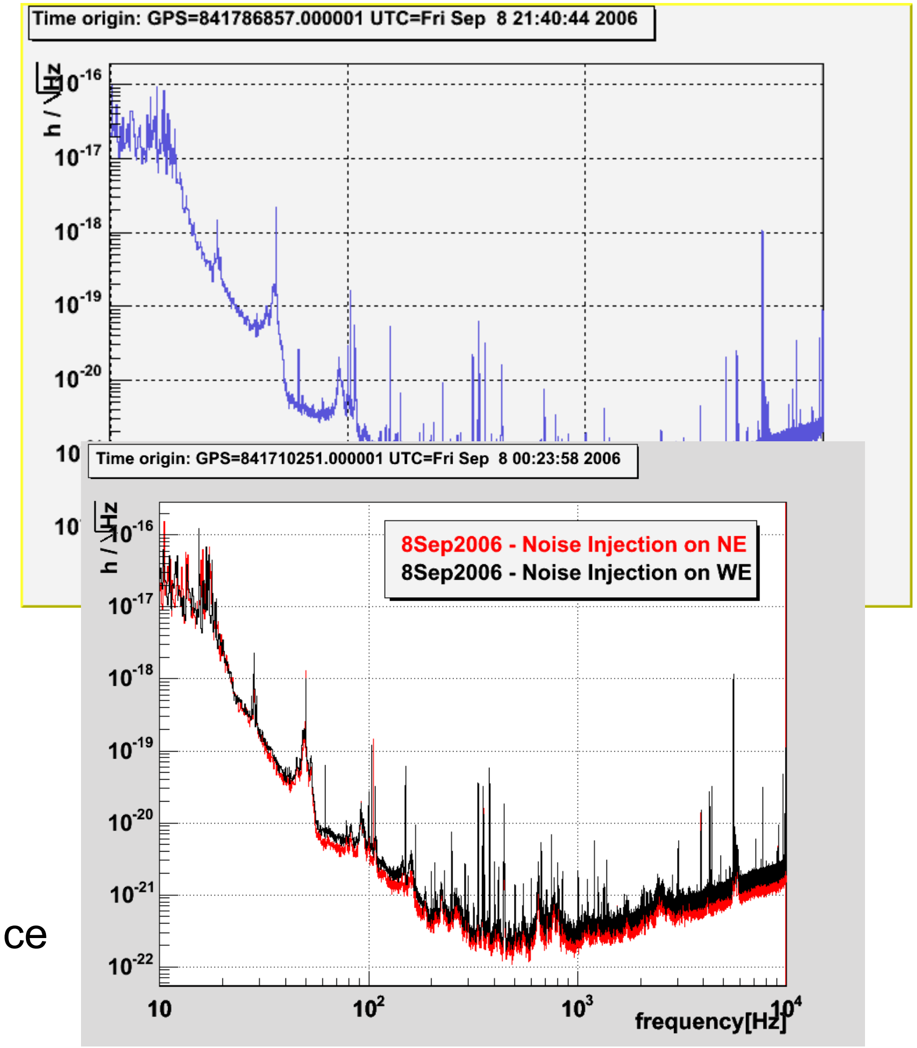
Model used

- Use raw transfer function in frequency band with good coherence (<700 Hz)
- Use fit above 700 Hz
  - ◆ Optical response with 2 free parameters: gain & delay
  - ◆ Cavity pole kept fixed @ 500 Hz
    - » Finesse of cavities well known
      - – $F_{North} = 49.0 \pm 0.5$
      - – $F_{West} = 51 \pm 1$
  - ◆ Include:
    - » Anti-alias filter on photodiode signal
    - » Pendulum response
      - – Actuator calibration !
  - ◆ Ignore: locking filters (high freq.)



Sensitivity

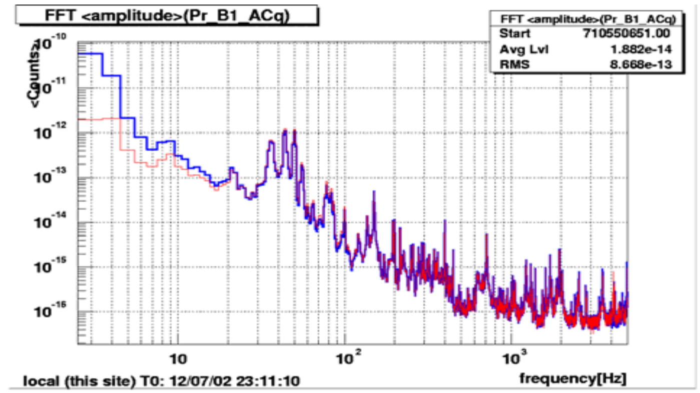
- Apply measured & fitted TF to B1_ACp spectrum
- Remark: Calibrations done injecting noise on NE or WE give different sensitivities
  - At ~40% level
  - Assume 14 μm/V for actuators
    - » WE is probably 15% smaller
    - » Does not explain all of the difference
    - » Work in progress

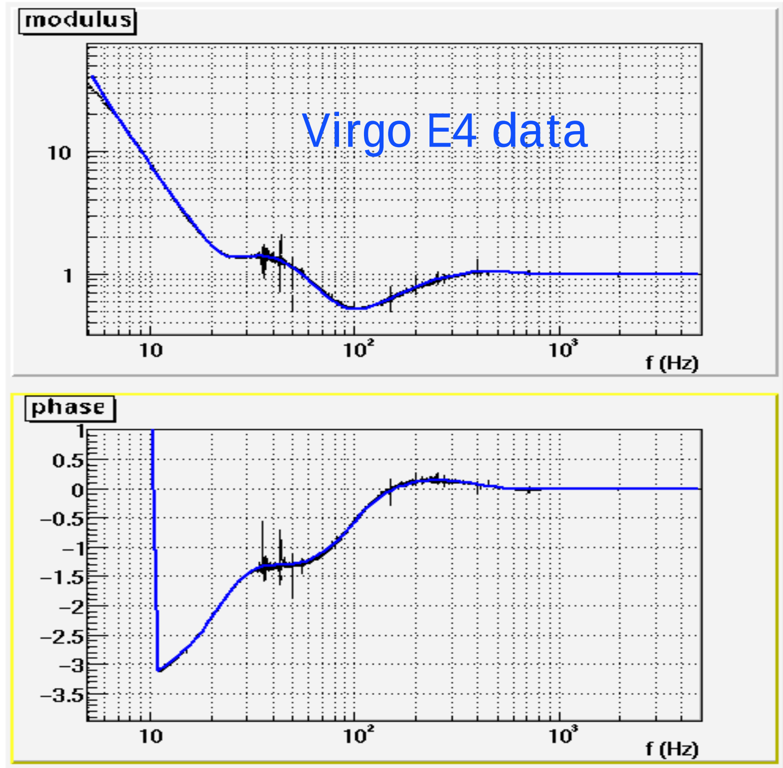


Building h(t)

h(t) reconstruction with filter

- Method:
  - Fit ITF response with pole-zero model
    - optical response + locking loop
  - Convert to Time Domain filters
  - Apply to dark fringe

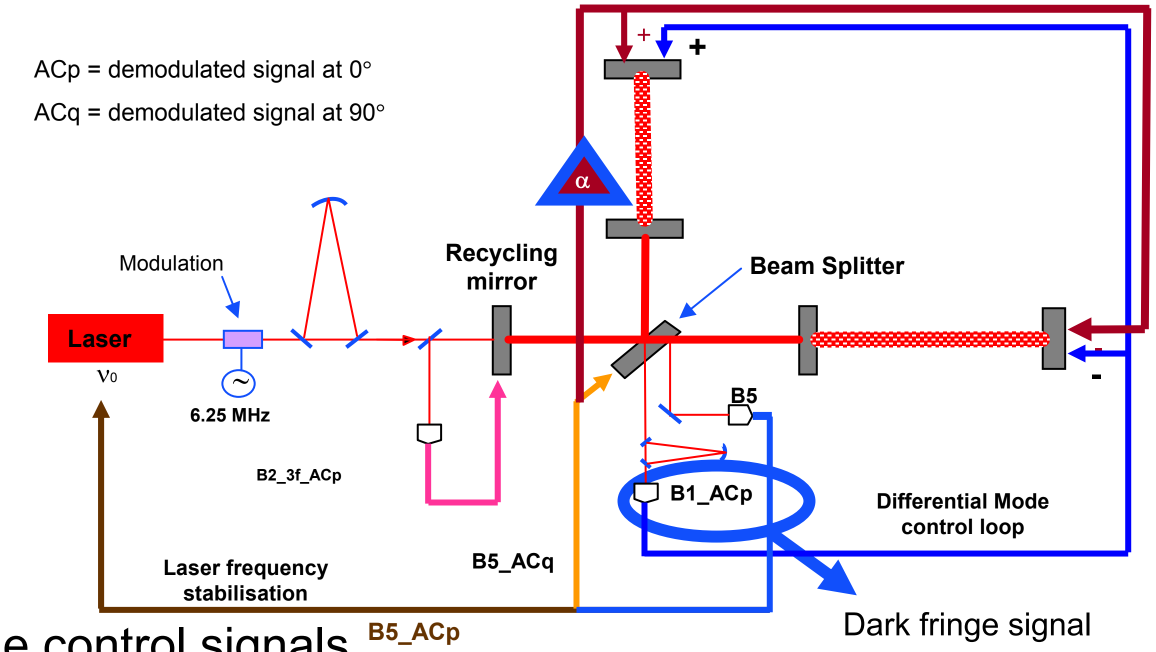




- Problems:
  - Complicated locking model (coupled loops)
  - Need to follow the coupling coefficient (the TF shape change with time)
  - End up with unstable filters

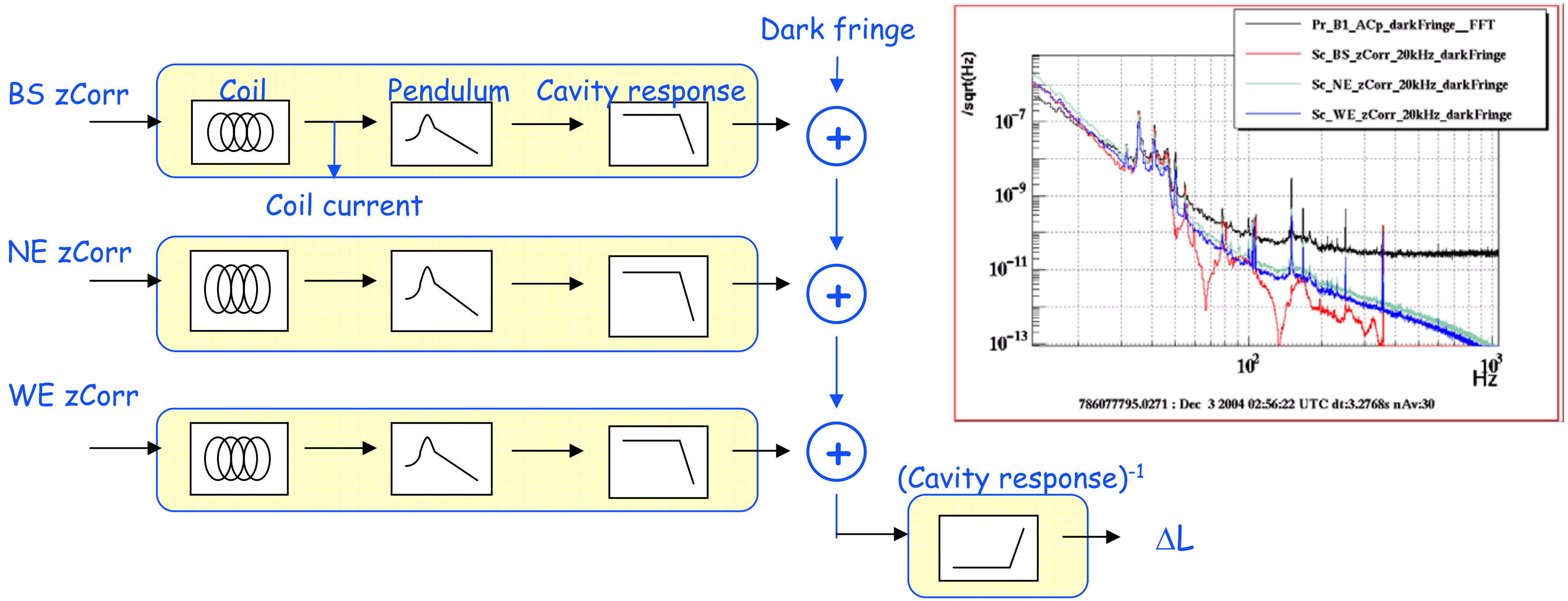
h(t) reconstruction using controls signals

- A locked ITF:



- Dark fringe signal:
  - Free ITF + effect of the control signals
- Control signals are known
  - Their effect on the mirrors motion is simple
- Free ITF = Locked ITF – control signal
  - + correction for the optical response (cavity filtering)
- Remark: this method remove some of the control noises

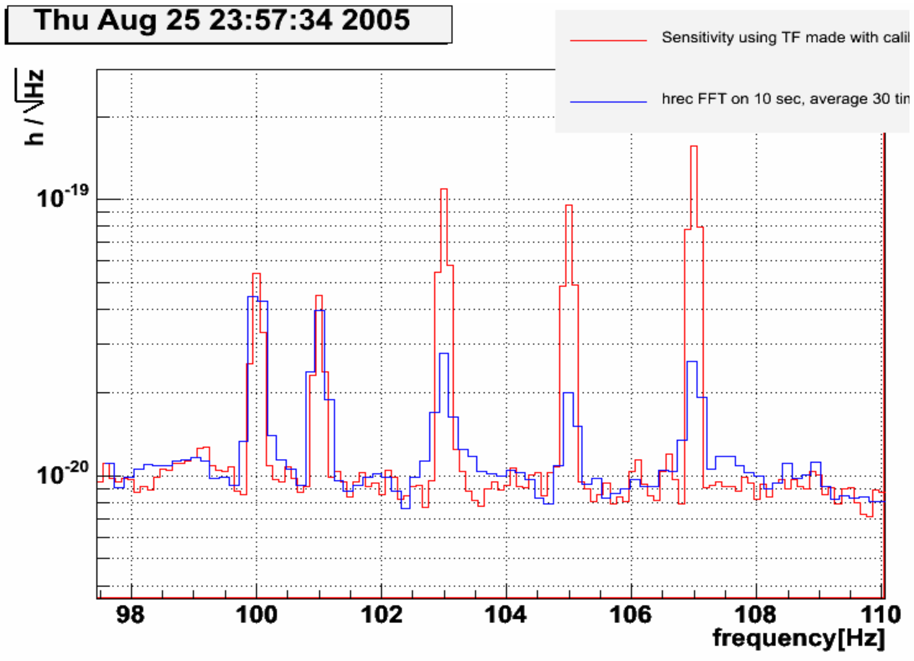
h(t) reconstruction details

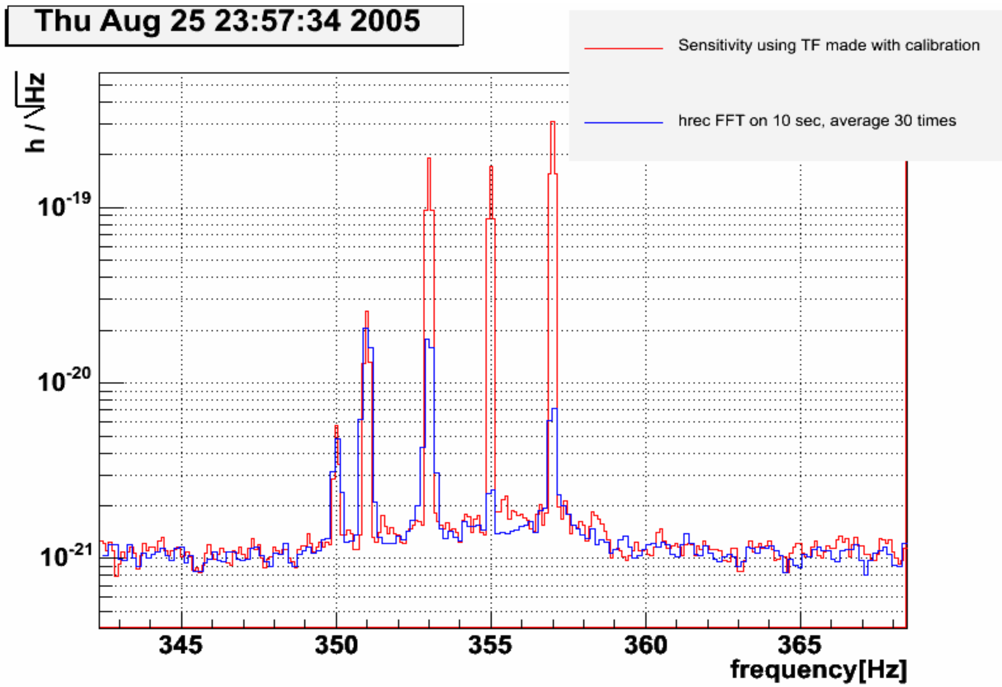


- Remove locking effects from dark fringe signal
  - using mirror correction signal as locking effects measurements
  - need actuators TF (assuming 14μ/V) and optical TF for three mirrors
  - Track the optical gain with calibration lines
- Convert dark fringe to ΔL
  - need inverse optical TF (assume a 500 Hz cavity freq. cutoff)

Optical gains tracking

- Monitor calibration lines amplitude in dark fringe and correction signals
  - ⇒ Update the optical gains for BS, NE, WE using the 350 Hz lines
  - ⇒ The “100 Hz” lines are used as a monitor of the quality

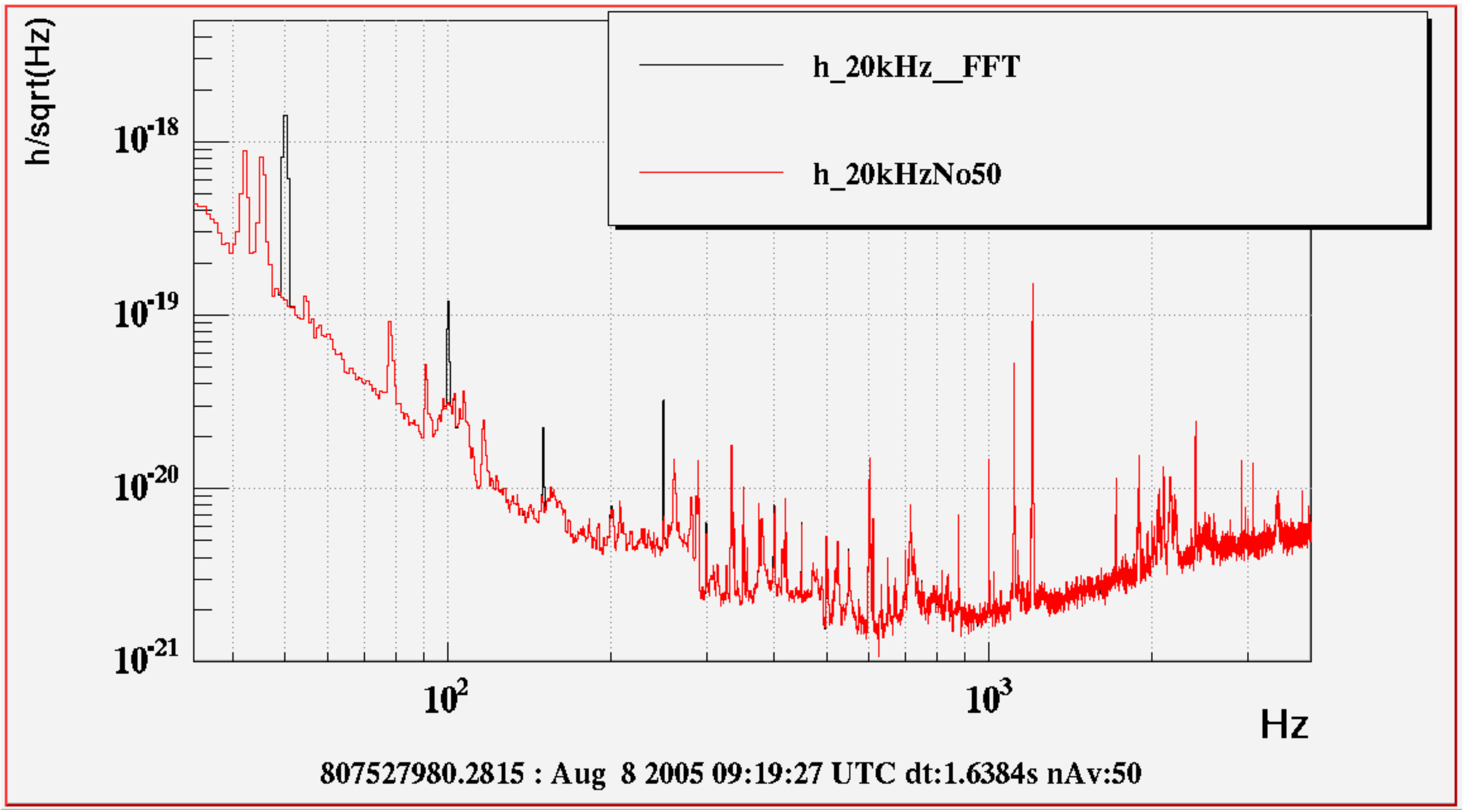




- Remark: Calibration lines removed by reconstruction
  - ⇒ Remaining lines amplitude used as error estimators: ~10-15% in WSR1

Additional noise removal: 50Hz lines

- Power line frequency is monitor using an auxiliary channel
- Track the coupling coefficient and phase
- Subtract the power lines in the time domain

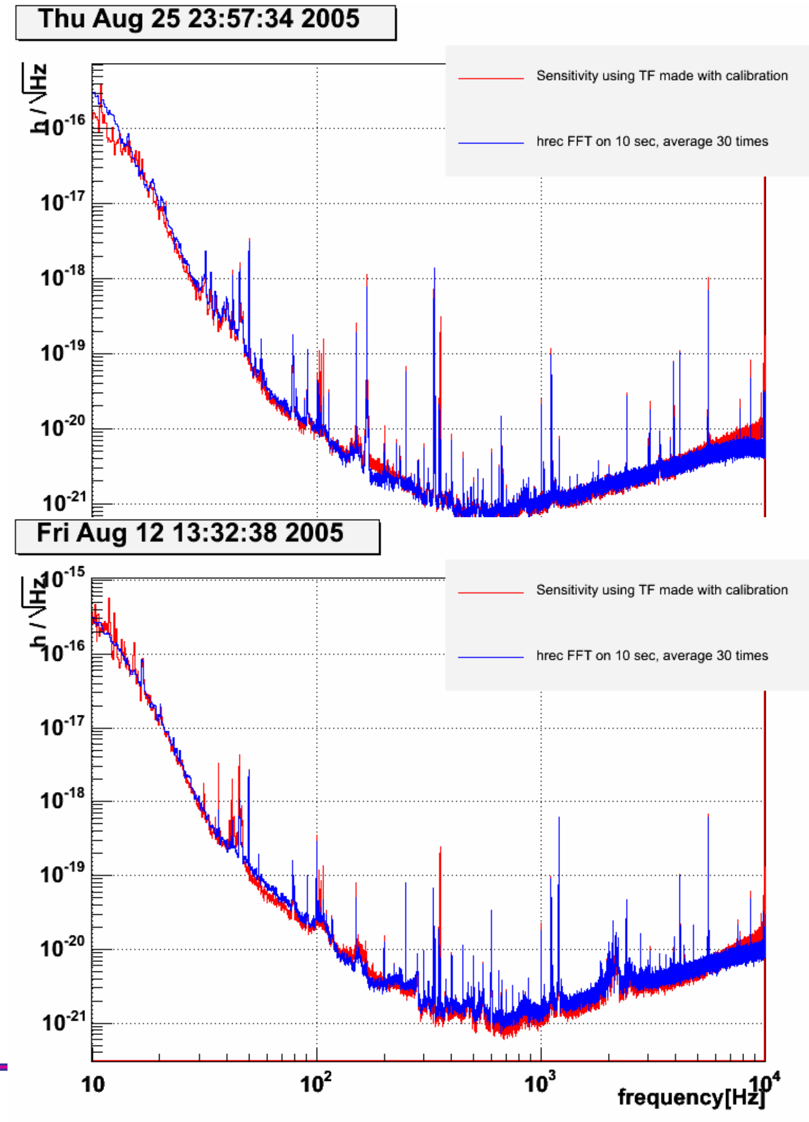


h(t) validation

1) Sensitivity vs reconstruction
2) Shot noise level
3) The photon calibrator
4) The hardware injection

Validation 1: Reconstruction vs Sensitivity

- Sensitivity from freq. domain calibration vs *h*(t) spectrum
- Limits of this comparison:
  - ◆ Sensitivities cannot be compared at exactly the same time
    - » Permanent lines needed for *h(t)* reconstruction are off when reference spectrum is measured
    - » Interferometer is non-stationary!
  - ◆ Sensitivities depend on different actuator gains
    - » Freq. domain: NE or WE depending on injection point
    - » *h(t):* average of NE and WE

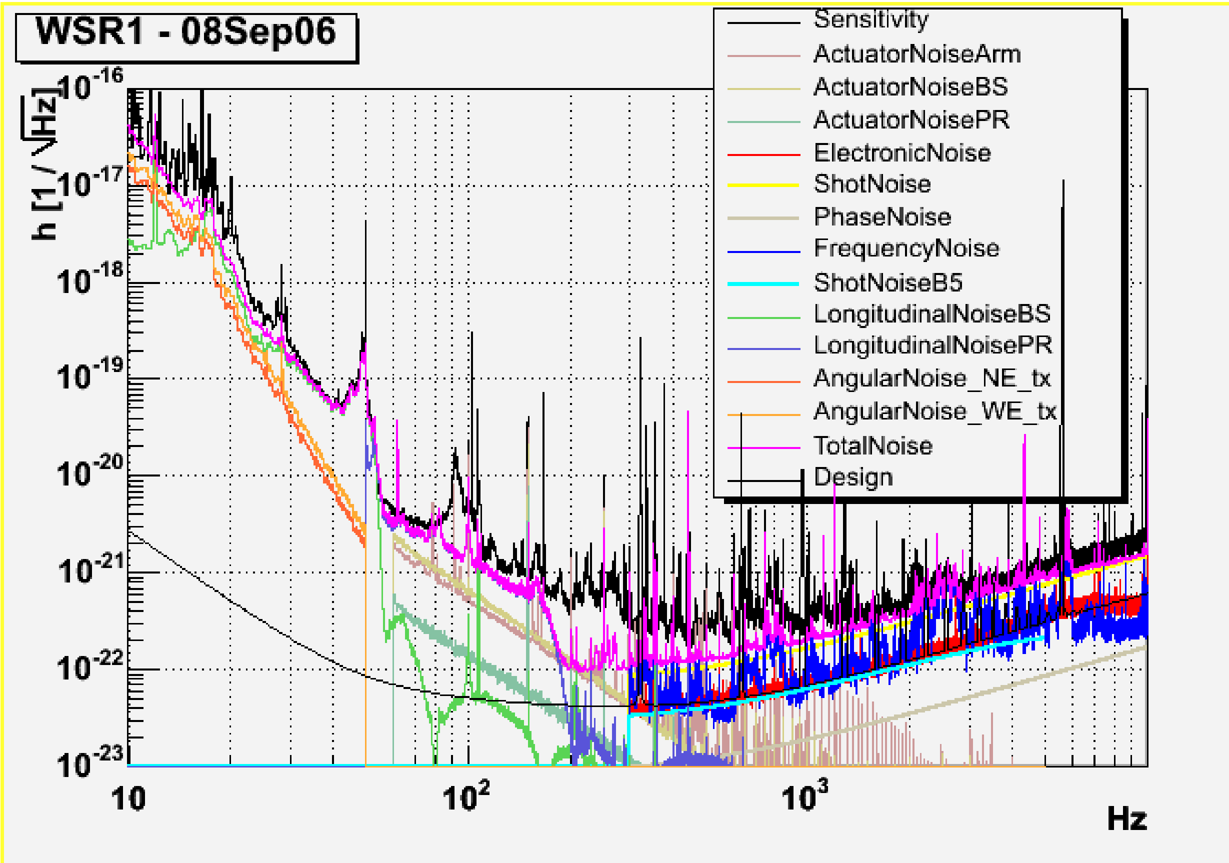


Validation 2: shot noise level

- Noise budget driven by shot noise at high frequency

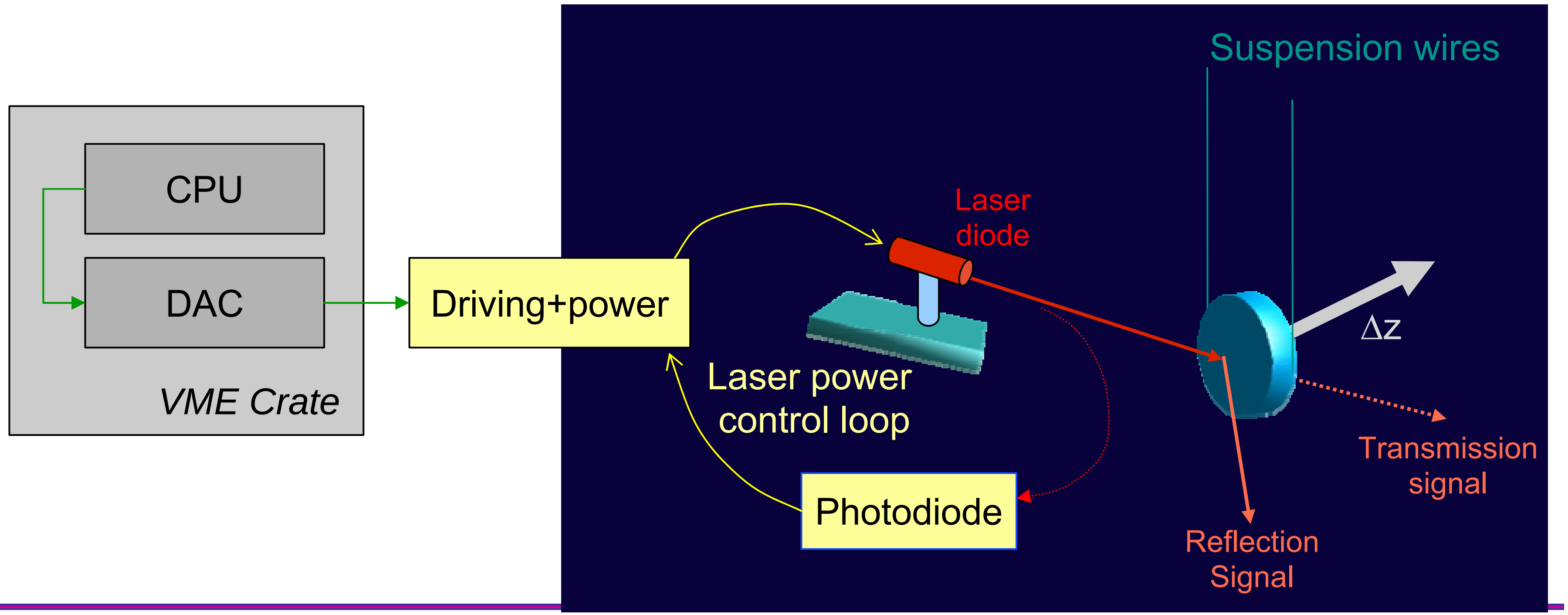
- Shot noise compute with
  - Output photodiode power
  - No actuator gain involved
  - No optical gain involved

- Absolute cross check



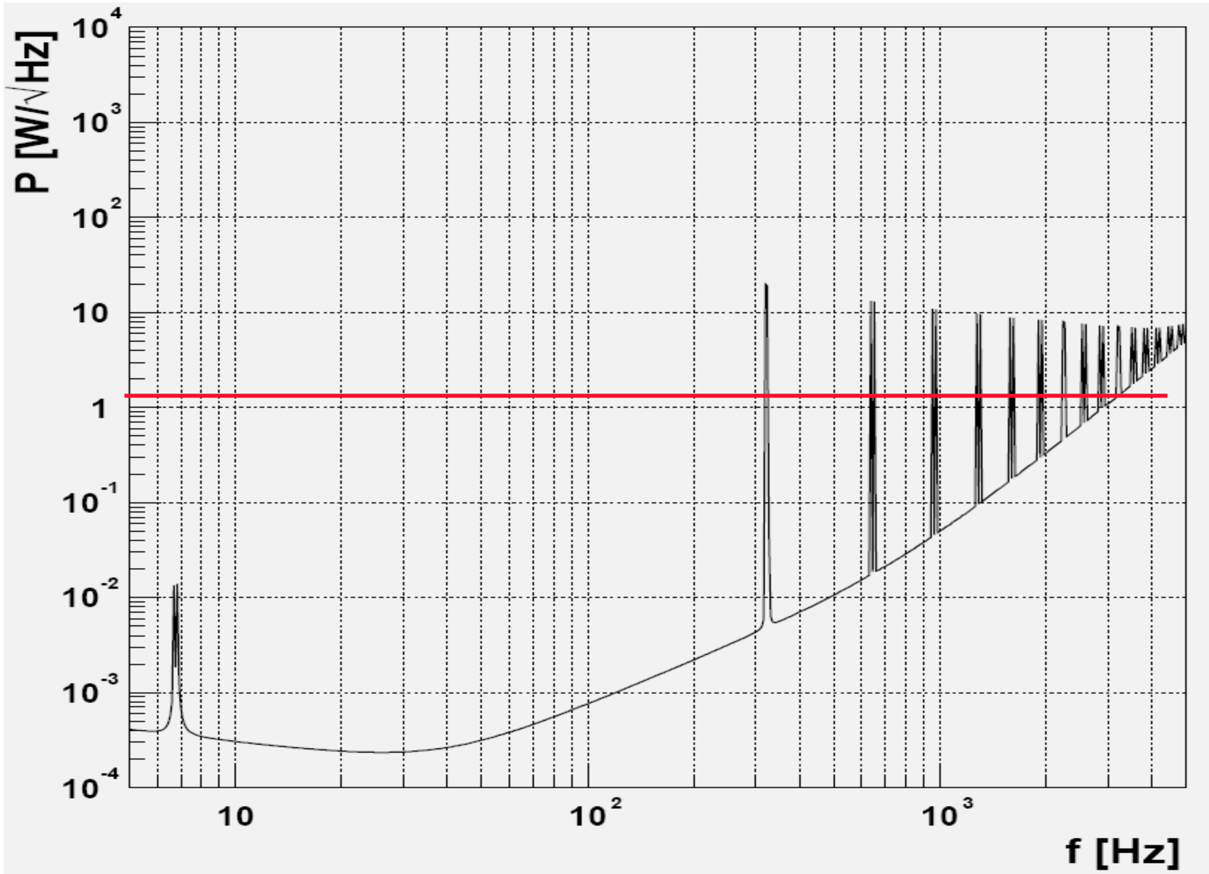
Validation 3: The photon calibrator

- Principle: Push the mirror with the radiation pressure of an auxiliary laser beam
- Power modulation



Laser power and design sensitivity

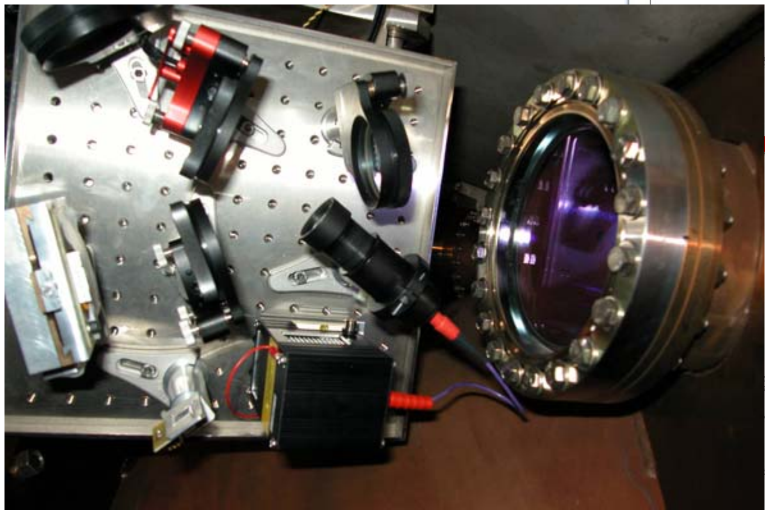
- Needed power to reach Virgo sensitivity:
  - 1 s integration time

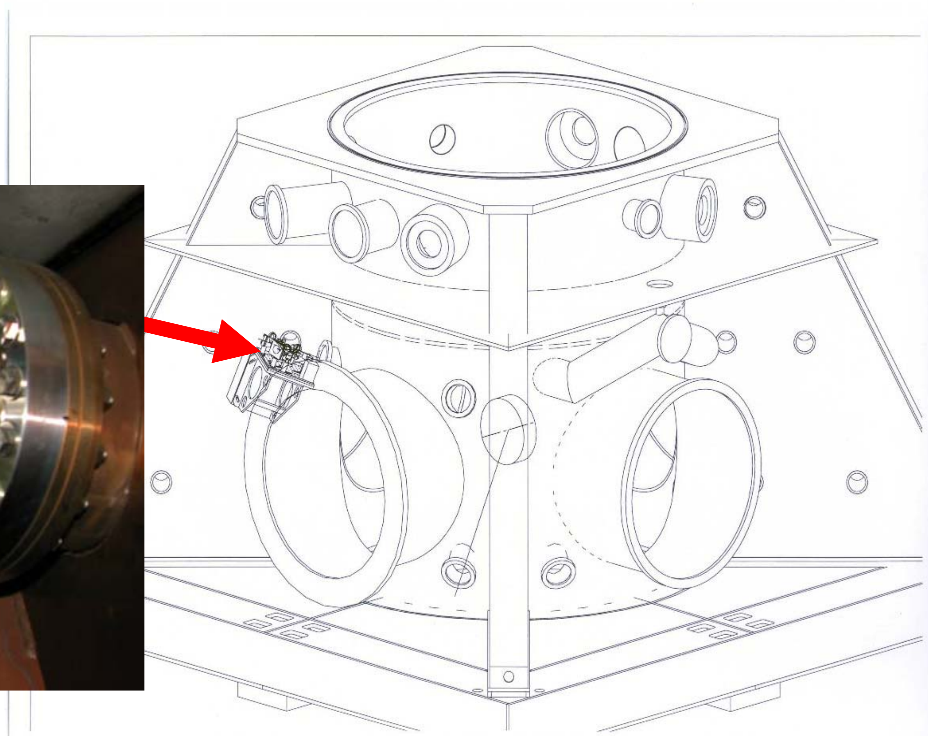


- Nominal values
  - m=20.5 kg
  - R~90%
  - P=1.2 W
  - i=40°

Photon calibrators

- In Virgo:
  - ◆ Installed but not yet used

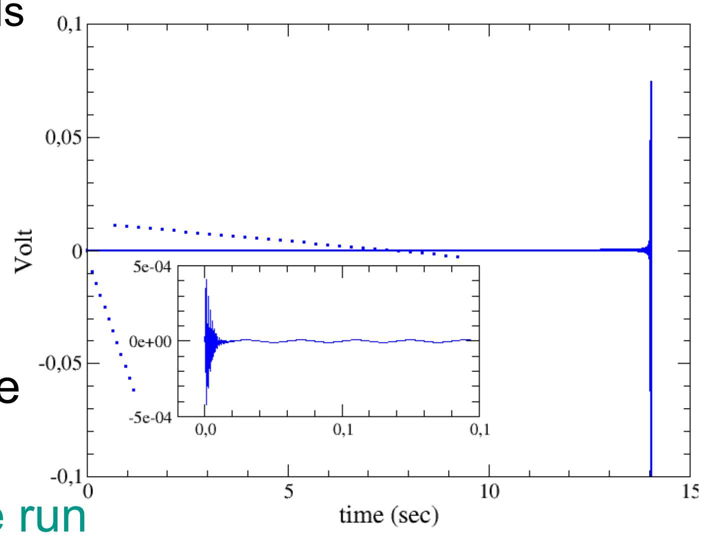




- In LIGO and GEO
  - ◆ in general agreement with the classical calibration
  - ◆ Work in progress to improve its systematic errors

Validation #4: Hardware injections

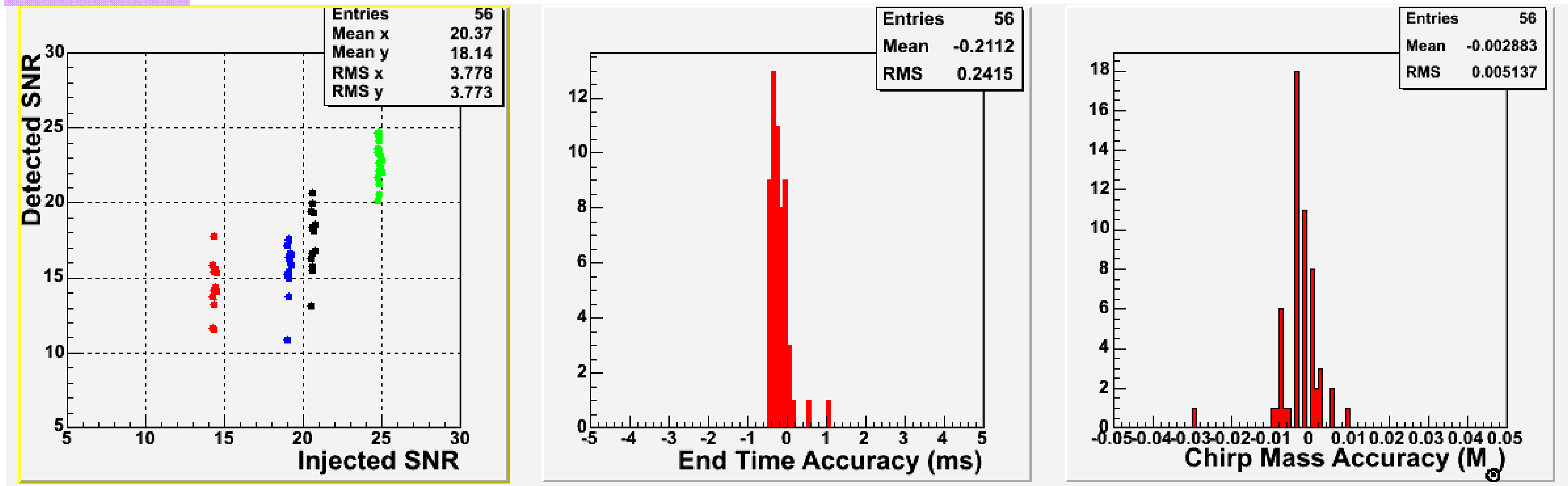
- Idea:
  - Inject in the ITF known waveform
  - Done by moving one of the uncontrolled mirror
    - » the h(t) reconstruction removed the control signals
  - Check the recovered event
- Waveforms:
  - Use different waveform
    - » Inspiral events sweep the frequency band!
  - Sending pre-shaped voltages to mirror coils
  - Takes into account electro-mechanical response
  - Need to provide a smooth termination
- Normalized with the sensitivity measured before the run
  - Some changes could be expected
  - But distance should be recovered
- Check reconstruction and the “pipelines”



Exemple: C6 hardware injections

- 56 inspiral hardware injections
  - 4 different periods, [1.4,1.4] $M_{\odot}$, SNR ranging from ~15 to 25
- All detected
  - Check timing and mass estimation accuracy
  - Check SNR recovery
    - ~ 10% loss might be due to sensitivity non-stationarity

MBTA



Summary

- h(t) is needed and produced routinely in Virgo
  - Code running online
    - » Use to produce the online horizon
  - Data are usually reprocess later on
- h(t) reconstruction provides some noise subtraction
- h(t) is the starting point for the Virgo data analysis
  - No other calibration parameters are provided
- Tools exist to validate the results
  - Work is in progress to use all of them