On-going improvements in the Virgo strain h(t) reconstruction and online noise subtraction in preparation for the O4 run

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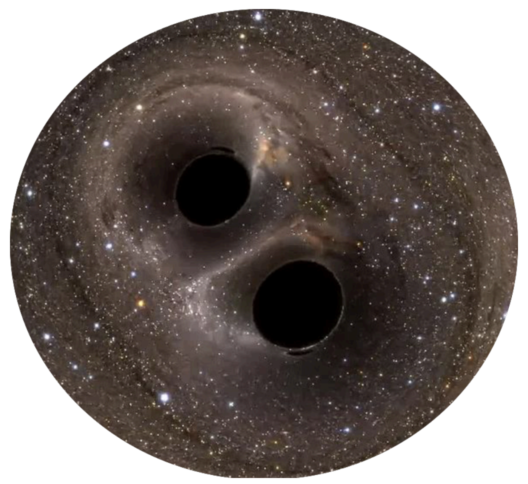
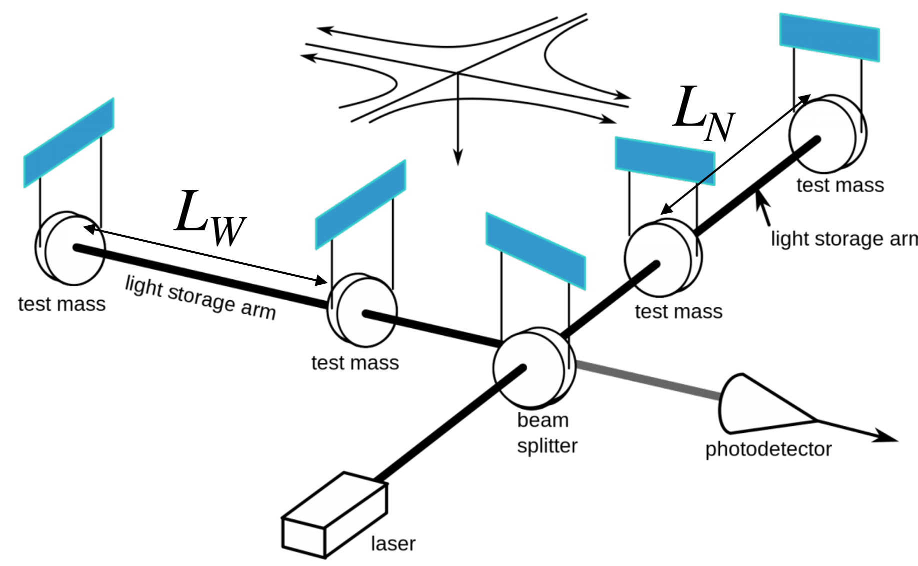
h(t) reconstruction in 2G interferometers

- The detector strain signal h(t) is the main observable of GW interferometers
- The length variations are observed as power variations on the output photodiode: the signal needs to be reconstructed to go back to h(t)



Interferometer



$$h = \frac{\Delta L_N - \Delta L_W}{L_0} = \frac{\Delta L}{L_0}$$

Low-latency h(t) stream → BNS Pre-merger Alerts

h(t) stream

DAQ → Detector Characterization

DAQ → h(t) reconstruction → Noise subtraction

Astrophysical analysis

- Compact binary coalescence analysis
- Continuous waves analysis
- Stochastic background analysis
- Test of GR analysis
- Etc.

Calibration → h(t) reconstruction

Via actuators.

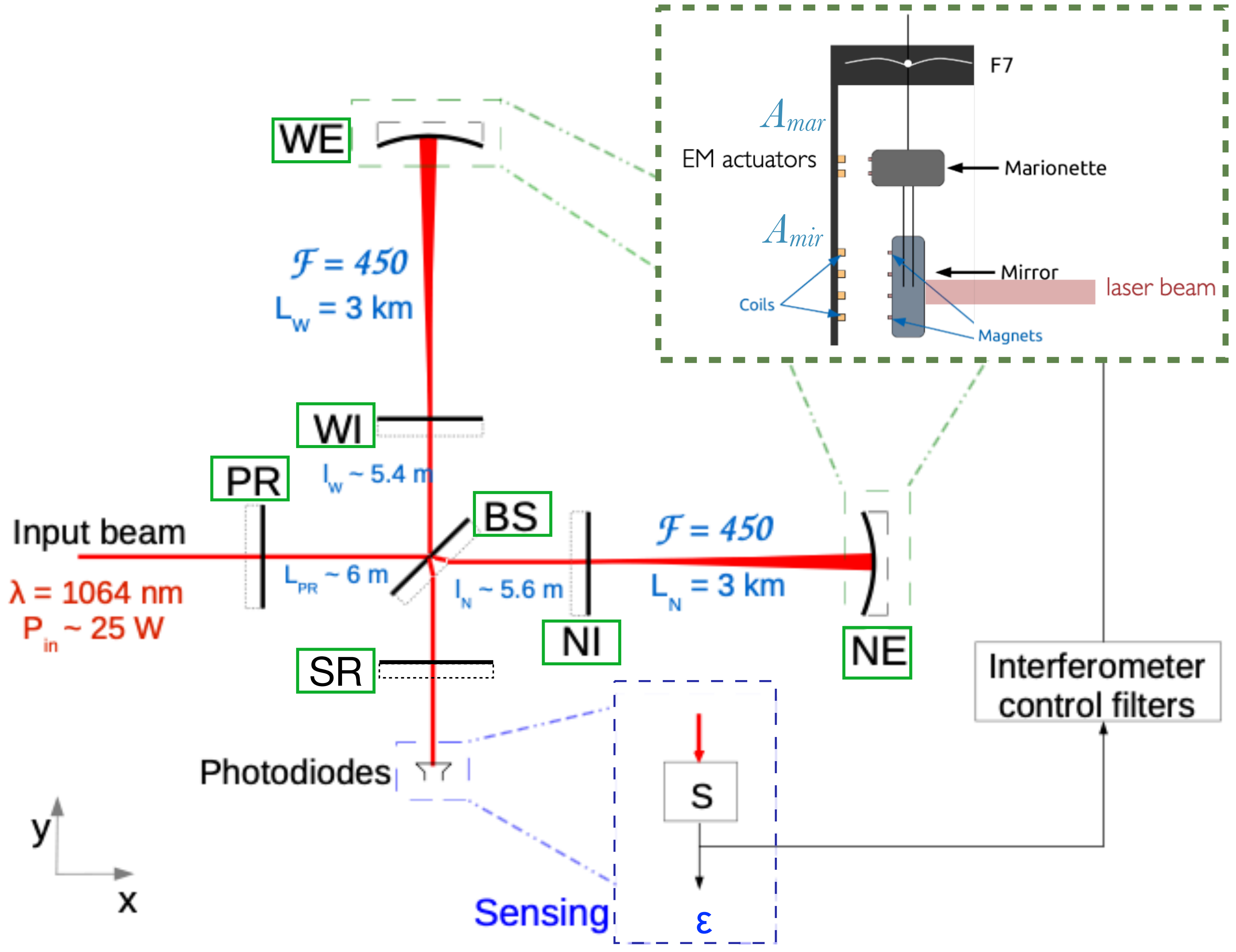
- Internal: electromagnetic
- External: photon calibrator, newtonian calibrator

h(t) reconstruction from an ITF and the link to calibration

- The ITF is controlled via control loops to be kept on a working point (i.e. close to dark fringe) to optimize the sensitivity
  - The control loops dominate the output signals between 10Hz -100Hz.

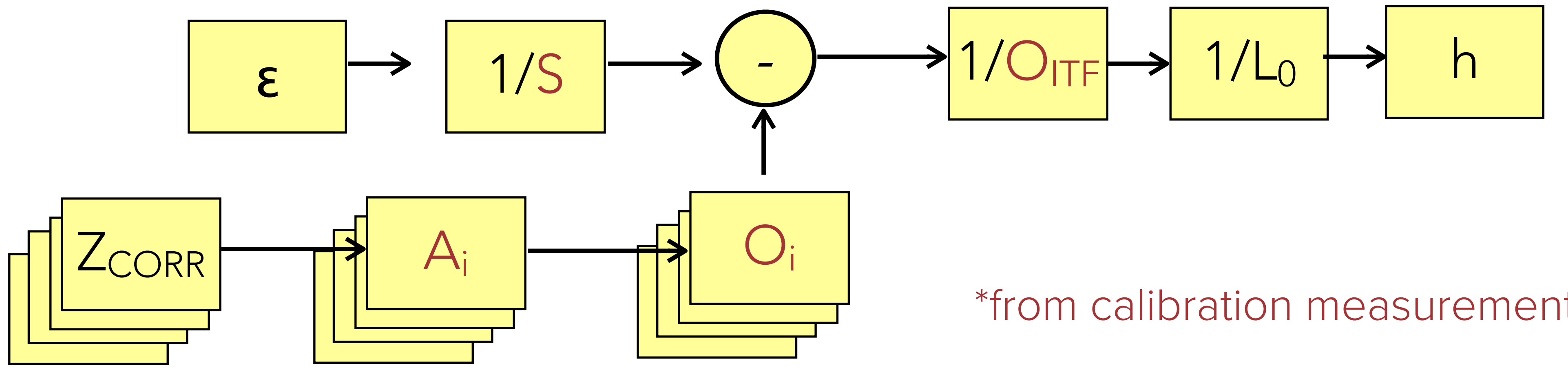
  => part of the GW signal is in the control signals

- The reconstruction of h(t) consists on
  - Accounting for readout electronics of the output photodiode S
  - Removing the control signals used in the ITF longitudinal control from h(t), which include the knowledge on the response of the mirror/marionettes actuators A_i
  - Updating the interferometer and mirror optical transfer function
    - 4 permanent calibration lines ~60/350 Hz to monitor optical gain of each mirror optical reponse and finesse of arm cavities
    - EM actuators (NE/WE/BS/PR)



Calibration-reconstruction connection

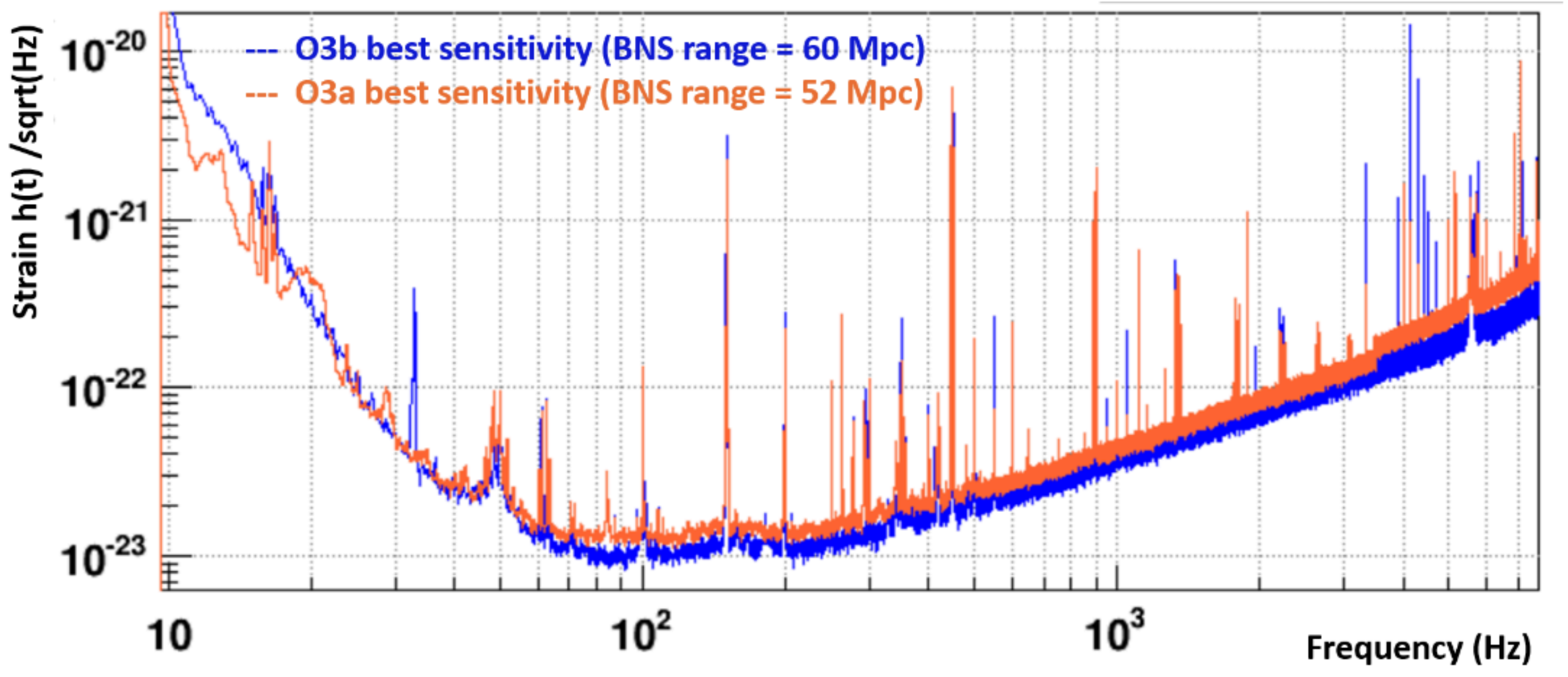
$$\mathcal{E}(f) = S(f)\left[\sum_{mir} O_i(f)\cdot(\Delta L_{mir,i}(f) + \Delta L_{mar,i}(f)) + O_{ITF}(f)\cdot h(f)\cdot L_0\right]$$



*from calibration measurements

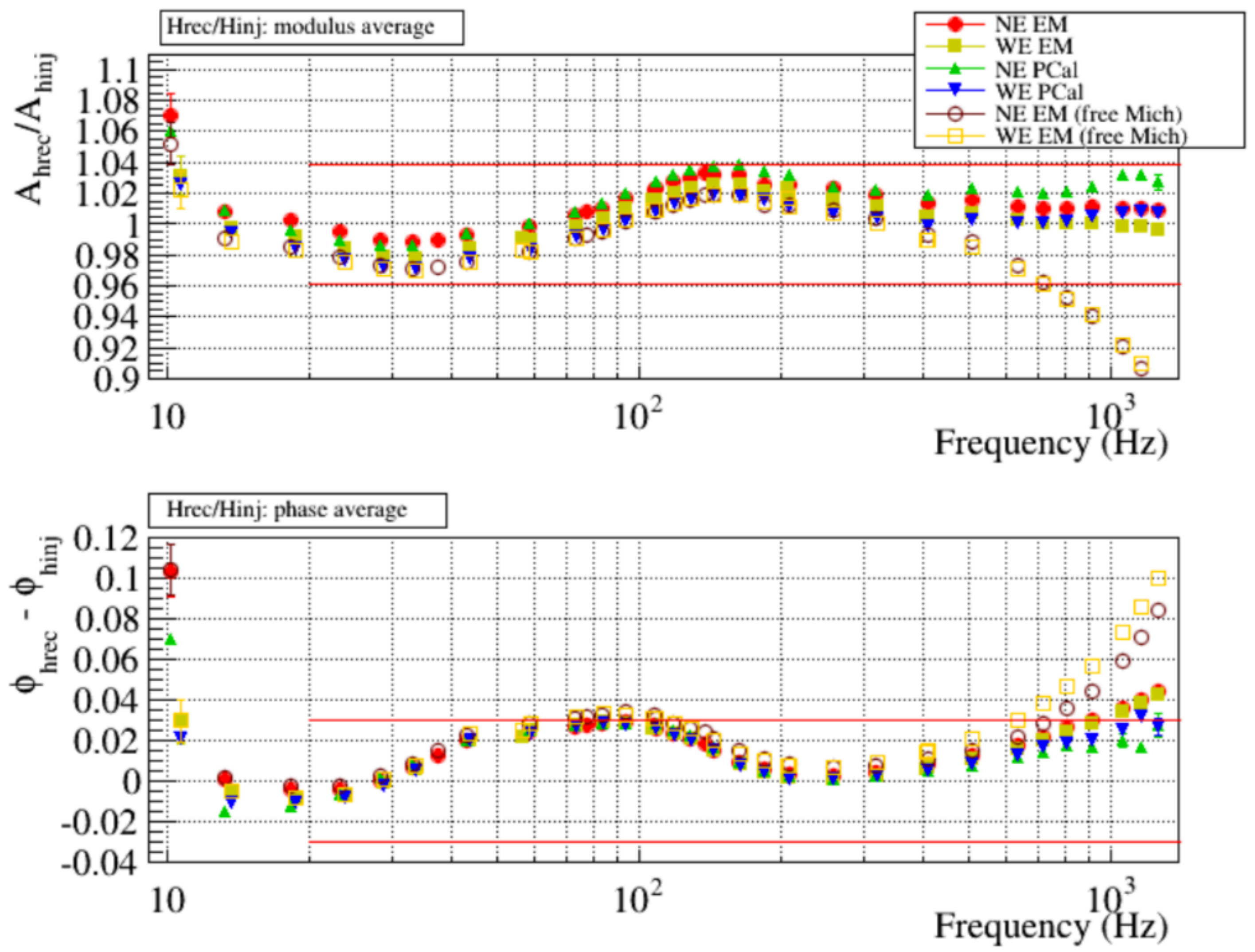
Overview of the h(t) reconstruction during O3 in Virgo

- During O3:
  - Online version of reconstruction provided h(t) at a latency of ~ 10-15 seconds
  - No further reprocessing has been needed for most of O3



- The h(t) uncertainties are computed as conservative, frequency-independent symmetric uncertainties from:
  - **Systematic errors from the actuator models** (external calibrator, e.g. photon calibrator or newtonian calibrator, plus EM actuator)
  - Uncertainties on the **sensing and timing**
  - Using $h_{rec}/\ h_{inj}$:
    - Frequency-dependent bias observed in averaged $h_{rec}/\ h_{inj}$ TF from **weekly monitoring**
    - **Shorter scale variations** observed during the $h_{rec}/\ h_{inj}$ monitoring (the largest between weekly and continuous)

Average of weekly $h_{rec}/\ h_{inj}$ TF for O3a (statistical)



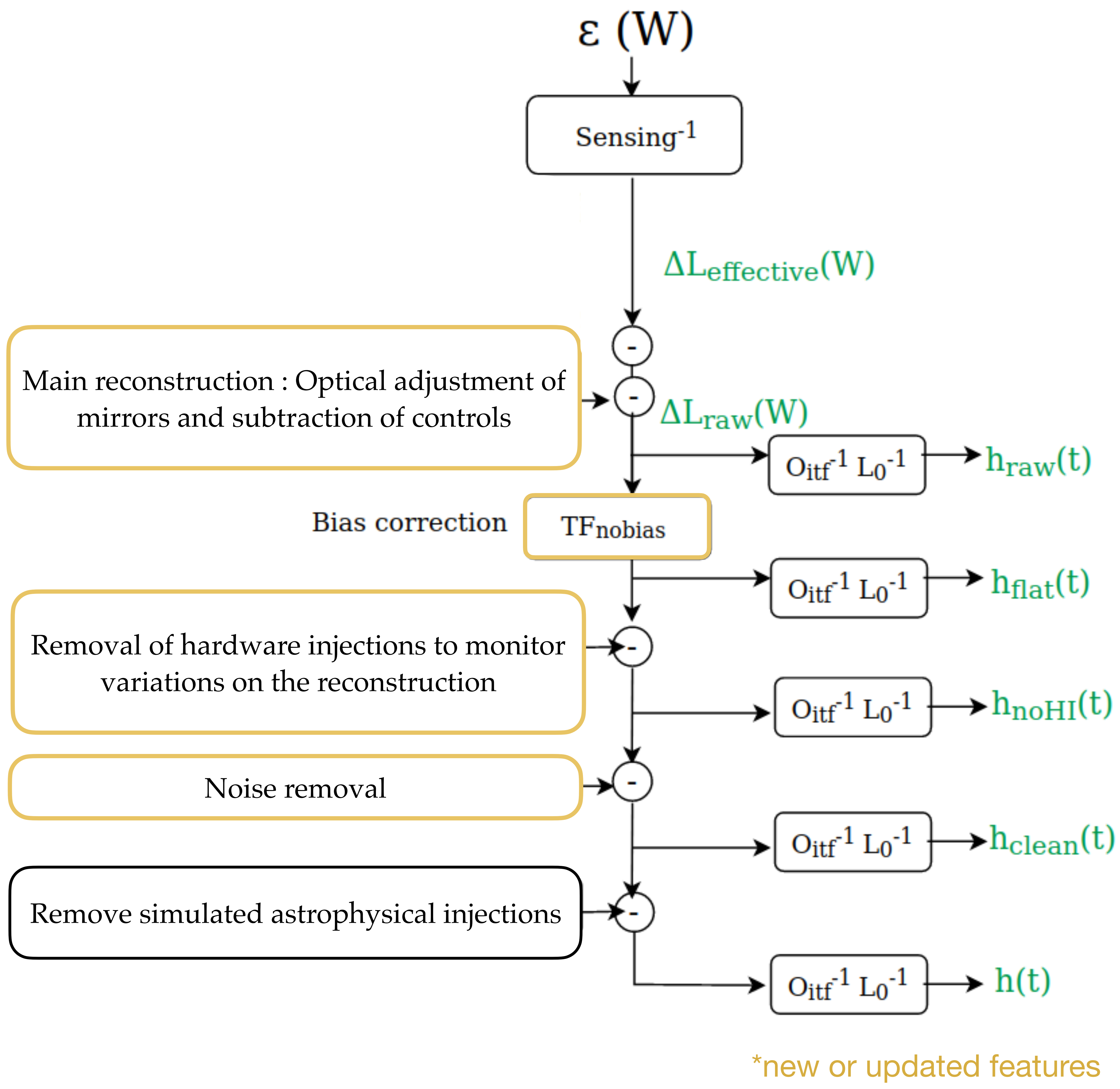
O3 h(t) uncertainties (20 Hz-2kHz)

- ± 5% on modulus
- ± 35 mrad phase
- ± 10 μs timing

Acernese, F., et al. , *CQG* 39.4 (2022): 045006.

Ongoing improvements in h(t) reconstruction for O4

- Main points:
  - Improve the precision of the optical characterisation of the infermeteromer and mirrors via their optical response functions
  - Better understanding of the h(t) frequency bias: correct it through correction factors
  - Improve the broadband noise subtraction online
  - Obtain frequency dependent uncertainties on h(t)
- Hrec turning **online**: latency ~10 s
  - Low-latency hrec: reduce latency to ~6s



Optical response of the ITF and mirrors

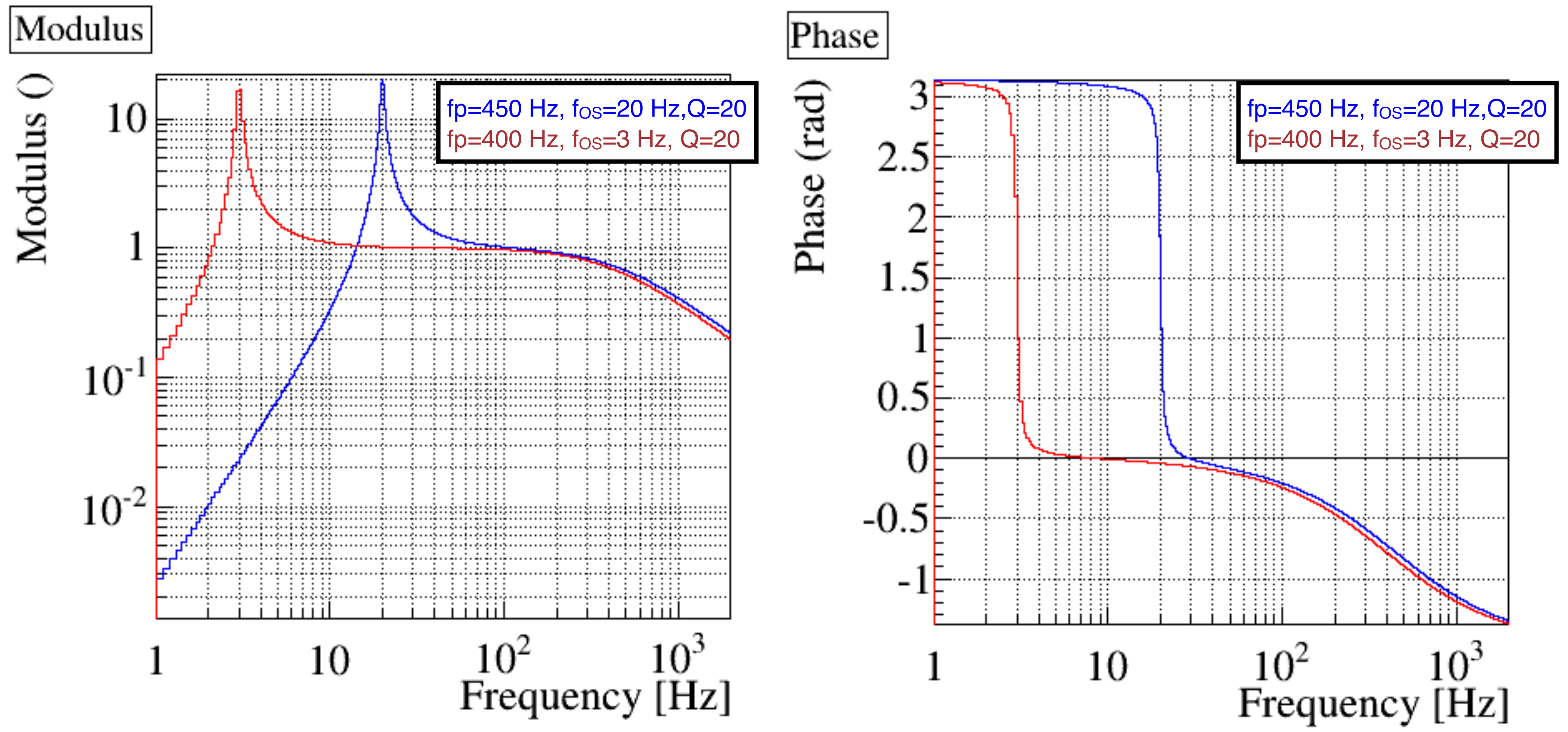
During observing run O3:

- Online monitoring of the optical model of mirrors
- NE, WE, BS, PR optical response modelled as a simple pole
- PR optical response was observed to be more complex.
    - The noise subtraction reduced the impact of the simplification of the reduced Power Recycling mirror model

In observing run O4: Signal Recycling mirror has been added

- Online monitoring of the optical model of mirrors NE, WE, BS, PR, SR
- More precise use of optical response in Hrec algorithm
- Monitor double cavity pole and optical spring

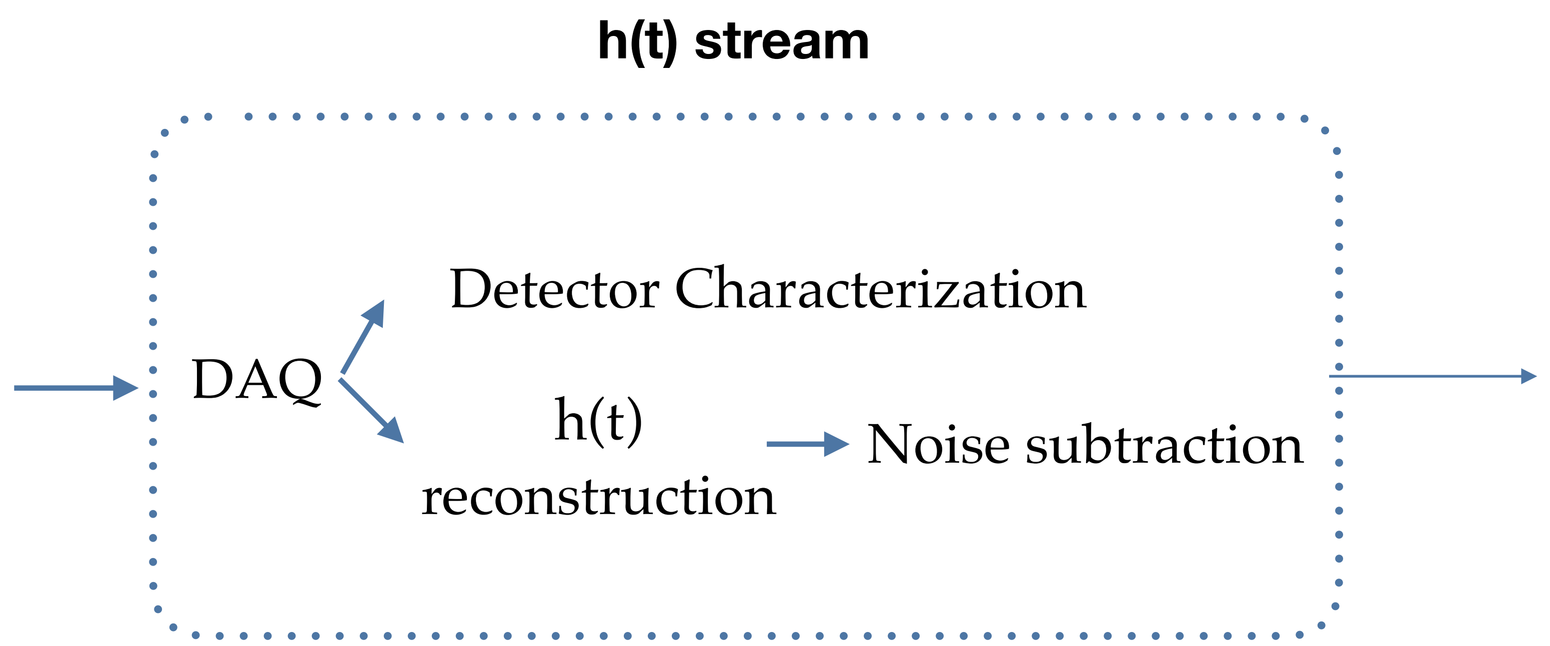
Example of optical spring+simple pole



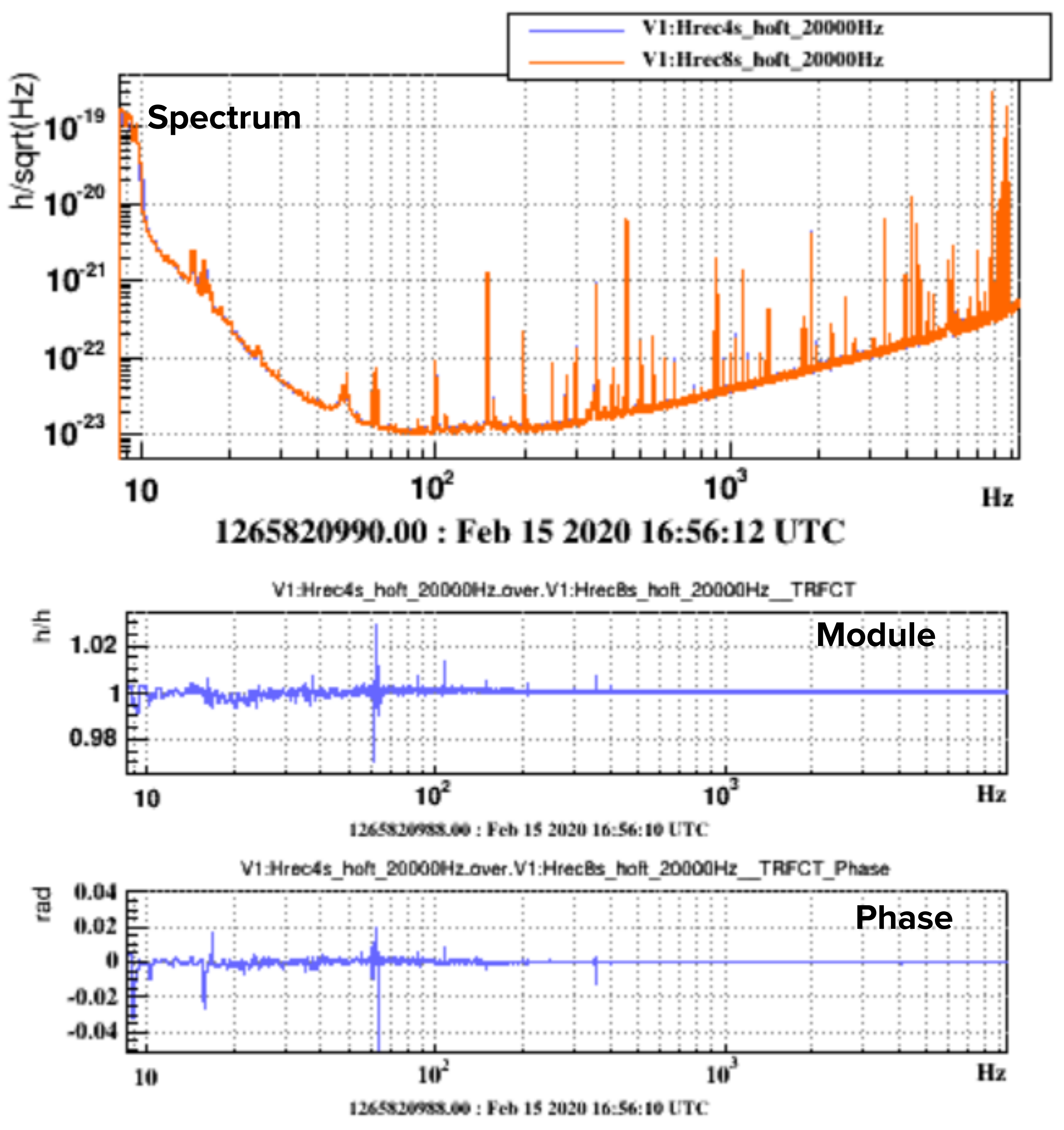
- Preliminary proposal for the optical response online adjustment during O4 via EM injections => to be tested and tuned during commissioning
    - Near the double cavity pole (expected ~400Hz): 3 calibration lines into NE, WE, BS→ **optical gain and double cavity pole**.
    - Around 60 Hz, adjust **optical response** of PR and SR
    - Around 10 Hz, inject lines into NE, WE, BS, PR, SR→ find the **pole and quality factor of the optical spring**

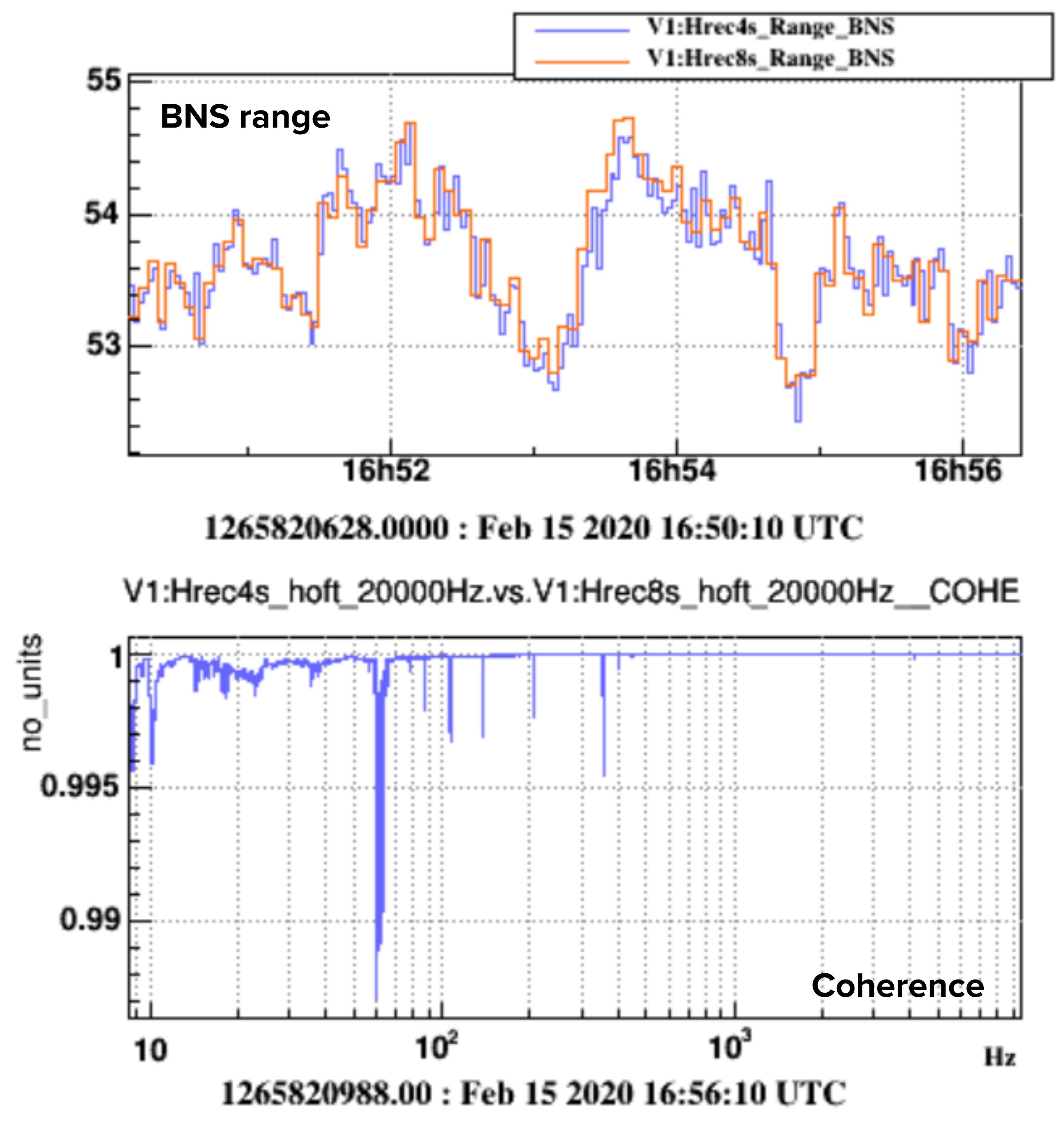
Plans on low latency h(t) reconstruction for pre-merger alerts

- Latencies during O3
  - Output from the IFO to end of DAQ input : ~ **3 seconds**
  - Reconstruction of h(t) in Hrec: dominated by the length of FFT (8 s during O3)
    - Cumulative latency (DAQ+Hrec)~ **11 seconds**
- Goal for O4: reduce latency while reaching a compromise between latency and precision



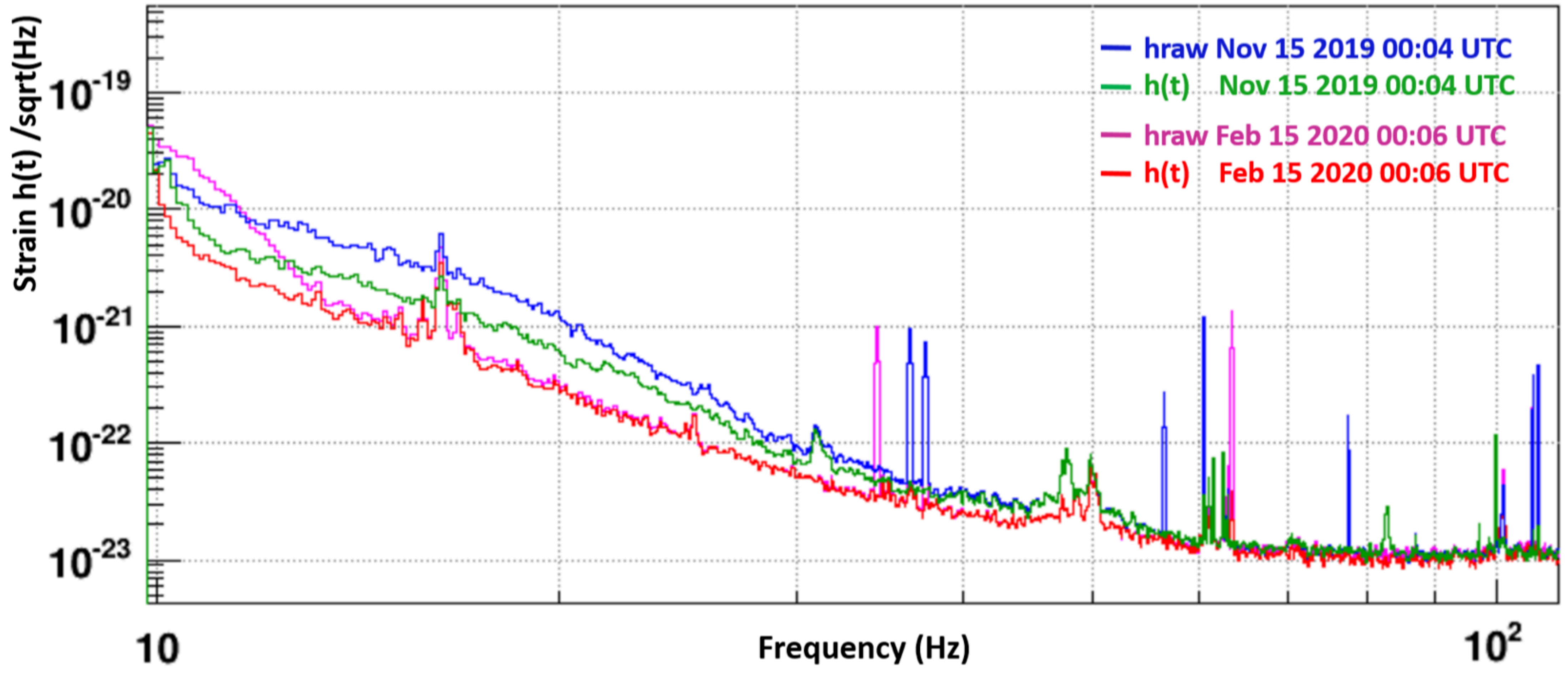
- Latency in Hrec is dominated by the size of the FFTs: 8s-FFT
- Create a low-latency Hrec process to reduce the latency to 5-7 s
  - Moving to 4s-FFT
    - Encouraging preliminary results using O3
    - May need to separate the calibration lines further to avoid overlap
  - Branch HRec upstream in the DAQ





Online noise subtraction using witness channels

- Noise contribution from many sources can couple to the h(t) signal
- Noise hunting searches are done during commissioning phase to asses and mitigate them
- Some noise are suspect to be coupled to h(t) but are not always present
- Noise subtraction done online after the h(t) reconstruction, depending on the noise level observed



- Several photodiodes are used as witness of the noise levels
  - The coherence between noise witness channels and h(t) are used to asses the noise level
  - Transfer functions are used to removed the noise linearly

- Observing run O3: Online linear noise subtraction with 5 witness channels for 5 noises (e.g. frequency noise, scattered light)

$$h_{clean}(f) = h_{raw}(f) - \sum_{ch=1}^{N} a_{ch}(f) \cdot c_{0,ch}(f)$$

- Observing rung O4: Optimization of the noise subtraction by using of decorrelated transfer functions of witness channels
  - Method based on Derek, D. et al., CQG 2019, vol. 36, no 5, p. 055011
  - Tests done with simulated data show better perfomances for noises observed with more than one witness channel.
  - Near future: test noise subtraction with commissioning data. Need to identify noise and NWCh for O4.

Summary of O4 goals

- Main goals:
  - Provide regularly uncertainties on online h(t)
  - Online linear noise subtraction done to h(t)
  - Correct the bias of the h(t) strain signal
  - Reduce uncertainties down to ~3% on most of the frequency band
- Still a lot of work to be ready for O4, many things to be tested in the forthcoming months!
- h(t) key in the part of the incoming (and last) part of commissioning, e.g. noise hunting activities

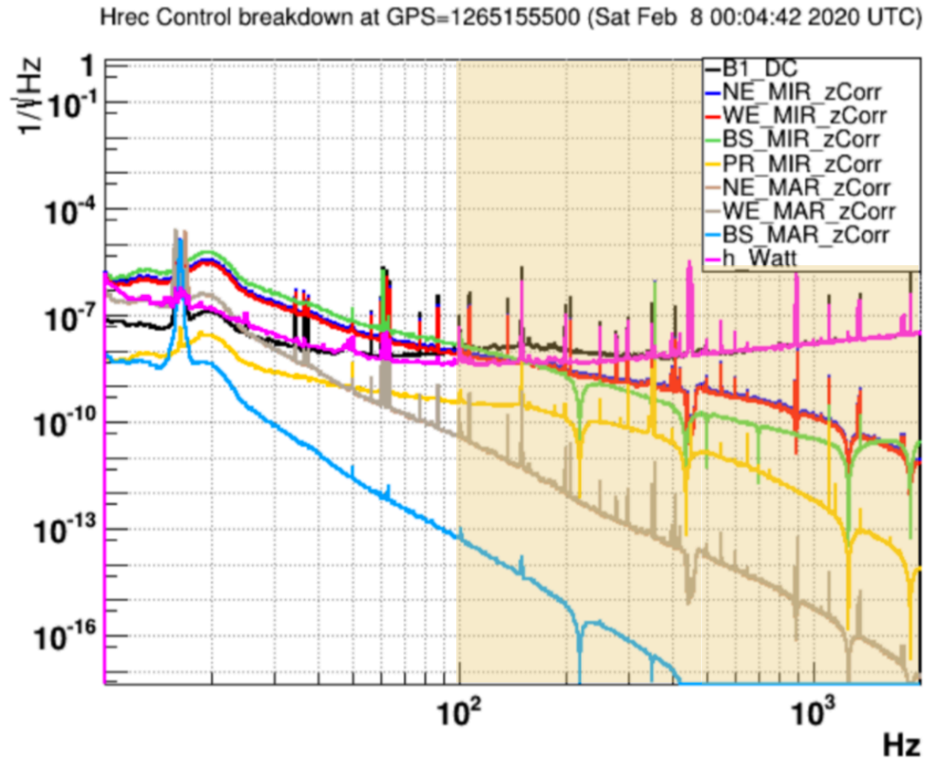
Thanks for your attention!

Back-up

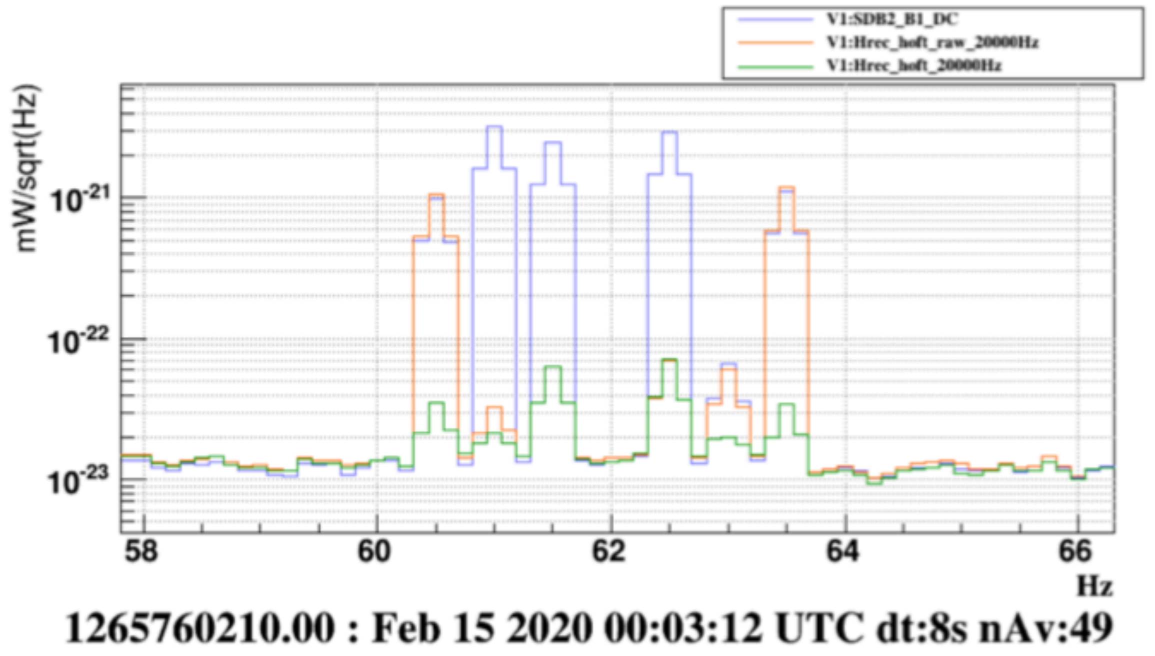
Controls, noises and injections during O3

Injection source	Line frequency	Line SNR
NE PCal	60.5 Hz	40
WE PCal	63.5 Hz	40
NE mirror actuator	62.5 Hz	120
WE mirror actuator	61.5 Hz	100
BS mirror actuator	61.0 Hz	120
PR mirror actuator	63.0 Hz	3

Breakdown of the control signals in h(t) during O3



Noise type	Frequency Band
Michelson noise	8-60 Hz
Frequency noise	60-3500 Hz
56 MHz RIN noise	20-2000 Hz
Scattered light noise at NE	10-70 Hz
Scattered light noise at WE	10-70 Hz



- Two cadences of the measurements of href/hinj:
  - Weekly monitoring:
    - Injections on wednesday afternoon in NON-observing mode
    - High SNR at large number of frequencies and broadband
    - Frequency range: 10 Hz - 1.5 kHz
  - Continuous monitoring:
    - Permanent injections during O3 in observing mode
    - 12 permanent sinusoidal lines with low SNR (~ 10) to not disturb the data taking
    - Frequency range: Most sensitive band of the ITF ~ 35Hz-400Hz
    - h_{rec}/ h_{inj} provided in the online data stream

Actuator	Line freq.	Line SNR
NE EM	37.5 Hz	3
NE EM	77.5 Hz	4.5
NE EM	107.5 Hz	13
NE EM	137.5 Hz	7.5
NE PCal	34.5 Hz	6
NE PCal	63.5 Hz	25
WE EM	56.5 Hz	5
WE EM	106.5 Hz	11
WE EM	206.5 Hz	11
WE EM	406.5 Hz	9.5
WE PCal	36.5 Hz	5
WE PCal	60.5 Hz	22

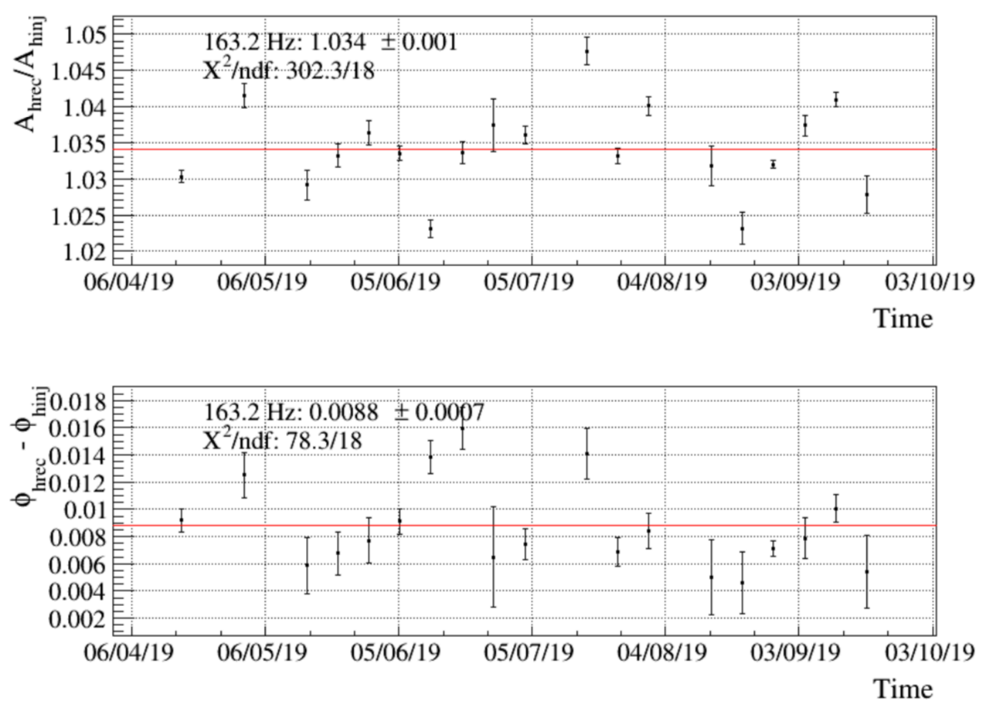
Weekly vs continuous monitoring

- Goal: Check the stability using transfert function of $h_{rec}/\ h_{inj}$ for each actuator, frequency and time.
  - Use of different actuators to have the independent measurement of the uncertainties
  - Obtain the average bias for each actuator in O3a/O3b and the variations from this value
    - Define the systematic uncertainties as those added to the error bars to have a p-value of 0.05

- Goal: Observe the fine variations of $h_{rec}/\ h_{inj}$ through a continuos monitoring
  - Systematic uncertainties as quadratic difference between uncertainties of the distribution and computed statistical uncertainties
- Maximum average bias observed: 1.4% modulus and 14 mrad in phase
- Continuous monitoring shows larger fluctuations of $h_{rec}/\ h_{inj}$ than what is observed in the weekly monitoring
  => The values from the continuous monitoring are selected to compute the overall uncertainty in h(t)

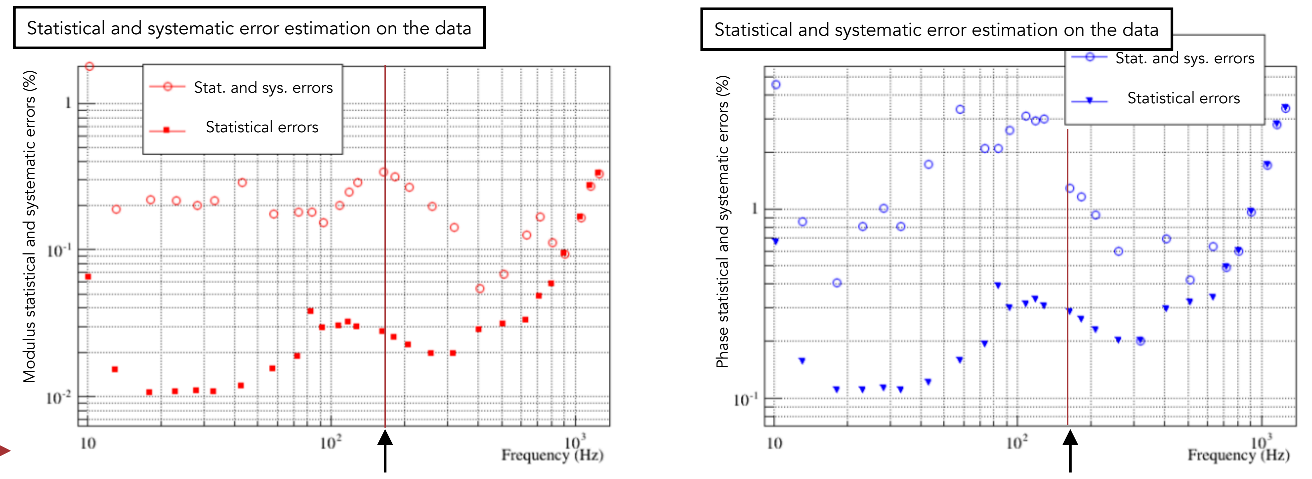
Evolution in time during O3 for a certain frequency

- Evolution of h_{rec}/h_{inj} transfer function **@163.2 Hz** during O3a with h_{inj} estimated from NE PCAL
- Average bias observed: 3% in modulus, 8 mrad in phase => extra systematic effect observed.



Mean over O3 for various frequencies between 10Hz-1.5 kHz

- Statistical and systematic errors in h_{rec}/h_{inj} during O3a with **NE PCAL**

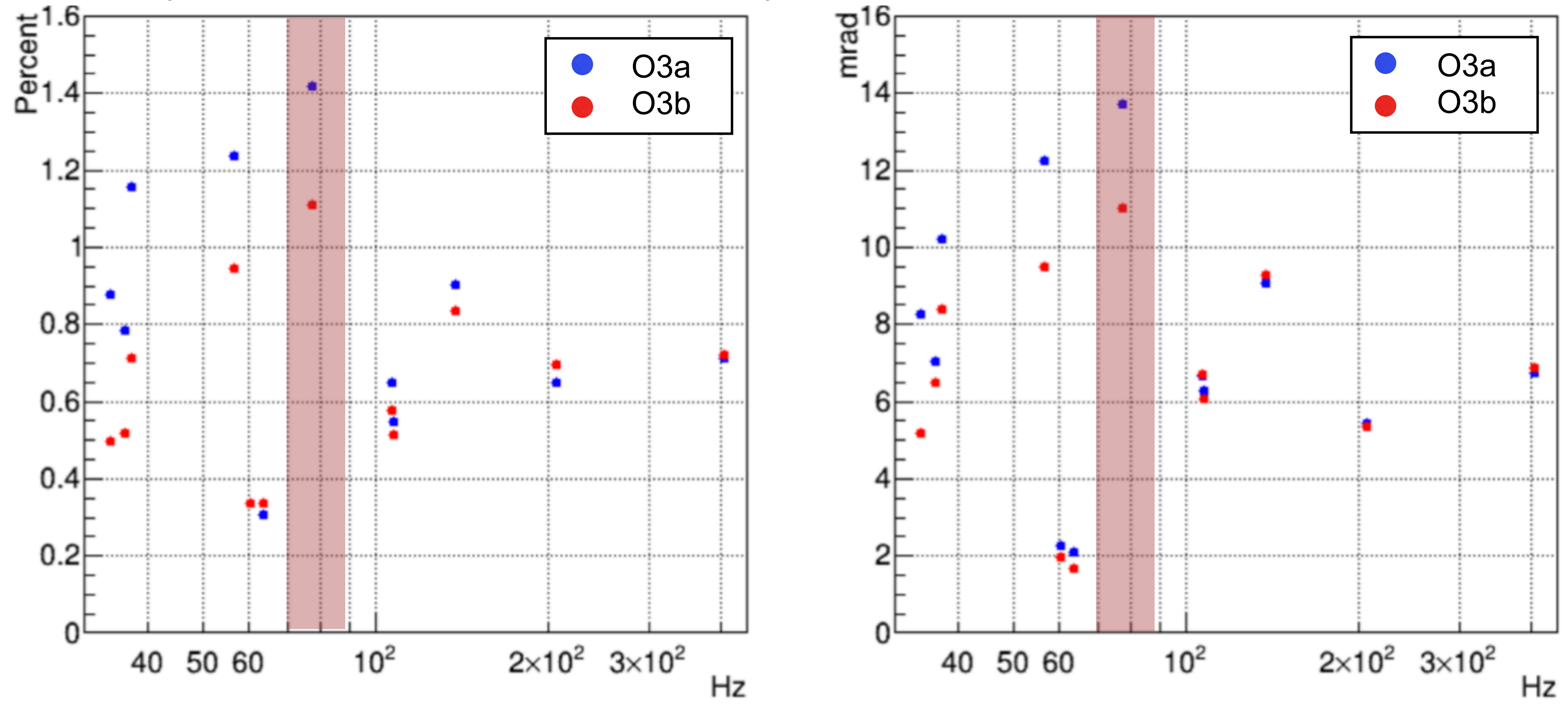


For independent injections fom 4 different actuators

- Errors estimated from weekly variations of h_{rec}/h_{inj} during O3a

	Actuator	NE PCal	NE EM	WE PCal	WE EM
O3a	Modulus error	0.4%	0.3%	0.4%	0.3%
O3a	Phase error (mrad)	4	3	4	3
O3b	Modulus error	0.4%	0.6%	0.5%	0.5%
O3b	Phase error (mrad)	4	5	6	6

Systematic uncertainties in $h_{rec}/\ h_{inj}$ modulus and phase for EM and PCAL



Timing and sensing calibration, uncertainties on the actuator model in O3

Sensing:

- The PD sensing has to be calibrated
- A model is associated that describes the transfer function of the sensing part and the time delay introduced by the sensing.
- The model is assumed as a flat modulus response + anti-alias filter + filter around 8 kHz.
- The readout delay of the PD is measured by using LEDs connected to a GPS receiver in front of the PD.
- The timing delay confirmed the expected value with systematic uncertainties < 3 microseconds

=> Updates on the sensing model ongoing for O4, since it has been observed that the response *as flat as expected*

Timing:

- The uncertainties on the absolute timing are obtained as quadratic sum of the following contributions:
    - Timing bias estimation from hrec/hinj: 7µs
    - Uncertainty on the PCal hardware injection: 3µs/2.8µs for O3a/O3b
    - Change on the detector photodiodes in early 2020 (affecting O3b): 1µs

The quadratic sum of these uncertainty sources => 10 µs

<table>
<tr><th colspan="2"></th><th>NE mirror</th><th>WE mirror</th><th>BS mirror</th><th>PR mirror</th></tr>
<tr><td colspan="2">Stat. uncertainty and fit residuals</td><td>0.2% (6 mrad)</td><td>0.2% (2 mrad)</td><td>1% (10 mrad)</td><td>2% (50 mrad)</td></tr>
<tr><td rowspan="6">Syst. uncert.</td><td>PCal calibration</td><td>1.39% (0 mrad)</td><td colspan="3">1.73% (0 mrad)</td></tr>
<tr><td>PCal to end transfer</td><td>0.3% (3 mrad)</td><td colspan="3">0.6% (4 mrad)</td></tr>
<tr><td>WE to WI transfer</td><td>–</td><td>–</td><td colspan="2">0.2% (1 mrad)</td></tr>
<tr><td>WI to BS transfer</td><td>–</td><td>–</td><td>0.6% (6 mrad)</td><td>–</td></tr>
<tr><td>WI to PR transfer</td><td>–</td><td>–</td><td>–</td><td>0.6% (6 mrad)</td></tr>
<tr><td>PCal readout delay</td><td colspan="4">3 µs</td></tr>
<tr><td colspan="2">Total uncertainty (quadratic sum)</td><td>1.44%
6.7 mrad
3 µs</td><td>1.84%
4.5 mrad
3 µs</td><td>2.18%
13 mrad
3 µs</td><td>2.78%
12.4 mrad
3 µs</td></tr>
<tr><td colspan="2">Validity range</td><td>20-1500 Hz</td><td>20-1500 Hz</td><td>20-500 Hz</td><td>20-500 Hz</td></tr>
</table>

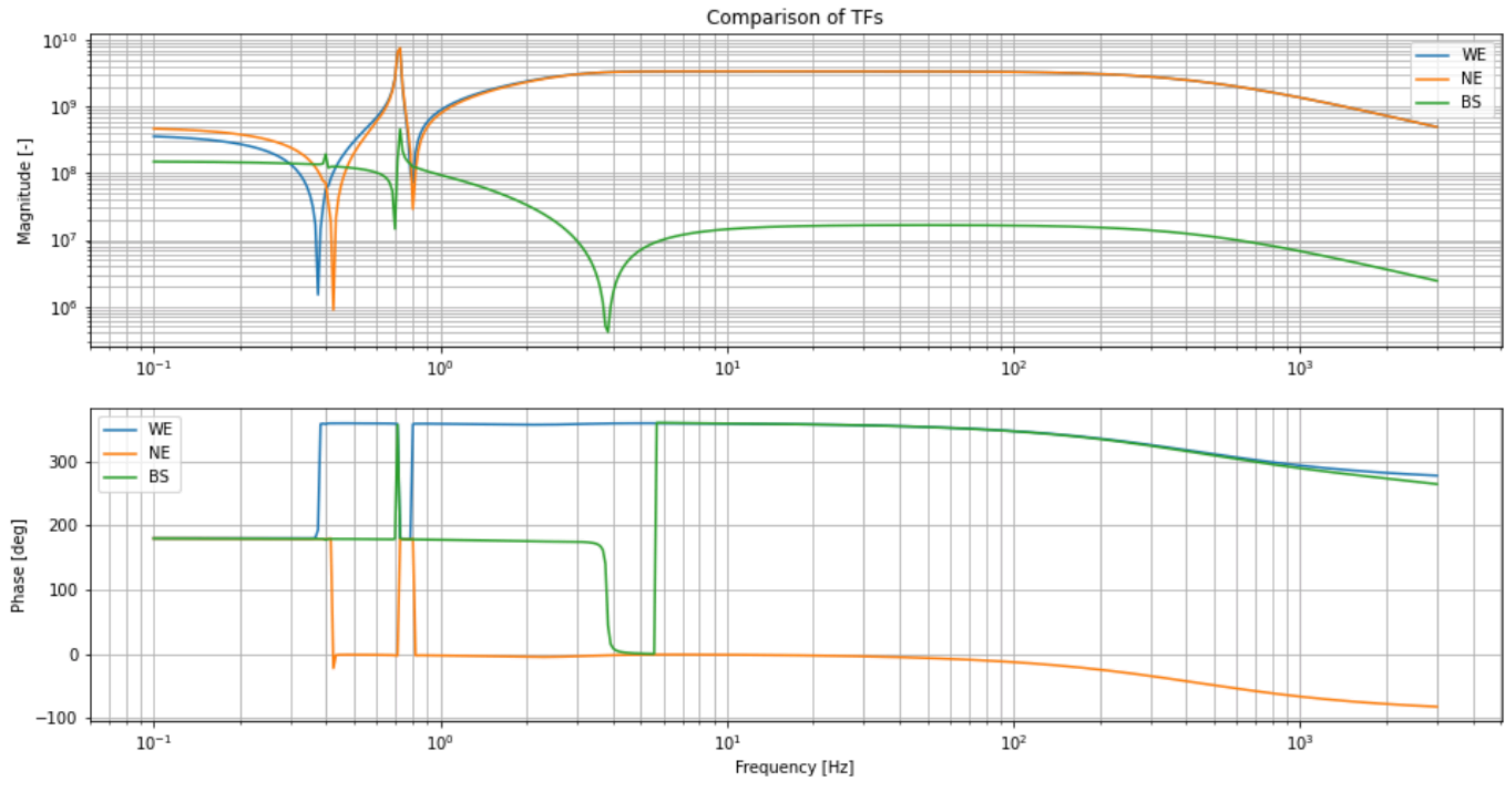
Table 3. Summary of the sources of statistical and systematic uncertainties on the mirror actuator models. For every source, the uncertainties on the modulus (phase) are given. The last lines give, for all the actuators, the sum of all the uncertainties reported in this table and their validity range. See text for details.

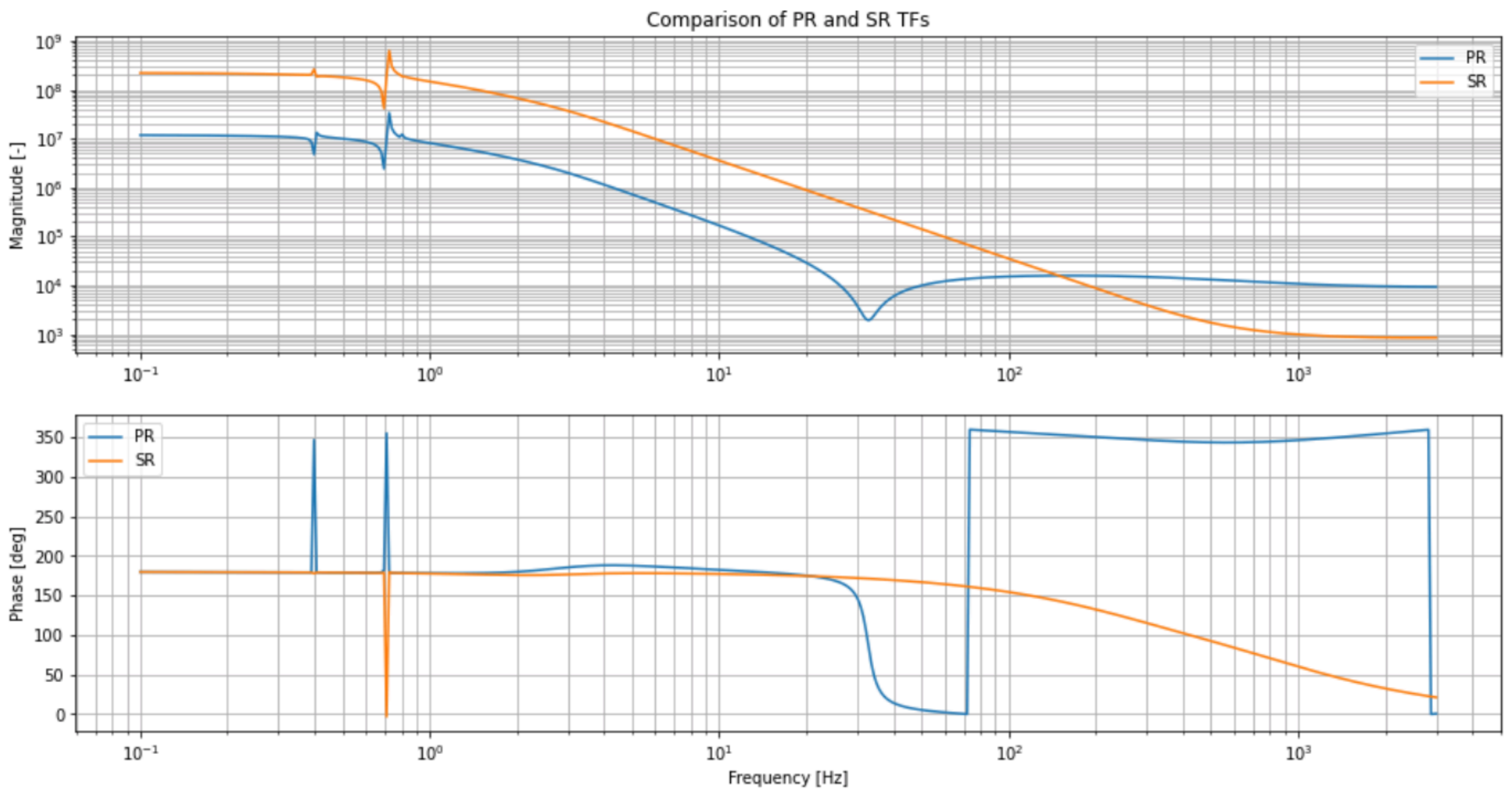
	NE mario.	WE mario.	BS mario.	NI mario.	WI mario.
Total uncertainty (quadratic sum)	1.5% 11 mrad 3 µs	1.9% 8 mrad 3 µs	2.7% 15 mrad 3 µs	3.3% 30 mrad 3 µs	3.5% 30 mrad 3 µs
Validity range	10-100 Hz	10-100 Hz	10-60 Hz	10-80 Hz	10-80 Hz

Table 4. Summary of the uncertainties on the marionette actuator models, along with their validity range. See text for details.

First simulations of the optical response of the mirrors

@40W input laser power





How is this affecting astrophysical analysis?

- The accuracy of the calibration and the reconstruction impacts astrophysical results:
  - Absolute calibration of the GW network
    - Impact on the luminosity distance estimation, e.g. determination of the Hubble constant
  - Relative calibration between ITFs
    - Impact on the accuracy of the timing of GW network, e.g. sky localization of a source when combining h(t) for data analysis => key in counterpart searches

What can we do to reduce uncertainties in h(t)?

- Calibration & hardware: => go back to Paul Lagabbe's talk
- h(t) reconstruction: improve the precision so that variation in h_{rec}/ h_{inj} are minimized

Goal for O4 h(t) uncertainties (20 Hz-2kHz)
- 3% on modulus (5% during O3)
- 35 mrad phase
- <10 µs timing
- latency ~10 s

Results of decorrelated noise subtraction for O4

- Tests done with simulated data using Calisimu tool:
  Example: 2 NWCh and 3 NWCh, which are correlated (see the same noise!)
  - Improvements that reach ~40% in BNS range for 3NWCh (previous method added noise)
  - Can deal with larger frequency ranges (no constraint on coherence between channels)

3NWCh in 30-100Hz cohe12= 94% cohe13= 80%