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Advanced Virgo calibration for O2: update for h(t) reconstruction reprocessing V1O2Repro2

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1 Introduction

This note is an update of the note VIR-0707C-17 [1] that describes the actuation models for the Virgo $h(t)$ reprocessing V1O2Repro1A of the O2 run. In this new release, we fixed a few typo found in the initial release VIR-0013A-18, in table 2.

One bias at the level of 0.3% on the NE and WE actuators that was present in the first release is now properly taken into account, hence reducing the corresponding systematic errors given in the previous note by 0.3%.

A delay in the interferometer (ITF) optical response to the end mirror motion was forgotten in the online and V1O2Repro1A h-reconstruction and will be included in the new reprocessing.

Finally, simulations of the ITF optical response to a motion of the PR mirror have been performed. The fitted model is given and its variation depending of the arm cavity finesse is highlighted.

2 Update of the NE and WE actuator models

This is an update of the section 9.1.2 of note VIR-0707C-17. When transferring the calibration from input to end mirror, the ratio $R_{ITF,in}/F_{ITF,end}$ between the ITF optical responses to input and en mirrors must be taken into account. This TF ratio is 1/1.0037 in modulus and its phase matches a 10 μs delay.

The figure 1 shows the modulus ratio obtained from ITF simulations with Optickle. The 10 μs delay is not reproduced by the simulation, but is due to the light propagation time from the end mirrors (see PhD thesis of M. Rakhmanov [2]). The delay was properly taken into account in the transfer described in note VIR-0707B-17.

The tables 1 and 2 give the updated models for the NE and WE mirror and marionette actuator models: only the gains have been modified by 0.3% (hence there is still 0.07% residual bias). The models for BS and PR are the same as the ones given in tables 4 and 5 of note VIR-0707C-17. The table 3 gives the updated systematic uncertainties on the mirror actuation models.

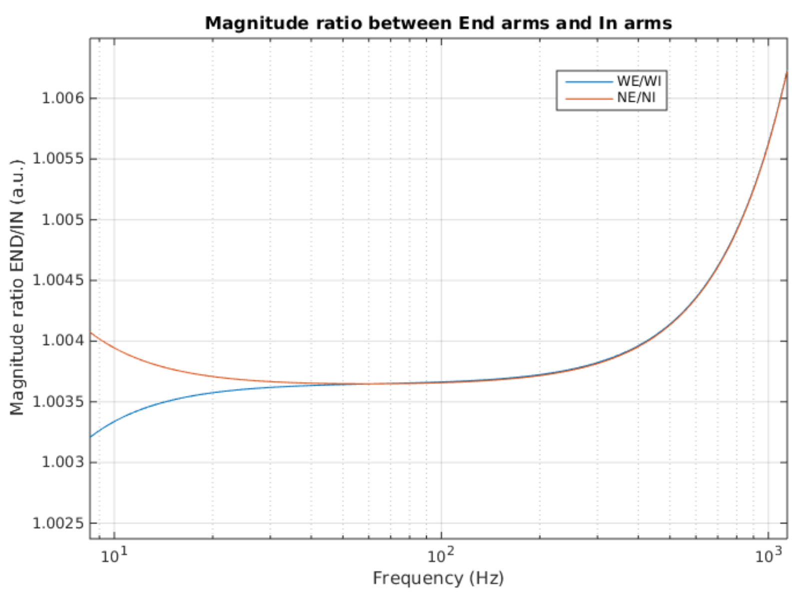

Figure 1: Magnitude ratio of the ITF optical responses between end mirrors and input mirrors for both arms.

Model		Mirror actuators			
Type	parameters	NE in LN2	WE in LN2	BS in LN1	PR in HP
Gain (µm/V)		0.473 ± 0.002	0.4345 ± 0.0024	1.07977 ± 0.00077	0.7938 ± 0.003
Delay (µs)		-240.2 ± 1.3	-242.9 ± 1.5	$+117 \pm 3.5$	-241 ± 8.7
Extra-delay (µs)		10	10	0	0
1st order pole	f_p (Hz)	17.15 ± 0.4	17.00 ± 0.41	49.4 ± 9	301.4 ± 7
1st order zero	f_0 (Hz)	16.13 ± 0.4	16.00 ± 0.39	50.4 ± 10	–
1st order pole	f_p (Hz)	109.2 ± 3	138.5 ± 4.6	–	–
1st order zero	f_0 (Hz)	117.1 ± 3	148.5 ± 5.0	–	–
2nd order zero	f_0 (Hz)	–	–	877.9 ± 15	–
	Q	–	–	0.668 ± 0.01	–
simple pendulum	f_p (Hz)	0.6			
	Q	1000			

Table 1: Summary of the mirror actuator calibration models useful for h(t) reconstruction: from Sc_MIR channel to mirror motion. Only statistical errors are reported here. The extra-delay reported here is a delay to be added to take into account that the arm cavity optical response is not exactly a simple pole.

Model		Marionette actuators		
Type	parameters	NE	WE	BS
Gain (µm/V)		1.483 ± 0.011	1.349 ± 0.01	4.645 ± 0.023
Delay (µs)		1106 ± 75	1326 ± 55	1259 ± 48
Extra-delay (µs)		10	10	0
1st order pole	f_p (Hz)	49.9 ± 3.3	43.6 ± 6	45.1 ± 4
1st order zero	f_0 (Hz)	96.6 ± 13	56.2 ± 10	63.0 ± 7
1st order pole	f_p (Hz)	–	–	–
1st order zero	f_0 (Hz)	–	–	–
2nd order zero	f_0 (Hz)	–	–	–
	Q	–	–	–
two simple pendulum in series	f_p (Hz)	0.6		
	Q	1000		
	f_p (Hz)	0.6		
	Q	1000		

Table 2: Summary of the marionette actuator calibration models useful for $h(t)$ reconstruction: from Sc_MAR channel to mirror motion. Only statistical errors are reported here. The extra-delay reported here is a delay to be added to take into account that the arm cavity optical response is not exactly a simple pole.

<table>
<tr><th colspan="3">Source of uncertainty</th><th>NE mirror</th><th>NE mario.</th><th>WE mirror</th><th>WE mario.</th><th>PR mirror</th><th>BS mirror</th><th>BS mario.</th></tr>
<tr><td rowspan="9">Systematic errors</td><td rowspan="4">Stability vs time</td><td>free Mich</td><td colspan="2">0.4%
0</td><td colspan="3">0.4%
0</td><td colspan="2">0.2%
3 mrad</td></tr>
<tr><td>in to end</td><td colspan="2">0
0</td><td colspan="2">0
0.5 mrad</td><td colspan="3">–
–</td></tr>
<tr><td>mir to mar</td><td>–
–</td><td>0.3%
3 mrad</td><td>–
–</td><td>0.2%
4 mrad</td><td>–
–</td><td>–
–</td><td>0
1 mrad</td></tr>
<tr><td>WI to PR</td><td colspan="4">–
–</td><td>0.3%
0</td><td colspan="2">–
–</td></tr>
<tr><td colspan="2">Fit residuals</td><td>0.5%
5 mrad</td><td>2%
10 mrad</td><td>0.5%
5 mrad</td><td>1%
10 mrad</td><td>2%
20 mrad</td><td>1%
5 mrad</td><td>0.5%
5 mard</td></tr>
<tr><td colspan="2">Δf in normalisation</td><td colspan="7">0.2% at 20 Hz and 0.04% at 100 Hz
0</td></tr>
<tr><td colspan="2">R_{ITF} diff (in vs end)</td><td colspan="4">0.07% bias
0</td><td colspan="3">–
–</td></tr>
<tr><td colspan="2">Timing (B1p)
Timing (GPS)</td><td colspan="7">4 µs
<4.5 µs</td></tr>
<tr><td colspan="2">Total systematics
(linear sum)</td><td>1.1%
5 mrad
4 µs</td><td>2.9%
13 mrad
4 µs</td><td>1.1%
5.5 mrad
4 µs</td><td>1.8%
14.5 mrad
4 µs</td><td>2.9%
20 mrad
4 µs</td><td>1.4%
8 mrad
4 µs</td><td>0.9%
9 mrad
4 µs</td></tr>
</table>

Table 3: Summary of the source of systematic uncertainties on the mirror and marionette actuator models. For every sources, the uncertainties on the modulus and on the phase are given in the first and second lines respectively (except for the systematic coming from the B1p timing). The last line gives, for all the actuators, the sum of all the systematic uncertainties reported in this table.

3 Optical response to NE and WE mirror motions

The optical response of the ITF to a GW is approximated by a simple pole at $c/(4\mathcal{F}L_0)$, where L_0 and $\mathcal{F}$ are the length and finesse of the ITF arm cavities. For a finesse $\mathcal{F} = 430$, the cavity pole is 58.1 Hz and the optical responses for NE and WE are shown in Figure 2.

As detailed in [3], the response of the ITF to mirror motion is the same for the input mirrors, and the same with an extra-delay of L_0/c for the end mirrors. For Virgo, the extra-delay is 10 μs.

As a consequence, for the end mirrors, in the $h(t)$ reconstruction, it is equivalent to increase the actuation delay by 10 μs and use the simple cavity pole model. **Hence the delays given in tables 1 and 2 must be increased by the extra-delay of $+10$ μs also stated in the tables.**

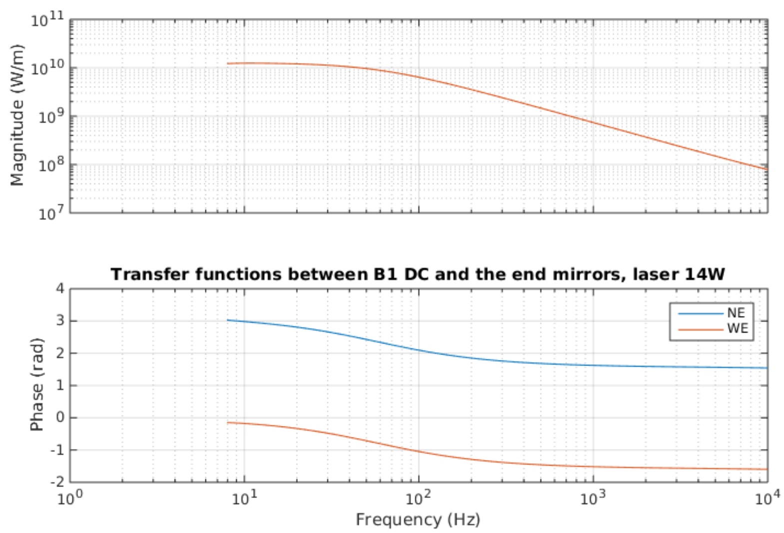

Figure 2: Simulated ITF optical responses to NE and WE mirror motions with a laser input power of 14 W and a finesse of 430.

4 Optical response to PR mirror motion

The optical response to PR mirror motion is simulated with the MATLAB based *Optickle* model for gravitational waves interferometers.
The interferometer is in *PRITF* configuration meaning that it is locked and has a power recycling cavity. The simulation is done with a laser input power of 14 W and an optical finesse of 430. The figure 3 shows, on the left panels, the optical response (modulus and phase) to a PR motion in blue, and a fit of the data in red. The fit residuals are shown in the right panels. Note that arbitrary statistical errors of 1% have been added to the simulated TF before running the fit. The fit parameters are given in table 4. From the residuals, the fit matches the data within 1% and 10 mrad up to 300 Hz.

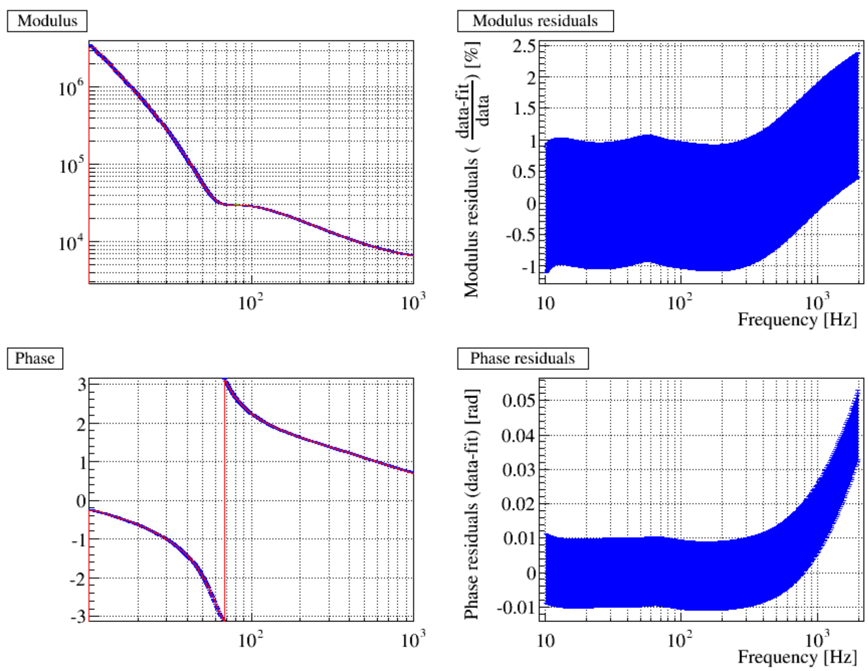

Figure 3: ITF optical response to PR mirror motion. Left panel: data in blue, and fit in red. The modulus (top) is in [W/m] and the phase (bottom) in [rad]. Right panel: fit residuals.

Simulations were also done to compare the optical responses to PR mirror motion with a finesse of 430 and of 450 since Advanced Virgo is expected to have a finesse around 450 but the finesse measured during O2 with hrec is around 430. Figure 4 shows the shape of the simulated optical responses with both finesses. A 5% error on the finesse changes the simulated response by $\pm 30\%$ in amplitude and $+0.2/-0.5$ rad in phase.

Model		Optical response
Type	parameters	PR
Gain (W/m)		$(-9.21 \pm 0.01) \times 10^8$
Integrator	–	–
Integrator	–	–
1st order pole	f_p (Hz)	58.1 (fixed)
1st order zero	f_0 (Hz)	0.0696 ± 0.0005
1st order pole	f_p (Hz)	57.3 ± 0.3
1st order zero	f_0 (Hz)	91.6 ± 0.4
1st order pole	f_p (Hz)	1.144 ± 0.008
1st order zero	f_0 (Hz)	-734 ± 3
2nd order zero	f_p (Hz)	-60.04 ± 0.02
	Q	1.770 ± 0.003

Table 4: Model for the ITF optical response to PR mirror motion.

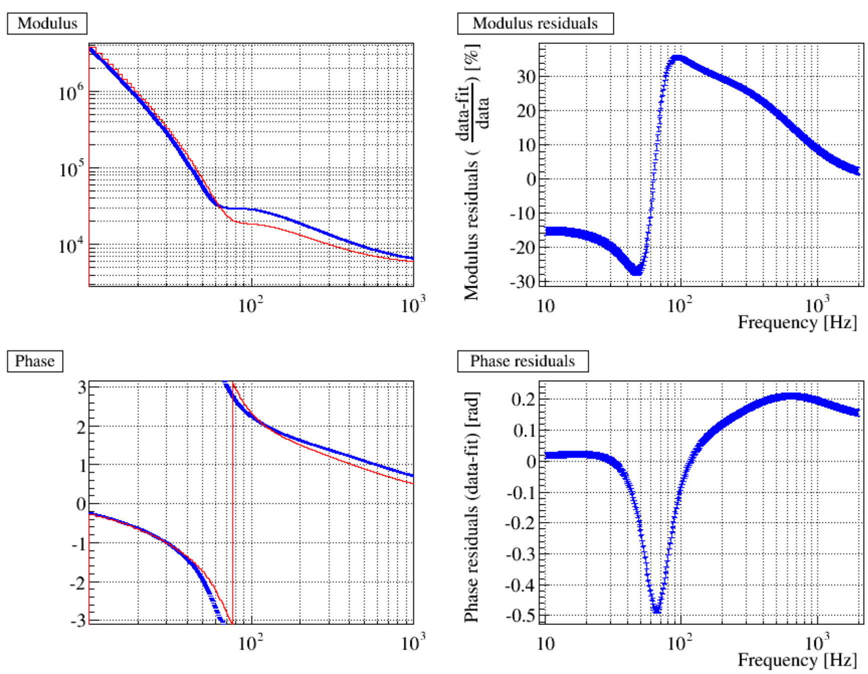

Figure 4: Comparison of the ITF optical responses to PR mirror motion with a finesse of 430 in blue and a finesse of 450 in red. The modulus is in [W/m] and the phase in [rad].

References

[1] L. Rolland *et al.*, "Advanced Virgo calibration for O2: photodiode sensing and mirror and marionette actuator responses," *Virgo note*, vol. VIR-0707C-17, Sept. 2017.

[2] M. Rakhmanov, *Dynamics of Laser Interferometric Gravitational Wave Detectors*. PhD thesis, CIT, 2010.

[3] M. Rakhmanov *et al.*, "High-frequency corrections to the detector response and their effect on searches for gravitationnal waves," *Class. Quantum Grav.*, vol. 25, no. 184017, 2008. (arXiv:0808.3805).