h(t) reconstruction for VSR3.

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Abstract

This note describes the h(t) reconstruction of the VSR3 data, from August 11th to October 19th 2010: method, parameters and checks made. It gives also the estimated errors on the reconstructed h(t) channel for the online and the reprocessed (V2) versions.

Summary

1 Introduction

The main differences between the Virgo Science Run 3 (VSR3) and VSR2 were the new set of mirrors which gives a finesse of about 150, instead of 50 previously, and the monolithic suspensions.

During VSR3, the h(t) production was done online (“HrecOnline”), using preliminary version of the actuators calibration and a fixed value for the finesse. A few changes were made during the run to the online reconstruction, to update calibration constants and to fix glitches observed when collecting the DSP data by the DAQ (the so called DSP-DAQ glitches).

Then a reprocessing (“Hrec-V2”) was made offline to include the variable finesse due to the etalon effect and to take into account the final actuator models, thanks to the regular measurements performed during the calibration periods, including a post run calibration period.

This note describes the methods used as well as the tests made to check h(t) validity and estimate its uncertainties.

2 Reconstruction method

The reconstruction method is the same as the one used for VSR2, described in VIR-0340A-10 (see this note for more details) with the following small differences:

- Use the new actuators/sensing parameters
    - The online version was using preliminary measurements from VIR-0477A-10 with the following differences:
        - On September 3rd 2010, it was discovered that the gain of the actuator were increased by 33% since the preliminary calibration. This rescaling was therefore applied on the actuator model used. This reduced the observed horizon by 33%.
        - At the beginning of the run, the model used for the marionette was the VSR2 model. It was switched to the model from VIR-0477A-10 (rescaled by 33%) on September 10th 2010.
        - For PR, since calibration was not yet available, the VSR2 model was used.
    - The reprocessed version used the final numbers from VIR-0610A-10.
- The PR_z(t)→h(t) optical TF is assumed to be flat. A small correction was applied during VSR2, but this small correction had little impact on the PR contribution and therefore it has been neglected during VSR3.
- Finesse:
    - The VSR3 hrec-online version used a fixed finesse of 150.
    - The reprocessing used the finesse extracted from the 35x Hz calibration lines. Since they were less sensitive to the finesses due to the reduction of the cavity pole, the finesse which is computed every 10 seconds like in VSR2 has been averaged over the last 100 seconds. Furthermore, since the finesse extracted from the BS line was noisier, instead of doing a plain average of the finesses computed using the NE, WE and BS lines, we used a weighted averaged using the line SNR to optimally combine the information.
- Since the early reprocessing checks indicated some slight mismatch (see later), 3+3µs have been added in sensing and actuation to get correct checks. This is equivalent to reduce the finesse by about 4%.
- The 50 Hz harmonic subtraction has been limited to 450 Hz for the reprocessing. In VSR2 and for the online production it was going up to 900 Hz
- The ACq saturation flag threshold is set to 9.5 V for the reprocessing (actually ±-990000 ADC counts). It was 5 V (±530220 ADC counts) for VSR2 and VSR3-Online.
- The 20 kHz h(t) channel is not distributed for the reprocessed data set. The 4096 Hz and 16384 Hz channels are made available as usual.
- For the reprocessing, the DSP-DAQ glitch fix has been apply for the whole run. It was implemented only for one day during online production and it was limited to the mirror zCorr channel online (see more details later).

2.1 Contribution of the various signals to h(t)

The following figures present the typical contribution of the different channels for the h(t) signal. As we can see, this is not very different from VSR2.

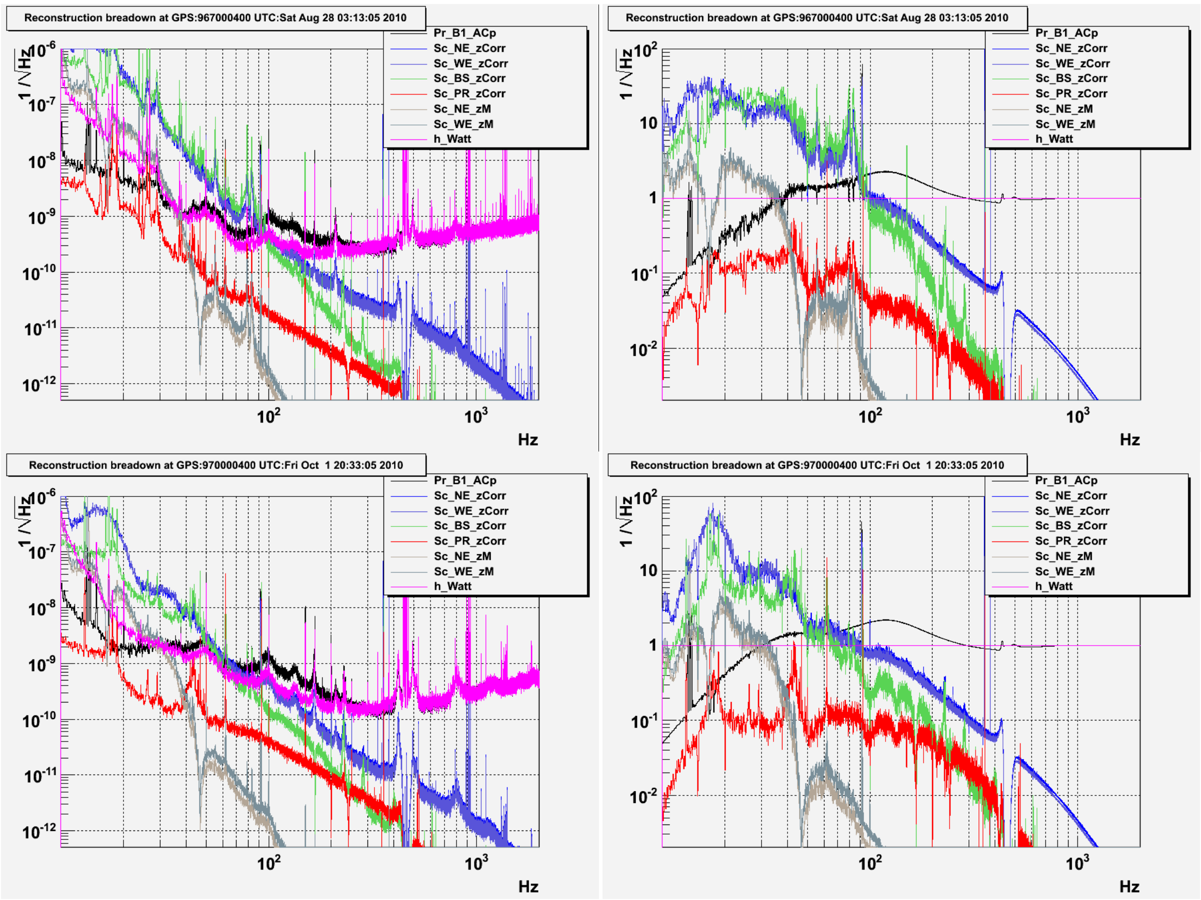

Figure 1 Left: typical spectrum of the different channels involved in the reconstruction for two different dates of VSR3. Right: all the spectrum have been normalized to the h(t) spectrum to easily see their relative contributions.

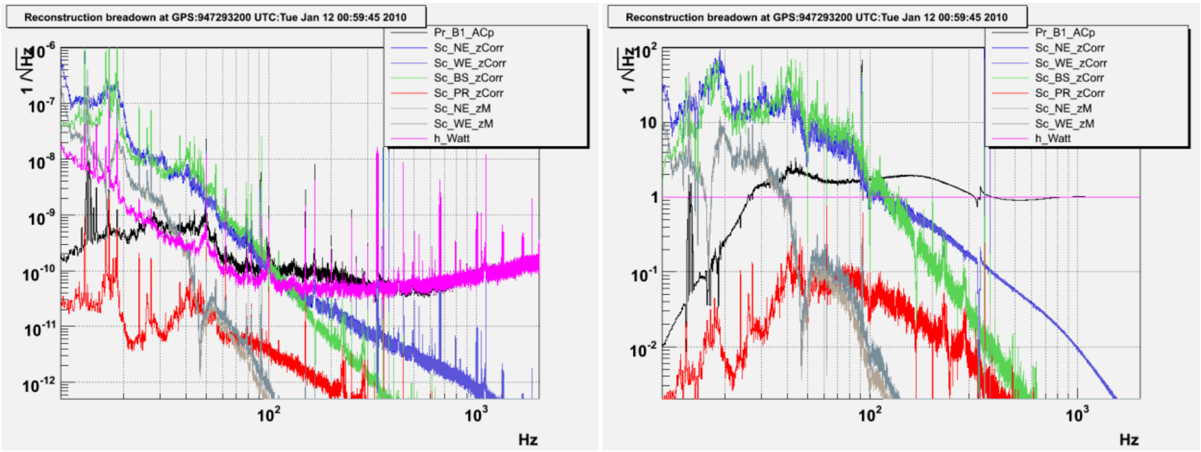

Figure 2 Same plots as the previous figure, but for VSR2 to show the variations since VSR2.

2.2 Measured optical gains

The following figure presents the typical variations of the observed optical gains. The fluctuations are at the level of a couple of percent for the main optical gains (NE and WE). This is comparable, although slightly larger than during VSR2.

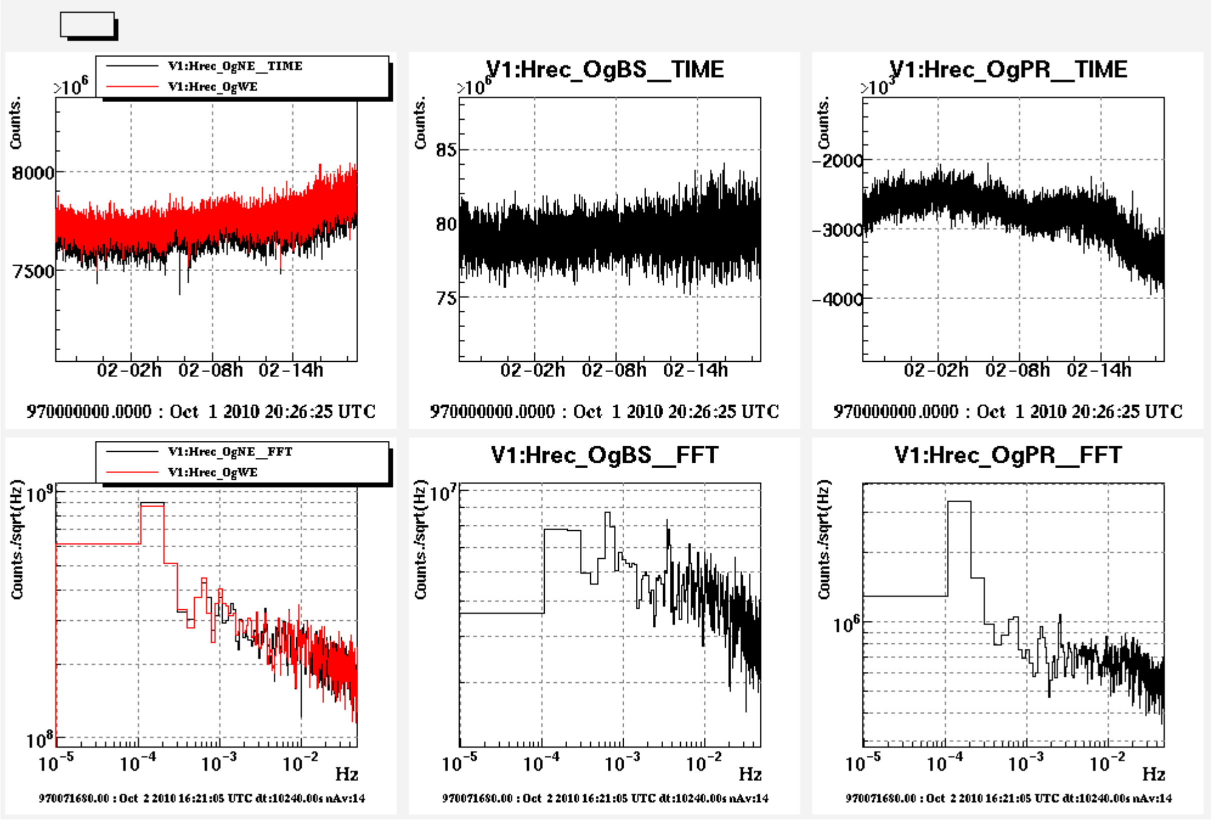

Figure 3 Typical fluctuations of the optical gains for NE and WE (left plots), BS (central plots) and PR (right plots) in the time domain (upper plots) and in the frequency domain (bottom plots).

2.3 The DSP-DAQ Glitches correction

Due to a misconfiguration of terminal building DSPs, some TOLM packets were lost by the DAQ from time to time at the beginning of the run (see logbook entry 27623 from August 31st). As a results of these missing data, the 1-second long vectors for the data coming from the WE and NE towers were incomplete from time to time, with a zero at the end, producing large glitches when using the corresponding channels (zCorr and zM) for the reconstruction.

However, this problem can be monitored since the GC_NE_z channel (same for WE) is simultaneously sent to the DAQ and to the NE tower, to be used by the DSP which also sends it to the DAQ, labelled as Sc_NE_zGC, at the next 10 kHz clock tick. In other words, when everything is perfect, the Sc_NE_z channel should be the same as the Sc_NE_zGC channel shifted by one sample. In case of a missing sample (see the following figure as an example), this one sampling shift disappears for all the channels provided by this DSP. Therefore, we know exactly which sample was missing and then we can put back the following samples at their right location, and fill the gap with a linear interpolation. Since these channels are only used at low frequency (they are low-pass filtered by the actuator response) the possible noise introduced by this linear interpolation of one 10 kHz sample is negligible.

A bug has been found after the reprocessing (end January 2011) when more than one sample was missing in a single second: (i) in the cases where the missing samples were within 100

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samples from each other, none was corrected and (ii) else only the first sample was fixed. 22+59 glitches from DSP-DAQ issues were found in HrecV2 during Science Mode segments. A veto called V1:DSPDAQ_MULTI_V2 has been defined by the VDQ group to flag these times.

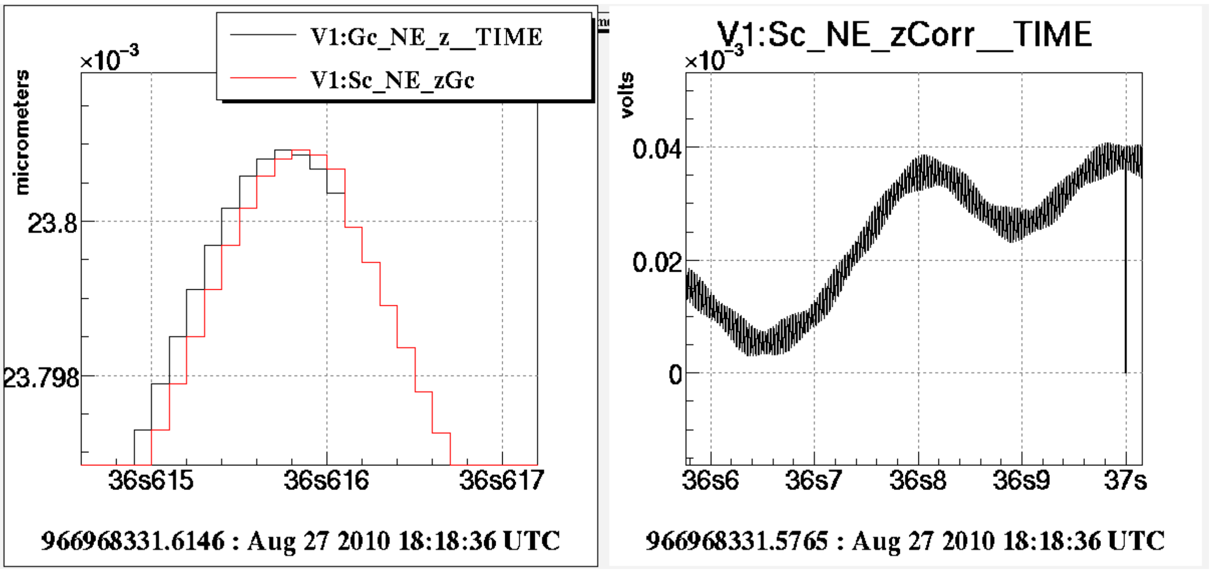

Figure 4 Example of a DSP-DAQ glitch. The Sc_NE_zGc channel(left plot) is delayed by one sample up to 36.6162 s where one sample is missed by the DAQ, shifting the vector by one sample and creating a zero at the end of the vectors coming from this DSP at 37 s (right plot)

2.4 Fine tuning of the timing

The method used to check the h(t) reconstruction is to inject some noise in a mirror actuator not used by the control system. During VSR3, we used the left and right coils of the WE mirror which, by the way, are used for the hardware injections. The injected signal could be translated to injected displacement (or h(t)) using the actuators calibration. Then the transfer function between this injected h(t) and the reconstructed h(t) signal is an estimation of the correctness of the reconstruction process.

A preliminary test of the reconstruction was performed with the nominal actuator response. With this preliminary reconstruction, this check was giving non perfect result (see Figure 5).

Further investigations have shown that using a different finesse improves the results. Actually, for each of the weekly test period, we evaluated the finesse that gives the best result for the h_{Rec}/h_{Inj} test. Then we compared this finesse with the value extracted from the calibration line measurement. We observed a clear correlation indicating an underestimation of the finesse by 5 (see Figure 6). This offset could be translated to a phase mismatch when measuring the calibration line or in other word, to a timing mismatch of 6 µs. Since we don't know if this error is coming from the actuator model or the sensing model, this error has been shared between the two parts, leading to a shift of 3µs for the timing model and 3µs for the actuator model. More specifically, the 59.7 µs nominal delay for the sensing has been increased to 62.7 µs and, for instance, the 275.1 µs delay for WE has been changed to 272.1 µs. It is worth noticing that with the time shift, the finesse extracted from the calibration lines is closer to the 150 nominal value.

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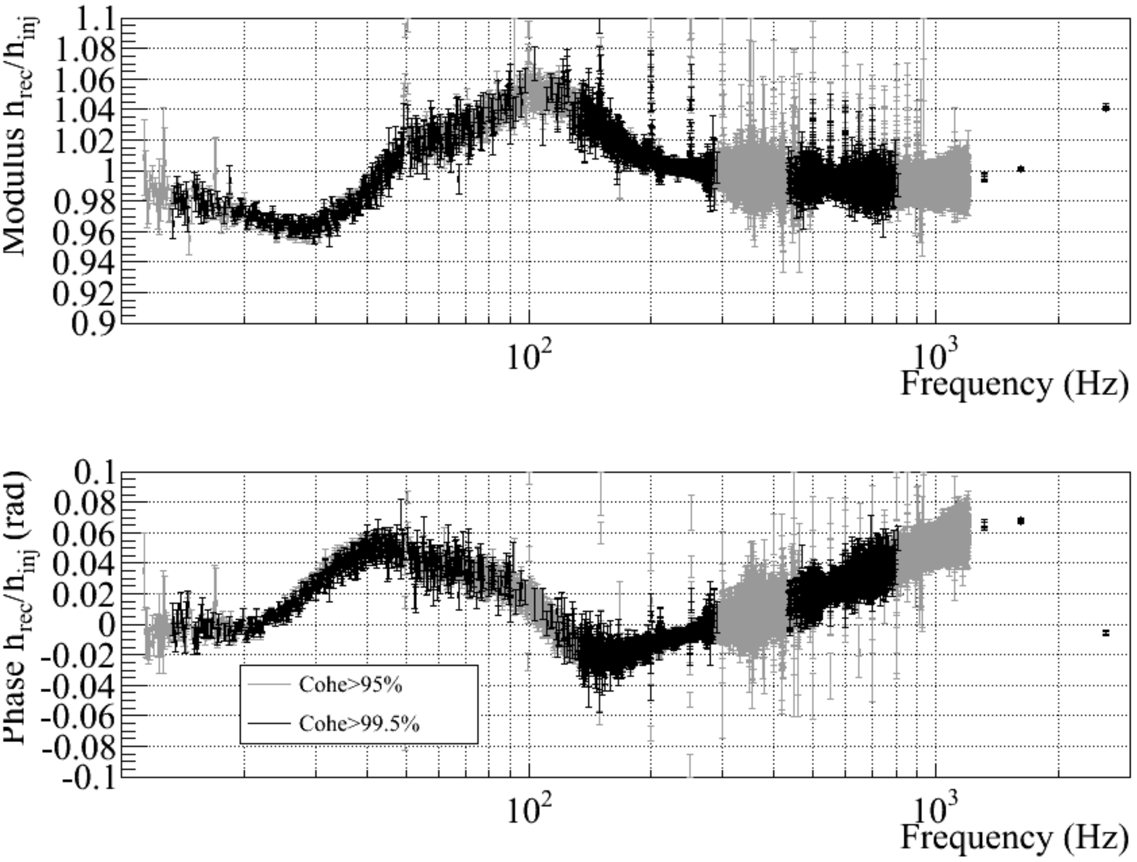

Figure 5 The h_{Rec}(t)Rec/h_{Inj}(t) test with the nominal value of the actuators model (without the extra 3+3µs). Black points correspond to points with the coherence between the injected and recovered signals above 99.5%. Grey points for coherence above 95%. The error bars display only the statistical errors

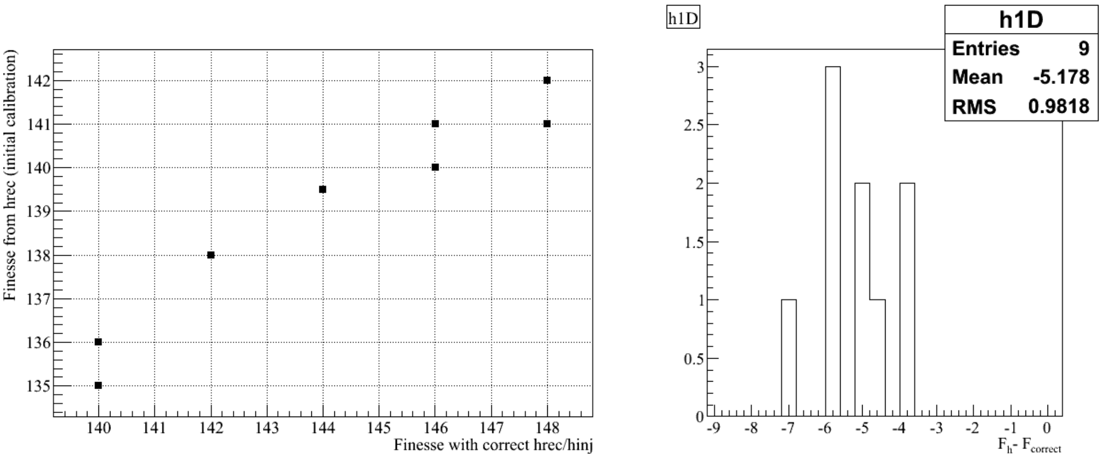

Figure 6 Correlation between the finesse from the calibration lines and the finesse that makes the h_{Rec}(t)Rec/h_{Inj}(t) plot flatter (left plot), and histogram of the difference (right plot)

3 Processing details

3.1 Data set processed

The GPS time range processed for VSR3 is from 965580000 (Aug11, 16:39:45 UTC) to 971558000 (Oct19, 21:13:05 UTC).

The reconstruction reprocessing was performed at Cascina restarting from the online buffer (/virgoData/ffl/raw.ffl) with the following granularity:

Start time	**Duration**
965580000	477000
966057000	452000
966509000	504000
966999500	78000
967070000	426000
967156840	339160
967496000	504000
968529700	475300
969005000	486000
969491000	600000
970091000	412000
970503000	543000
971046000	512000

In case of overlap between jobs, the duplicated frames have been discarded to guaranty a single answer.

The HrecV2 data set was released on December 21st, 2010.

3.2 Software version

The software version used for this reprocessing was Hrec/v2r18.

The only difference with the version used online was the capability to average the finesse over a longer time. And the improvement of the correction of the DSP glitches to detected NE and WE glitches (due to a sign difference, only one type was fixed online) and also to fix the marionetta information (“zM”).

3.3 Data Quality flags

The h(t) quality is evaluated for each 10 seconds frames. The conditions to get a good quality are:

- The interferometer is locked in step 12
- All the needed channels are available for the current, previous and following 10 seconds frames. This is needed by the frequency domain filtering.
- The SNR of the NE, WE, BS calibration lines is above 3.
- The individual finesse extracted from the phase of each calibration lines (NE, WE and BS) is in the 100-200 range.
- The channel (V1:Pr_power50) for the power line subtraction is available

The results of these tests are recorded as the following 1 Hz ADC channels:

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- “Hrec_Flag_quality” for the overall quality (1 means OK)
- “Hrec_Flag_Frame” if the previous/following frames are present (1 means OK)
- “Hrec_Flag_Channel” if all channels are available (1 means OK)
- “Hrec_Flag_SNR” if the SNR test is OK (1 means OK)
- “Hrec_Flag_Finesse” if the finesse test is OK (1 means OK)
- “Hrec_Flag_LineRmvl” if the power monitoring channel is present (1 means OK)

3.4 Channels produced

The reprocessing produced two h(t) channels named V1:h_4096Hz, V1:h_16384Hz corresponding to the frequencies given by their names. The V1:h_20000Hz channel was also produced but was not distributed. It is just available at Cascina and was used for reconstruction checks.

In addition to this fast channels, and the data quality channels described in the previous section, the following 0.1 Hz channels are available:

- V1:Hrec_OgPR: the optical gain measured with the 92.5Hz PR calibration line
- V1:Hrec_OgBS: the optical gain measured with the 357Hz BS calibration line
- V1:Hrec_OgWE: the optical gain measured with the 356.5Hz WE calibration line
- V1:Hrec_OgNE: the optical gain measured with the 356Hz NE calibration line
- V1:Hrec_OgCAVITIES: the average of the NE and WE optical gains
- V1:Hrec_finesse channel: the finesse measured with the calibration lines
- V1:Horizon_BHBH_Average: the averaged horizon (or range) for 10+10 solar mass black holes
- V1:Horizon_NSNS_Average: the averaged horizon (or range) for 1.4+1.4 solar mass neutron stars

The “V1:Horizon*”, channels contain the horizon computed out of the 20 kHz h(t) channel for BNS and 10+10 solar mass BBH. The h(t) spectrum is computed on two-second long FFTs with Hanning windows and a 50% overlap, averaged with an exponential decay over 15 FFTs, starting from 10 Hz. The optimal horizon is dived by 2.26 to get the quoted averaged horizon.

4 Reconstruction checks for HrecV2

4.1 Checking the correctness using injections with out-of-loop actuators

Like for preliminary tests of the reconstruction described in section 2.4 , we can check that we correctly reconstruct a signal injected on some out-of-loop coils (the coils used for the hardware injections). Figure 7 presents this measurement averaged over all VSR3 weekly calibration periods. Only data below 1 kHz could be trusted in this measurement. As we can see, the modulus of the transfer function is flat with a variation of less than ±2.5% around 1, except for frequencies at the power lines for which a larger dispersion is observed due to a lower coherence. The phase is also within ± 30 mrad around zero below 500 Hz, except again for the power line frequencies. Above 500 Hz, the phase difference could be modelled as a 9.5 µs delay.

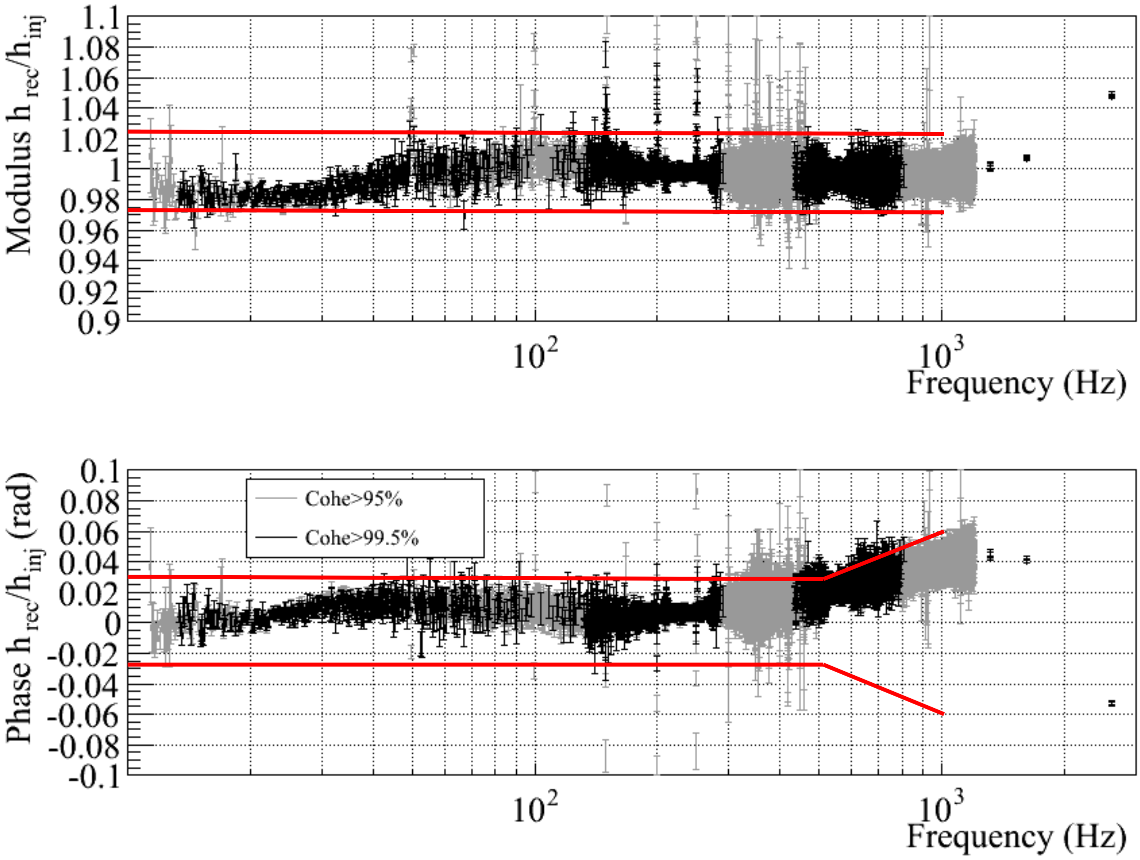

Figure 7 Checks of HrecV2 using the WE-LR injections. The errors bars display only the statistical errors. The black points have coherence above 99.5%, while the grey points have coherence between 95 and 99.5% and therefore could be perturbed by the presence of lines like the 50 Hz harmonics. The weekly measurements have been averaged over VSR3 to produce this curve. The red lines indicated the maximum excursion (±2.5% in modulus and ±30 mrad below 500 Hz, and 9.5µs above 500 Hz in phase) and are used to determine the systematic errors

In order to show that the averaging of the weekly measurements is not cancelling out some fluctuations, the Figure 8 presents this transfer function measurement for a few frequencies over VSR3. No time dependent effect is observed. The appendix presents the weekly plots over the full measurement bandwidth.

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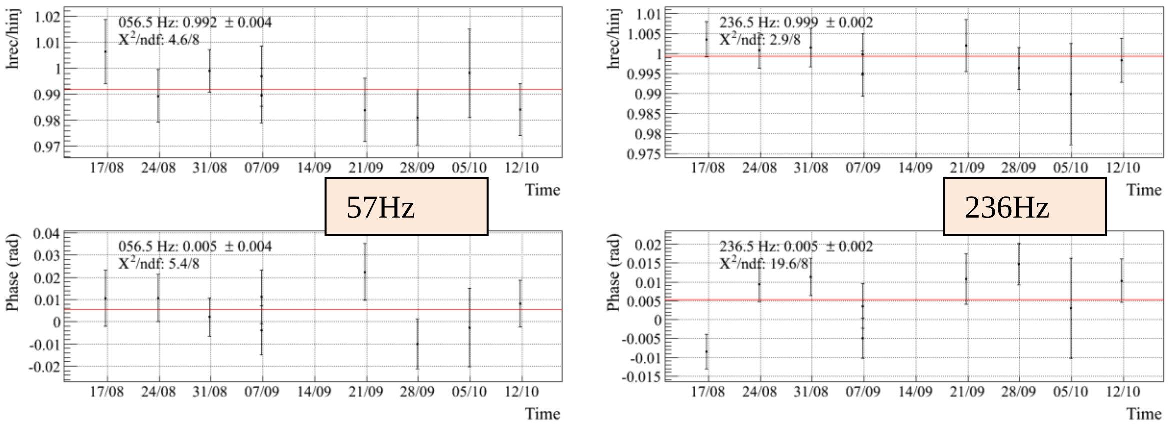

Figure 8 Ratio between the injected h(t) and recovered h(t) during VSR3 for the extra calibration lines at 57 Hz (left) and 237 Hz (right). The top plots show the ratio of the amplitudes, while the bottom plots show the phase difference.

4.2 Check of the noise level in h(t)

4.2.1 h(t) spectrum versus the sensitivity computed in the frequency domain

The reconstruction process could reconstruct with the right transfer function the h(t) signal, but could also add extra noise if the controls signals are not properly cancelled out. If the online cancelation of the control signal is not optimal, the h(t) reconstruction could remove some of this control noise, in addition to the calibration lines subtraction. This is a more difficult check to perform since, we do not expect the h(t) signal be just the dark fringe signal on which a transfer function is applied. Nevertheless, since during VSR3, various techniques of noise cancelation have been applied by the global control team ("α, β, γ techniques"), we can assume in first approximation that the dark fringe is a clean signal.

Like for VSR2, we can compare the h(t) spectrum to the sensitivity computed in the frequency domain, i.e., the spectrum of Pr_B1_ACp on which the transfer function has been applied. Figure 9 presents these two curves overlapped at the time of one of the calibration period (see the Appendix for more plots), while Figure 10 presents their ratio averaged over all the weekly measurements. The blue and green curves show the fluctuation observed during the run, plus the statistical fluctuation of the measurement.

Vertical lines below 1, indicate the power lines and calibration lines which are subtracted by the reconstruction process. The 10-15 Hz range should not be trusted too much, since some of the transfer functions (and therefore h(f) spectrum) were not properly measured in this band. In the 15-20/25 Hz band, this ratio shows some large variations, depending of the sensitivity. This is the frequency band were the controls contribution is the largest (see Figure 1) and therefore were the h(t) reconstruction is not perfectly cancelling out the control signals, leaving some extra noise compared to the Pr_B1_ACp spectrum. Above 20 Hz, the ratio is usually close to one within a few percents.

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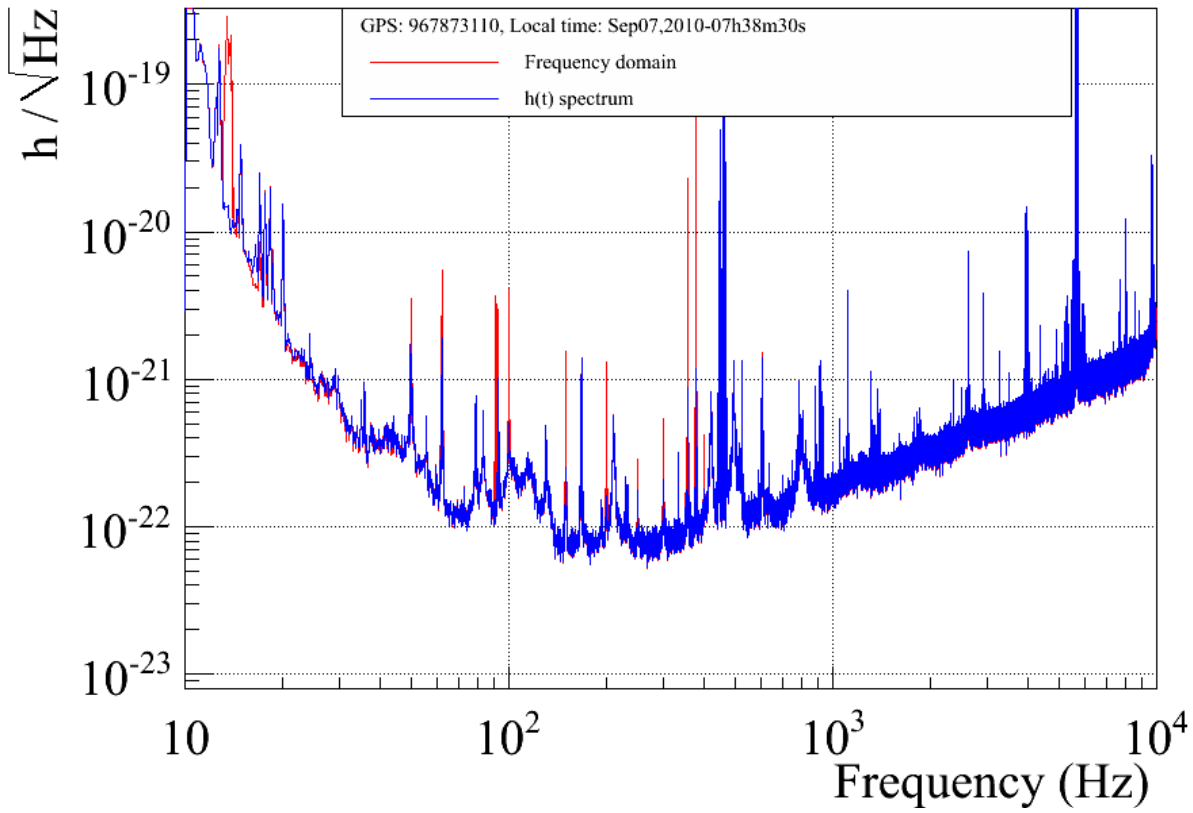

Figure 9 h(t) spectrum for HrecV2 (blue curve) compared to the sensitivity spectrum (red curve) built from the dark fringe signal corrected for the interferometer transfer function. Data from September 7th 2010. See the appendix for other dates

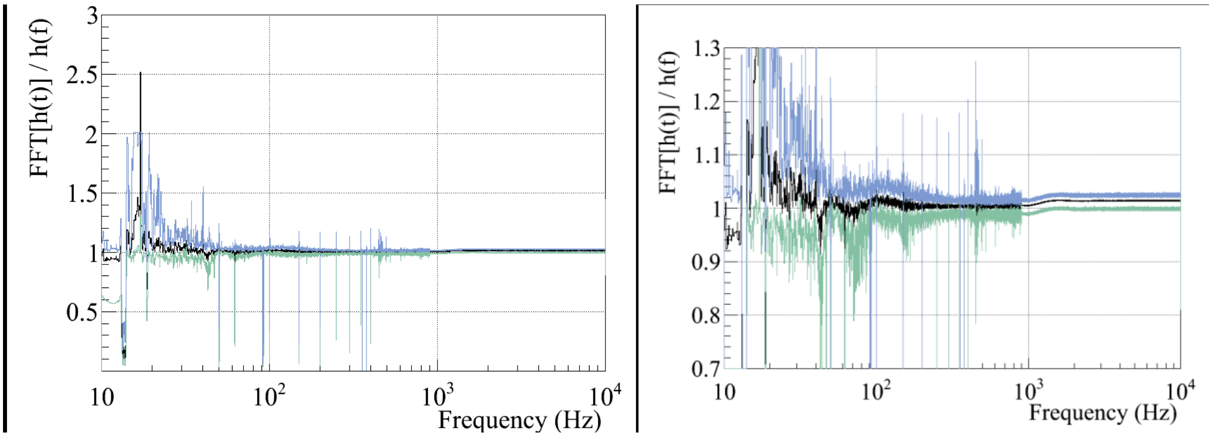

Figure 10 Ratio of the h(t) HrecV2 spectrum and h(f). The black curve is the mean value over the weekly calibration periods. The blue/green curves are the maximum/minimum of this ratio to indicate the typical fluctuations. Right plot: a zoom within 30% around a ratio of 1.

4.2.2 Coherence between h(t) and the auxiliary degrees of freedom

As for VSR2, it is possible to look for the presence of residual control noise in the h(t) signal, as an indication of the remaining noise in the h(t) channel. Figure 11 presents the sum of the coherence between h(t) and the three main auxiliary degrees of freedom (*Gc_Michelson*, *Gc_Recycling*, *Gc_Common*) in red as well as for Pr_B1_ACp in black. Beside the power

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lines, the coherence is pretty low indicating that the remaining control noise is small. The behaviour of h(t) and Pr_B1_ACp is about the same.

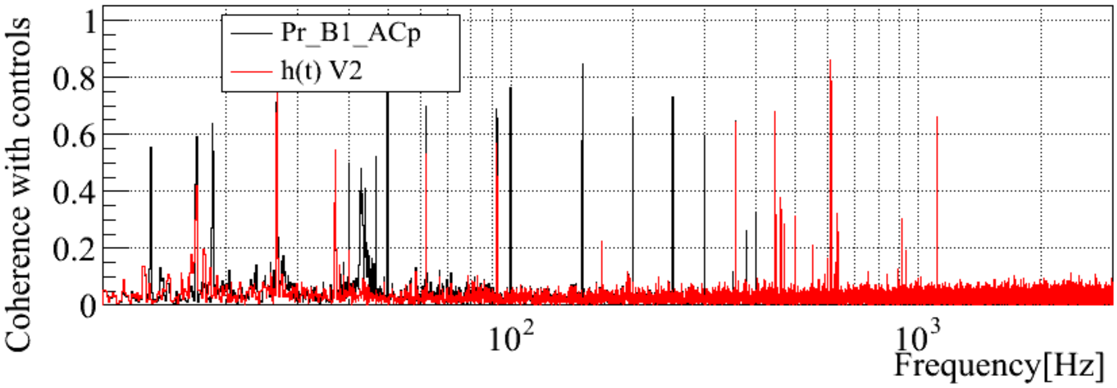


Figure 11 Sum of the coherences between h(t) (red) or Pr_B1_ACp (black) and the Gc_Michelson, Gc_Recycling, Gc_Common controls signals on August 27th. The same plots computed during the weekly calibration periods are available in the appendix

4.2.3 Coherence between h(t) and the Pr_B1_ACp signal

Again, as for VSR2, another way to check for extra noise in h(t) is to look at the coherence between h(t) and Pr_B1_ACp.

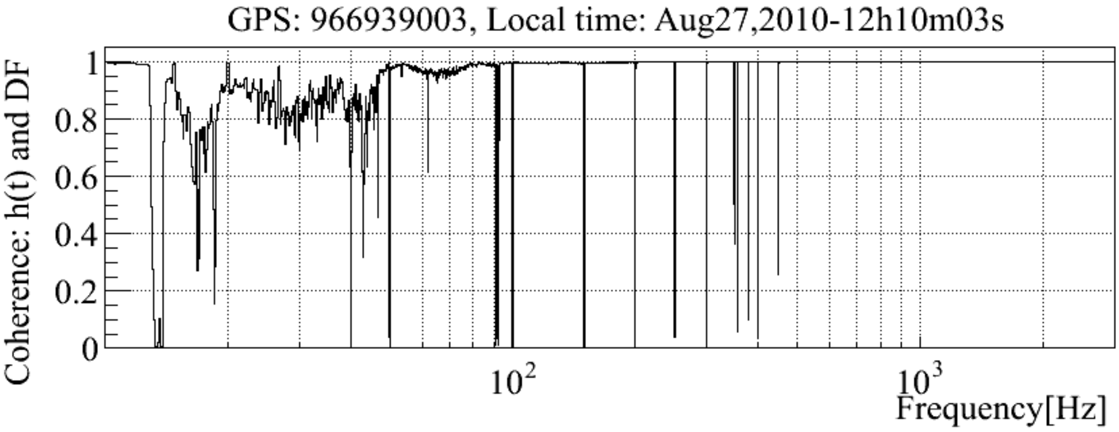


Figure 12 presents such coherence for HrecV2. A coherence below 1 indicates that either extra noise is still present in h(t) or noise has been subtracted in h(t) like for the power lines or calibration lines around 13 Hz. There is a very good coherence above 50 Hz. Below 50 Hz, the two signals do not give exactly the same answer, but this is the frequency band where there is still some residual control noise in both signals.

The appendix presents this coherence for all the weekly calibration periods.

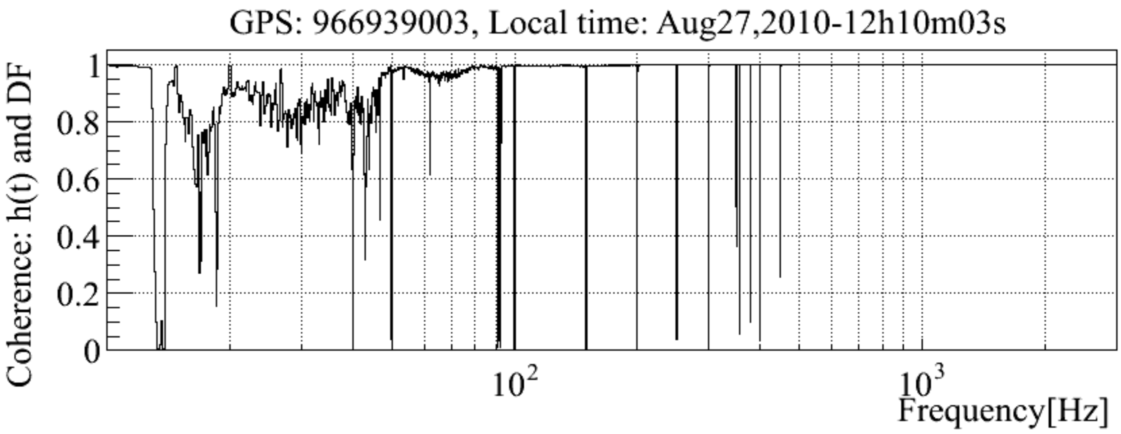


Figure 12 Coherence between h(t) (HrecV2) and the Pr_B1_ACp signal

4.3 Calibration lines cancellation

Another way to check that the reconstruction is properly working is to look and the residual amplitude of the calibration lines. Figure 13 presents the calibration lines for the main triplet in the Pr_B1_ACp signal and the corresponding h(t) spectrum. One has to remember that the optical gains have been adjusted on the 356-357.5 Hz lines, as well as the cavity finesse (phase of the NE and WE line). So, one should expect good cancelation for this band, except if there is some phase error in the actuator or sensing model.

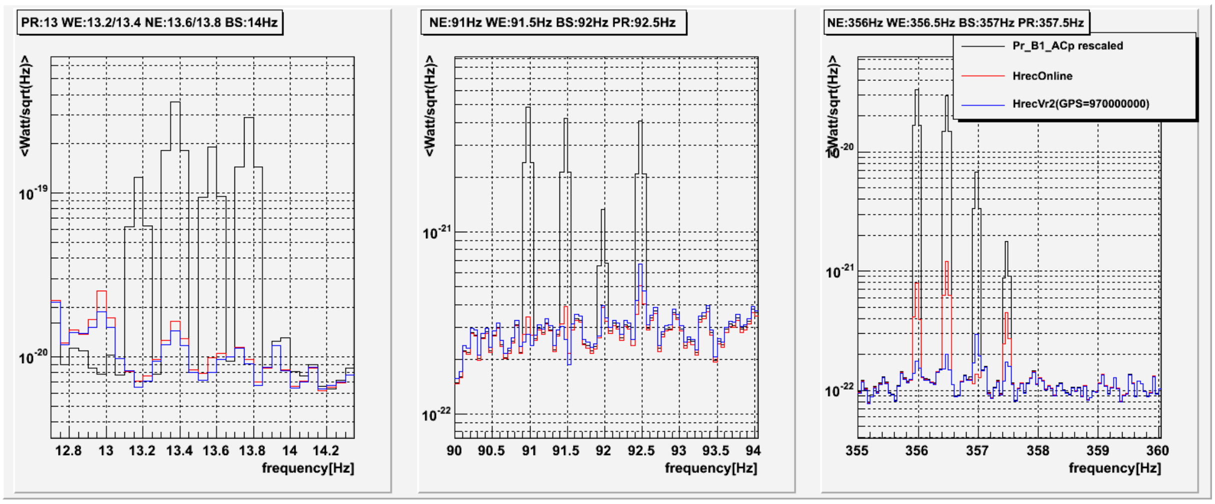


Figure 13 Calibration lines in the dark fringe signal (black curve) compared to the amplitude of the h(t) HrecOnline (red curve) and HrecV2 (blue curve). The Pr_B1_ACp spectrum have been rescaled to the match the noise floor level of the h(t) spectrum.

A good cancelation of the 90 Hz lines is an indication that the models are correct in the frequency band of the reconstruction. On can see that the lines cancelation has been improved in HrecV2 compared to HrecOnline.

5 Comparing HrecOnline to HrecV2

Section 2 describes the differences in the processing between HrecOnline and HrecV2: ignoring quality flags and glitches corrections, there has been three periods for HrecOnline due to the two changes for HrecOnline during VSR3:

- September 3rd 2010: Fix (increase) the actuator gains by 33%
- September 10th 2010: Fix the marionetta model

5.1 hrec/hinj test for HrecOnline

The Figure 14 shows the hrec/hinj test for HrecOnline averaged with the weekly data after Sept 10th 2010. Errors below 200 Hz are much larger than for the HrecV2 version (see Figure 7). Also, the amplitude of the wiggles below 200 Hz varies with time since they depend on the actual finesse value wrt to the fixed value of 150 used in hrec online.

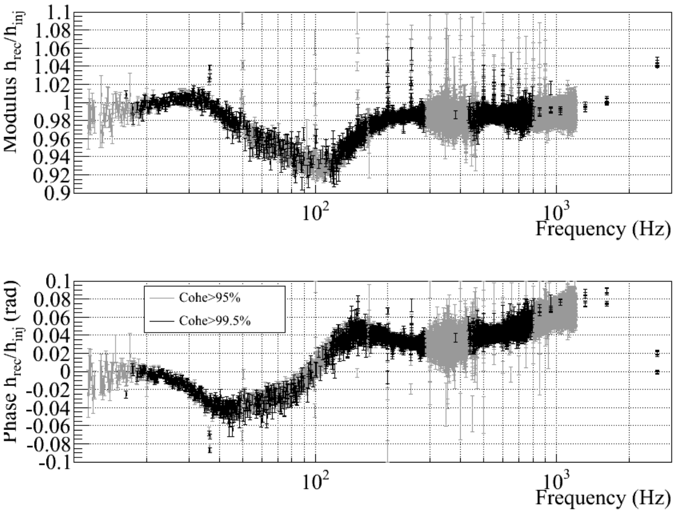


Figure 14 Check of HrecOnline using WE injections from Sep 10th 2010 to the end of the run (before that date, there was a too much bias).

5.2 Spectrum change from HrecOnline to HrecV2

Figure 15, Figure 16 and Figure 17 present the typical differences between HrecOnline and HrecV2 for the 3 periods. Similar plots measured during weekly calibrations periods are given in appendix.

The top left plots is the ratio of the h(t) HrecOnline spectrum to the h(t) HrecV2 spectrum. The main differences are:

- Before September 3rd: the 33% miss-scaling in Figure 15, due to the change in the actuator model. Other effects are similar are between Sept 3rd and 10th:
- Sept 3rd to Sept 10th: below ~200 Hz, up to 10% frequency-dependent scaling differences and up to 100 mrad frequency-dependent phase differences due to the use of a fixed finesse in HrecOnline. These effects have some variations since the finesse variations were not monitored in HrecOnline. At high frequency, 3 µs difference in timing. Extra-noise in HrecOnline compared to HrecV2 due to the use of an old model for the marionette actuation.

- After Sept 10th: similar differences as in the previous period, but no more extra-noise in HrecOnline wrt HrecV2 since the correct marionetta models were used.

The phase difference being close to 0 indicates that both versions of h(t) have the same sign.

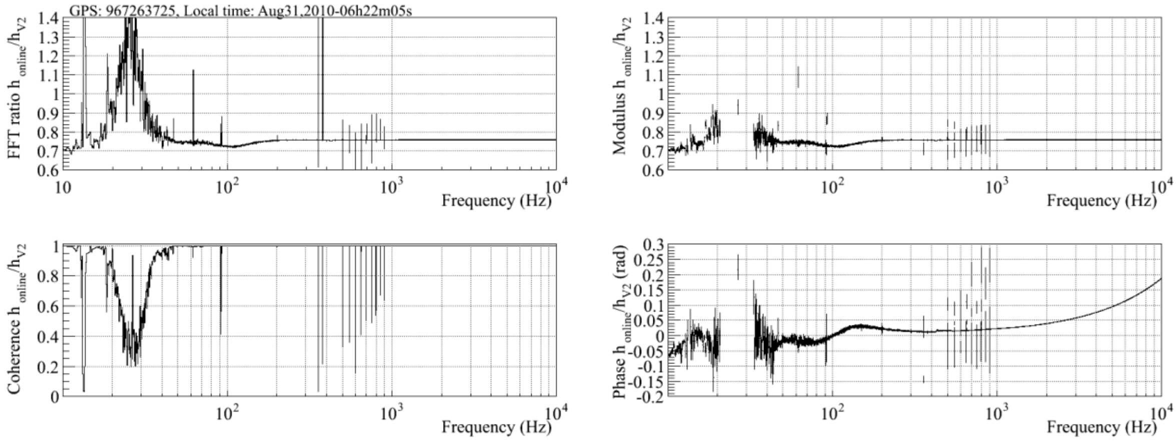


Figure 15 HrecOnline compared to HrecV2 before August 31

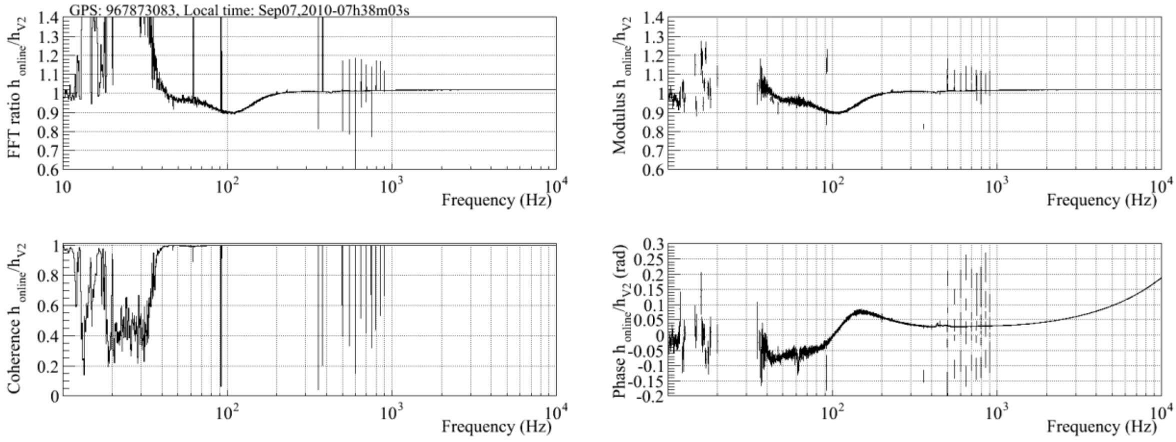


Figure 16 HrecOnline compared to HrecV2 on September 7

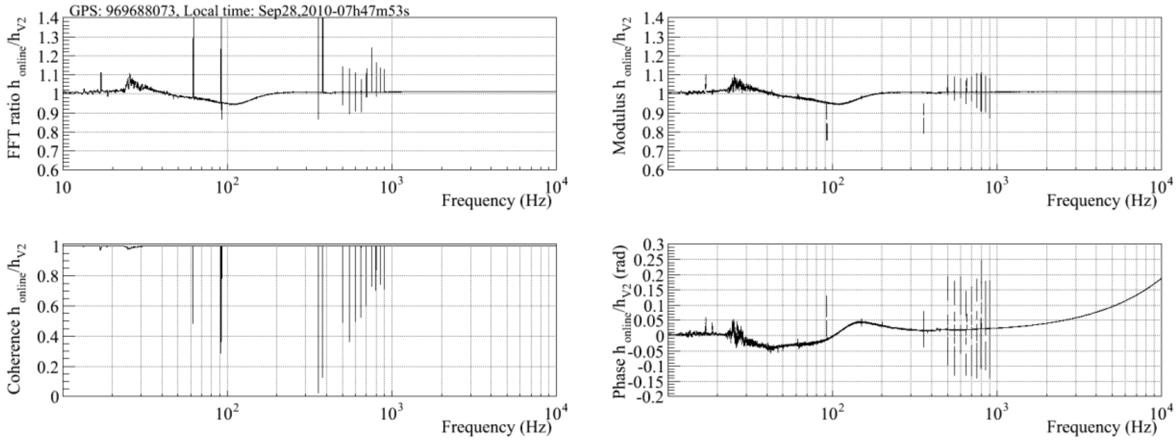


Figure 17 HrecOnline compared to HrecV2 on September 28

5.3 Inspiral horizon change from HrecOnline to HrecV2

Another way to quantify the change of the noise level is to look for the differences of the horizons computed by HrecOnline and HrecV2. As it can be seen in the Figure 18, the main difference is due to the wrong actuation gain for the beginning of the run which introduced the 33% overestimation of the online horizon. For the remaining part of the run, this difference is (0.1 Mpc)/(5.0 Mpc) = 2%.

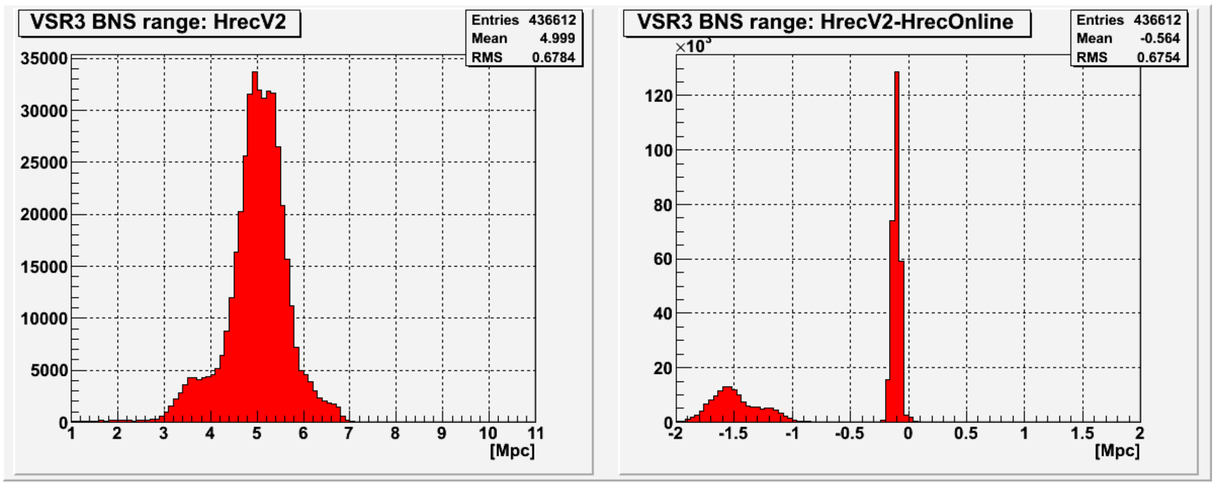


Figure 18 BNS inspiral range: left distribution for the full VSR3 run. The mean BNS range was 5.0Mpc. Right plot: difference between the HrecOnline and HrecV2 values.

6 Sign of h(t)

As for VSR1 and the definition of the sign of h(t) has been agreed between LIGO and Virgo: h(t) = (Lx-Ly)/L. For Virgo, Lx is the length of the north arm and Ly the length of the west arm. L is of course their average length, L = 3km for Virgo.

The method to check the sign of h(t) using the photon calibrator (PCal) is based on the fact that an optical power is always positive and therefore, by simply looking at the time series of the photon calibrator power on which a sine wave is injected and at the h(t) signal we can validated the sign of h(t).

The photon calibrator is installed on the north input tower, pushing the mirror from the input of the cavity (i.e. from north to south). Therefore when the PCal power increases, we expect to increase the north (i.e. x) arm and therefore increase h(t). However, since we are injecting a sine wave well above the pendulum resonance, we expected that the response of the mirror be in opposition of phase compared to the injected signal. In other word, given the above definition of h(t), we expect that the observed h(t) signal should be in opposition of phase compared to the PCal power signal.

The sign of HrecOnline h(t) is first checked with this direct method in the time domain. For HrecV2, the method has been applied in the frequency domain.

6.1 HrecOnline

The version of the reconstruction used online during VSR3 has been started on August 2nd 2010 (logbook entry 27221). On August 3th afternoon, a single line at 11.1 Hz has been injected through the NI PCal, such that it is stronger than the h(t) noise amplitude at any frequency (see Figure 19) . It allows to see the effect of the PCal line directly in the h(t) time series. As expected, the h(t) times series is in phase opposition with respect to the PCal laser power (right plot). It confirms that the sign of h(t) (HrecOnline) fulfils the above-mentioned definition.

Note that in the frequency domain, the measurement of the phase from Ca_NI_PCal to h_20000Hz gives -3.133 ± 0.008 rad, close to ±π as expected.

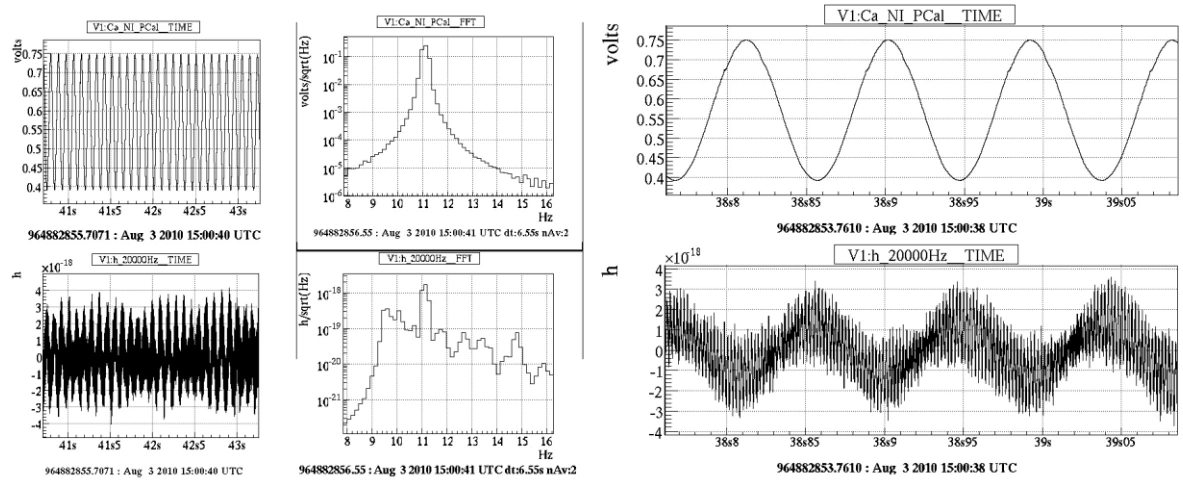


Figure 19: Checks of the sign of h(t) HrecOnline with the photon calibrator. Left: time series and amplitude spectrum of the injected PCal power (Ca_NI_PCal) and h(t) HrecOnline. Right: zoom on the time series. Data from August 3rd 2010.

6.2 HrecV2

The pre-VSR3 data used online to check the sign of h(t) in the above-section have not been saved properly. The post-VSR3 data with the 11.1 Hz PCal line are shown Figure 20: the low-frequency noise in h(t) being larger at that time, the 11.1 Hz PCal line is not strong enough to be well visible in the time series and check the h(t) sign directly.

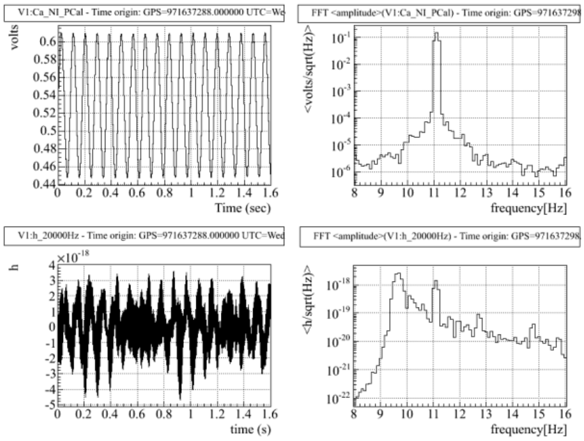


Figure 20: time series and amplitude spectrum of the injected PCal power (Ca_NI_PCal) and h(t) HrecOnline. Data from October 20th 2010.

The sign is thus checked applying the same method but in the frequency domain. An indirect check consists in comparing the sign of HrecV2 and HrecOnline.

6.2.1 Phase of HrecV2 h(t) with respect to the PCal signal

The same method as described above can be applied in the frequency domain: the phase of h(t) with respect to the power of the PCal is expected to be around ±π. The transfer function from Ca_NI_PCal to h_20000Hz has been computed at the time of the 11.1 Hz line PCal excitation. The phase is measured to -3.137 ± 0.008 rad, as expected. It confirms that the sign of h(t) HrecV2 is correct.

6.2.2 Sign of HrecV2 compared to the sign of HrecOnline

An an additional indirect check, the comparison of HrecV2 with HrecOnline is shown Figure 15, Figure 16Figure 17. The phase between both reconstructed h(t) is close to 0. It confirms that the sign of HrecV2 is the same as the sign of HrecOnline.

7 Systematic errors

7.1 Computing the systematic errors for HrecV2

The h(t) channel is obtained by a complex process of combining different channels. The direct propagation of the model/parameters uncertainties is difficult. Therefore a more global approach is used, based on the check of the recovery of the injections made with the out-of-loop coils (see section 4.1). The observed dispersion of the points on Figure 7 is therefore the starting point, on which we are adding the systematic error of the actuator model taken from the actuator calibration note (see page 61 of VIR-0610A-10).

However, this approach works only below 1 kHz when the actuator model is well known. Above this frequency, the control signals contribute to less than 0.5% to h(t) (see Figure 2, right plots). Therefore, in this high frequency band, the systematic error is coming only from the sensing model (see again page 61 of VIR-0610A-10), the uncertainty on the optical gain, and the uncertainty on the optical model (the simple cavity model) which is small since we are well above the cavity pole. The Figure 21 shows the typical statistical fluctuations on the finesse measurement: 0.30 for a finesse of about 142 (a relative error of 0.2%).

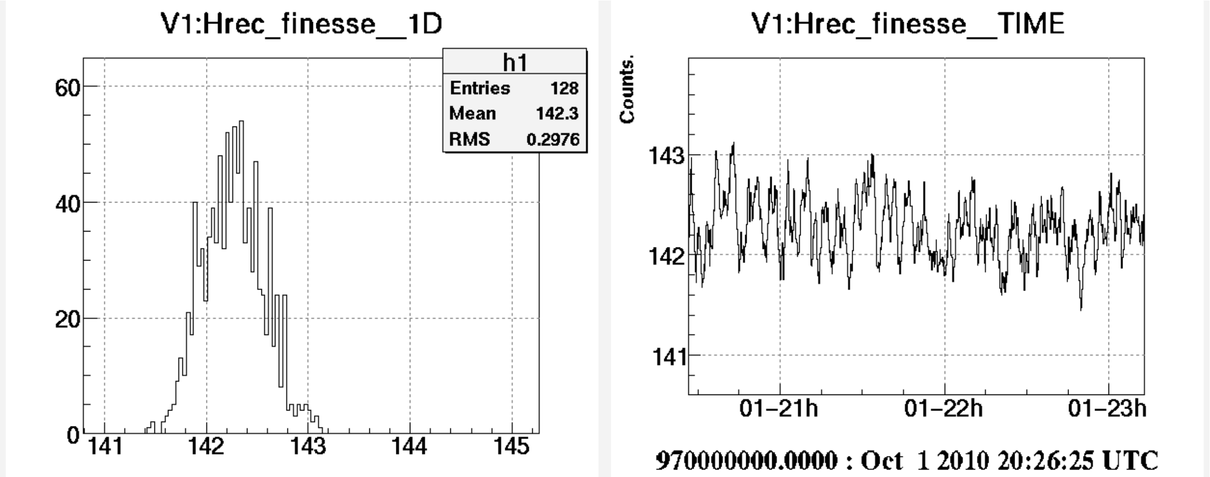


Figure 21 Typical fluctuations of the finesse measurement

7.1.1 Amplitude error for HrecV2

Below 1 kHz, the amplitude ratio on Figure 7 is within 2.5%. The systematic error of the actuation model is 3% plus 1% and 0.3% statistical errors (see table on page 61 of VIR-0610A-10). Therefore, below 1 kHz, the systematic error on the h(t) amplitude is $2.5+\mathrm{sqrt}(3^2+1^2+0.3^2)=5.7\%$ which is rounded to 6%.

Above 1 kHz the systematic error is coming from:

- The optical gain, which is known to better than $1+\mathrm{sqrt}(3^2+1^2+.3^2)=4.2\%$. The 1% is given by the SNR of the calibration line amplitude which is larger than 100 and the rest by the actuator absolute calibration.
- The electronic response in the 1-10 kHz band is flat within better than 1% since we are far away from any analog filtering (the first analog filter, for the ADC analog anti-aliasing filter is at 150 kHz).
- The uncertainty due the optical model is given by the fluctuations of the cavity finesse, typically 0.2% (see Figure 21) which translates to the same amount on the amplitude

error above the cavity pole. Therefore we use a conservative 0.5% error for the model uncertainty.

Adding up all together we get for the h(t) amplitude systematic error is 4.2+1+0.5=5.7%, rounded to 6% above 1 kHz, like below 1 kHz.

7.1.2 *Absolute phase or timing for HrecV2*

We have three different frequency bands:

- **Below 500 Hz**: Figure 7 indicates that we get the correct phase within 30 mrad. From the table on page 61 of VIR-0610A-10, the statistical error of the model is sqrt(10^2+3^2)~10 mrad, and the systematic errors are 3+1+4=8µs. This gives a total of 30+10+8x2πf = 40+50*f mrad, with f the frequency given in kHz. This translates to 65 mrad at 500 Hz.
- **Between 500 Hz and 1 kHz**: Figure 7 indicates that we get the correct phase within 9.5 µs. If we add linearly the systematic errors of the model, we get 10+(9.5+8)x2πf = 10+110*f mrad, with again the frequency f given in kHz.
- **Above 1 kHz**, the sensing systematic error is 4 µs. Since we added 3 µs as systematic offset when doing the reconstruction, the overall systematic timing error is 4+3=7 µs above 1 kHz. The model uncertainty could be neglected since at 1 kHz, the 0.2% change of the finesse induces a 0.15µs timing change. However, this systematic error is less than the one obtained with the actuator check below 1 kHz. Therefore, to insure the continuity of the error across frequency and to be conservative, we get a fixed 10+110*1=120 mrad error from 1 kHz up to 2.7 kHz where to error becomes 7 µs.

7.2 Computing the systematic errors for HrecOnline

The systematic error on HrecOnline is computed by taking the systematic error on HrecV2, and then adding the observed difference between HrecOnline and HrecV2 described in the Section 5.

The errors estimated for the three periods of HrecOnline are:

- Before September 3rd: the validity range is starting only at 40 Hz. Lower frequency band should be ignored since it contains extra noise and has some significant bias.
    - Above 40 Hz, HrecOnline is underestimated by a factor 1.33. Up to 200 Hz, the relative fluctuations of the HrecOnline/HrecV2 transfer function are less than 10%. This gives 10+6=16% systematic errors on HrecOnline over the whole frequency band. Above 200 Hz, there is a much better agreement between HrecOnline and HrecV2, typically 2% and therefore the error is 2+6=8% above this frequency.
    - For the phase, the differences between HrecOnline and HrecV2 are less than 100 mrad up to 200 Hz, then they go down and at high frequency where the difference is primarily the 3µs offset which has been added in HrecV2. A conservative way to combine this observation with the HrecV2 error is to use a 140 mrad systematic error below 2.2 kHz and 10 µs above.
- From September 3rd to September 10th: the situation is the same as the previous one, except that there is not the 1.33 scaling factor.
- After September 10th, the low frequency part has been fixed. The difference between HrecOnline and HrecV2 are similar to what was observed previously above 40 Hz. Therefore we can state that the systematic errors are:
    - Amplitude: 16% below 200 Hz and 8% above.
    - Phase: 140 mrad below 2.2 kHz and 10 µs above.

[3]

8 Summary: validity range and errors

The h(t) **HrecV2** version has been produced for VSR3, from 965580000 (Aug11, 16:39:45 UTC) to 971558000 (Oct19, 21:13:05 UTC).

The h(t) channel is valid from 10 Hz up to the Nyquist frequency of the channel used, i.e. up to 2048, 8192 or 10000Hz.

In this validity range, the systematic error on the h(t) amplitude is 6%. The systematic error on the h(t) phase/absolute timing has a more complex dependence (see Figure 22: Frequency-dependent error on the phase of h(t) are shown in the Figure 22:

- Below 500 Hz: 40+ 50*f mrad, with f the frequency expressed in kHz.
- From 500 Hz to 1 kHz: 10+110*f mrad (f in kHz).
- From 1 kHz to 2.8 kHz: 120 mrad
- Above 2.8 kHz: 7µs.

The errors estimated for **HrecOnline** are:

- Amplitude: 16% below 200 Hz and 8% above.
- Phase: 140 mrad below 2.2 kHz and 10 µs above (see Figure 22).

Before September 3rd 2010, a systematic scaling factor of 1.33 must be added and the validity range starts at 40 Hz only.
After September 3rd, the validity range starts at 10 Hz.

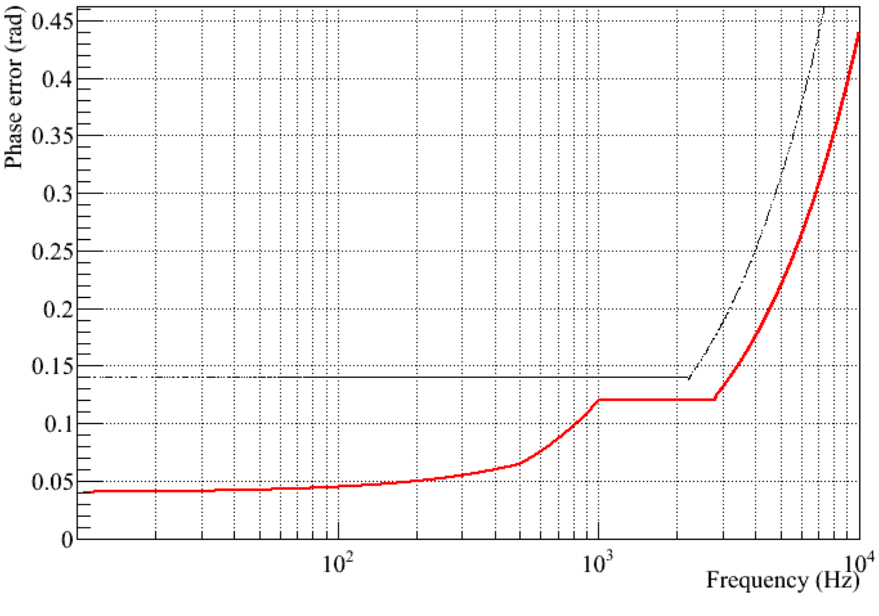
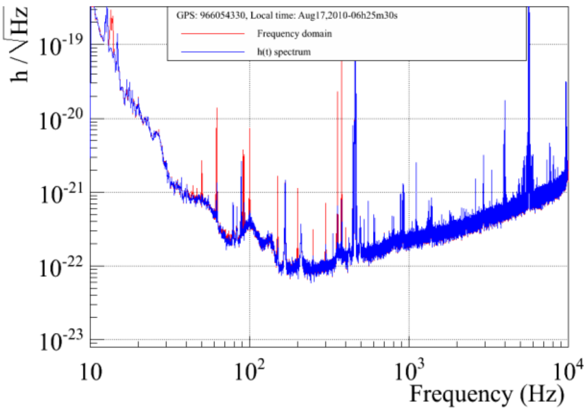
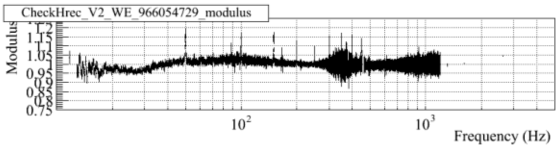


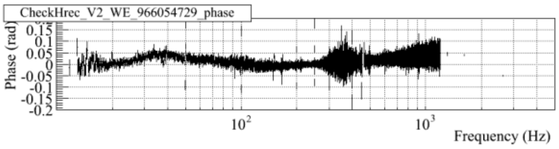
Figure 22: Frequency-dependent error on the phase of h(t). Thin dotted black line: HrecOnline; bold continuous red line: HrecV2.

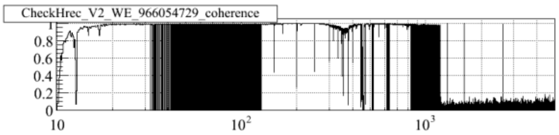
Appendix: Weekly calibration checks of HrecV2

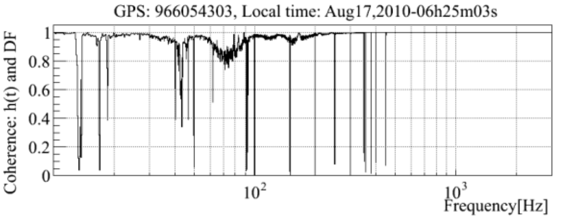
The following figures present the results of the checks made during the weekly calibration periods.

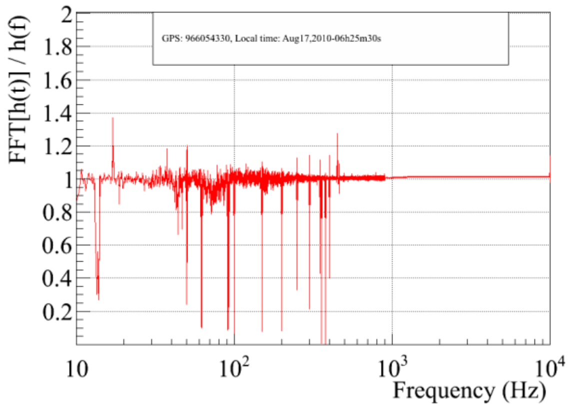


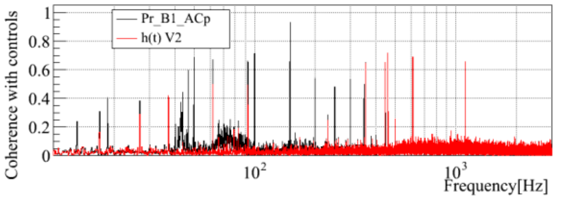


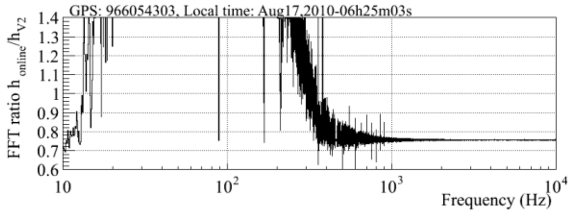


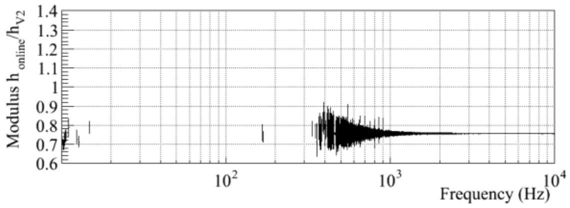


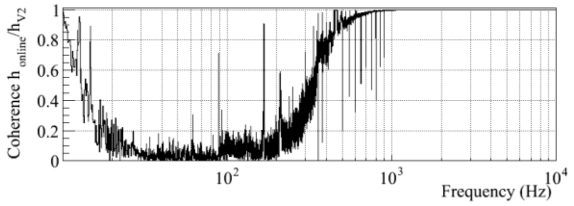


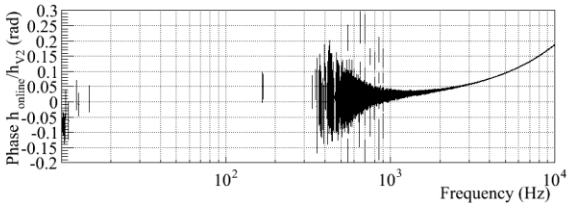




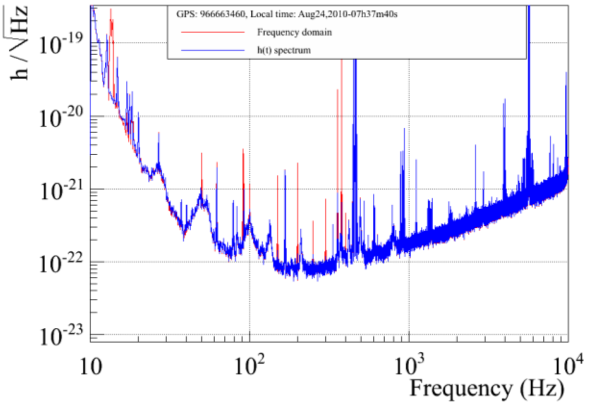


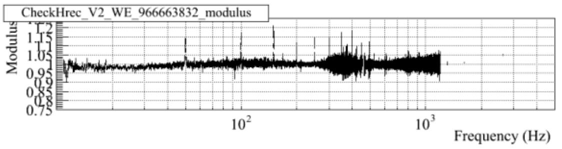


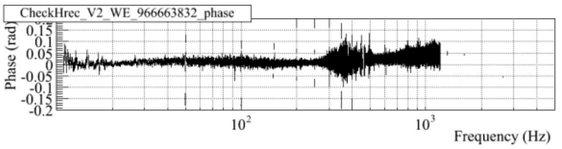


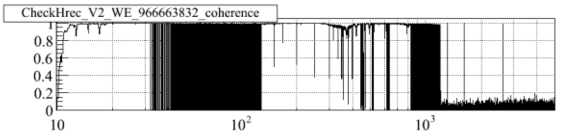


3


GPS: 966663460, Local time: Aug24,2010-07h37m40s
Frequency domain
h(t) spectrum
h / √Hz
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10
10^2
10^3
10^4
Frequency (Hz)


CheckHrec_V2_WE_966663832_modulus
Modulus
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
10^2
10^3
Frequency (Hz)


CheckHrec_V2_WE_966663832_phase
Phase (rad)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
10^2
10^3
Frequency (Hz)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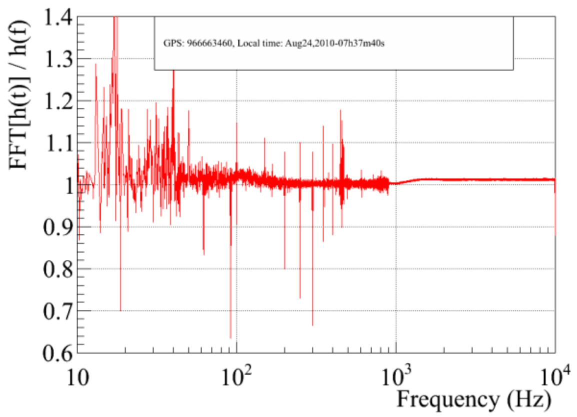
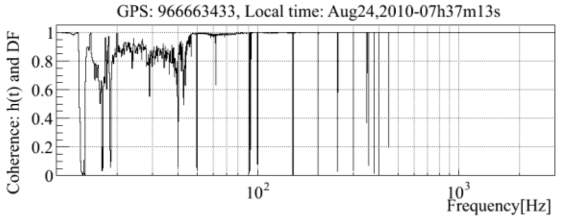
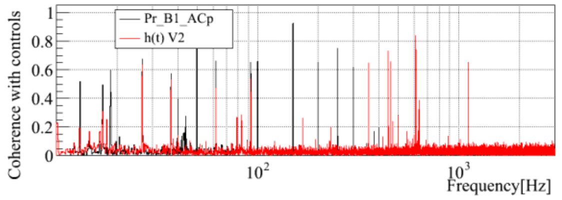
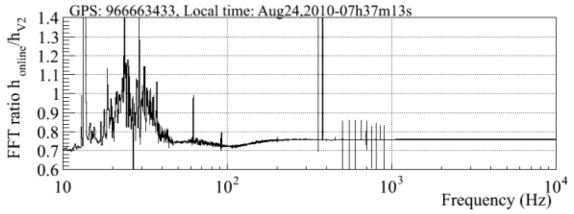
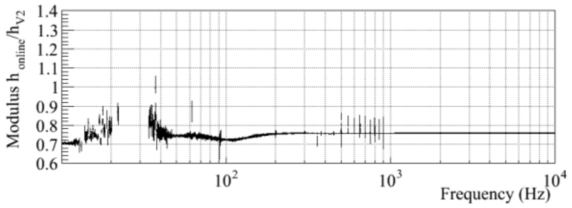
1
0.8
0.6
0.4
0.2
0
10
10^2
10^3

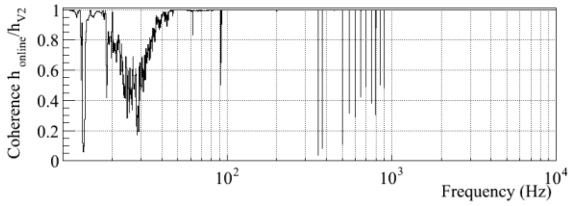

GPS: 966663460, Local time: Aug24,2010-07h37m40s
FFT[h(t)] / h(f)
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
10
10^2
10^3
10^4
Frequency (Hz)

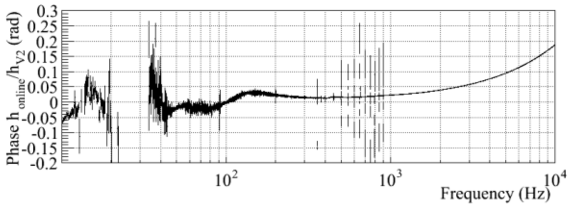

GPS: 966663433, Local time: Aug24,2010-07h37m13s
Coherence: h(t) and DF
1
0.8
0.6
0.4
0.2
0
10^2
10^3
Frequency[Hz]


Pr_B1_ACp
h(t) V2
Coherence with controls
1
0.8
0.6
0.4
0.2
0
10^2
10^3
Frequency[Hz]

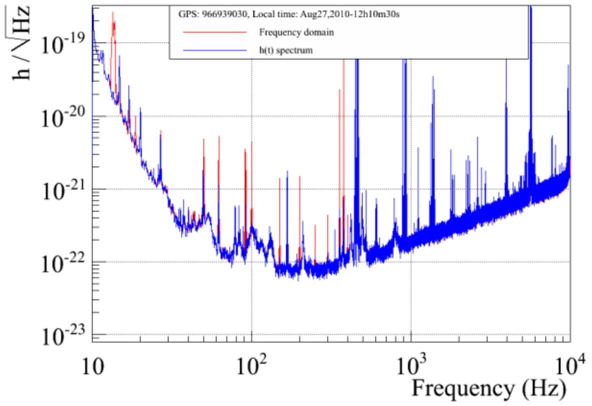

GPS: 966663433, Local time: Aug24,2010-07h37m13s
FFT ratio h_{online}/h_{V2}
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
10
10^2
10^3
10^4
Frequency (Hz)

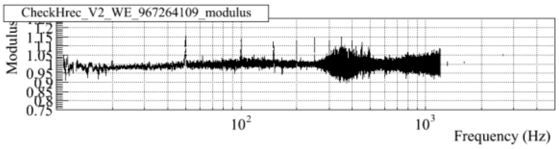

Modulus h_{online}/h_{V2}
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
10^2
10^3
10^4
Frequency (Hz)


Coherence h_{online}/h_{V2}
1
0.8
0.6
0.4
0.2
0
10^2
10^3
10^4
Frequency (Hz)


Phase h_{online}/h_{V2} (rad)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
10^2
10^3
10^4
Frequency (Hz)

3


GPS: 966939030, Local time: Aug27,2010-12h10m30s
Frequency domain
h(t) spectrum
h / √Hz
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10
10^2
10^3
10^4
Frequency (Hz)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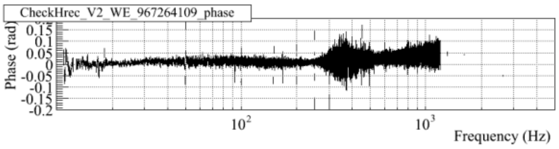
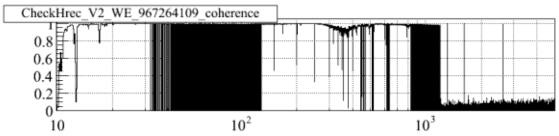
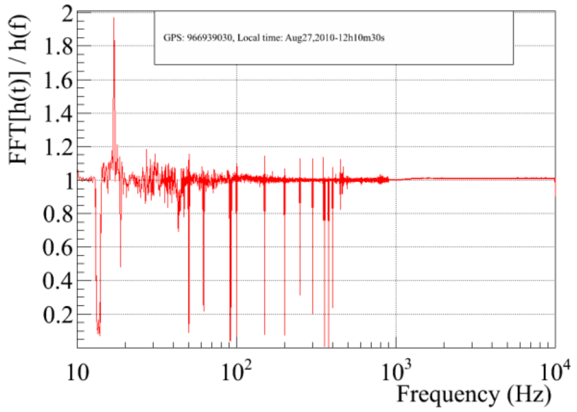
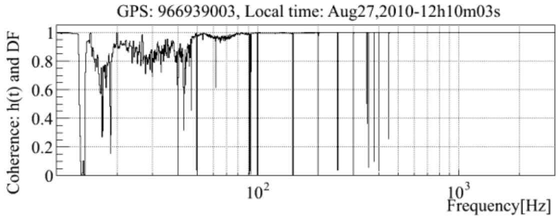
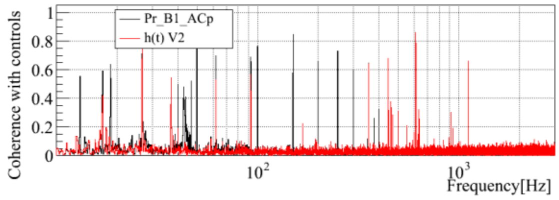
Modulus
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
10^2
10^3
Frequency (Hz)

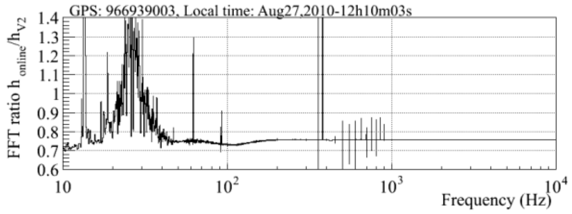

CheckHrec_V2_WE_967264109_phase
Phase (rad)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
10^2
10^3
Frequency (Hz)

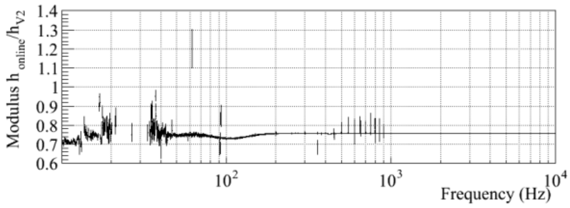

CheckHrec_V2_WE_967264109_coherence
1
0.8
0.6
0.4
0.2
0
10
10^2
10^3

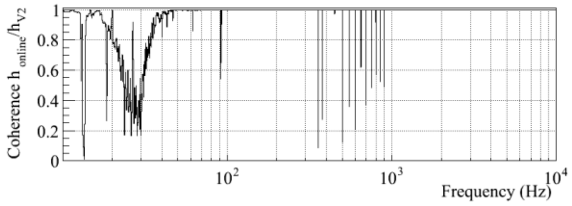

GPS: 966939030, Local time: Aug27,2010-12h10m30s
FFT[h(t)] / h(f)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
10
10^2
10^3
10^4
Frequency (Hz)

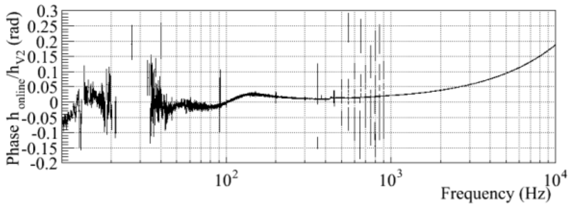

GPS: 966939003, Local time: Aug27,2010-12h10m03s
Coherence: h(t) and DF
1
0.8
0.6
0.4
0.2
0
10^2
10^3
Frequency[Hz]


Pr_B1_ACp
h(t) V2
Coherence with controls
1
0.8
0.6
0.4
0.2
0
10^2
10^3
Frequency[Hz]

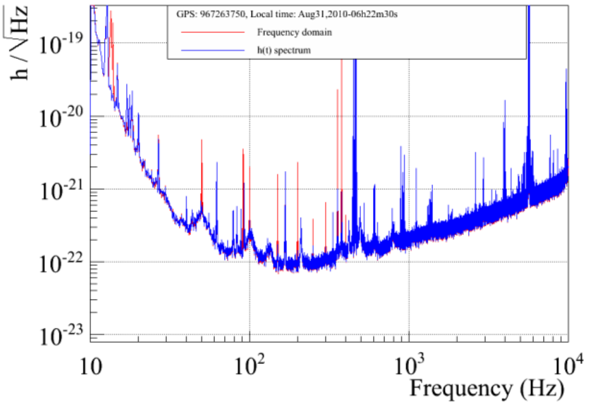

GPS: 966939003, Local time: Aug27,2010-12h10m03s
FFT ratio h_{online}/h_{V2}
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
10
10^2
10^3
10^4
Frequency (Hz)

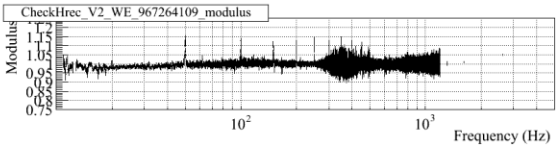

Modulus h_{online}/h_{V2}
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
10^2
10^3
10^4
Frequency (Hz)

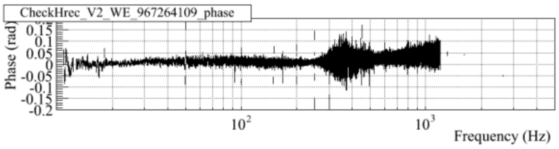

Coherence h_{online}/h_{V2}
1
0.8
0.6
0.4
0.2
0
10^2
10^3
10^4
Frequency (Hz)

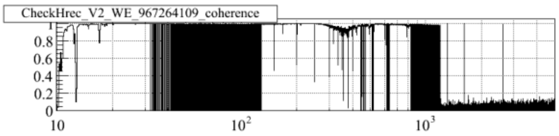

Phase h_{online}/h_{V2} (rad)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
10^2
10^3
10^4
Frequency (Hz)

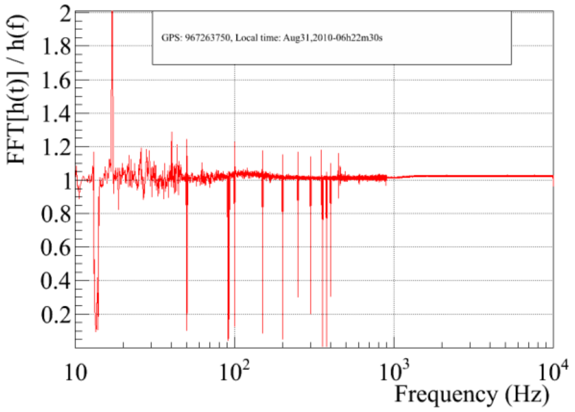
3

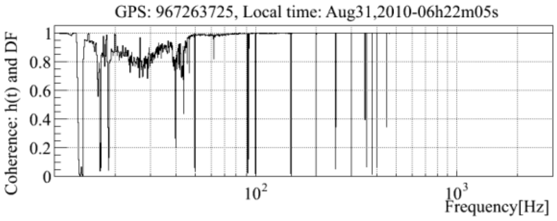

GPS: 967263750, Local time: Aug31,2010-06h22m30s
Frequency domain
h(t) spectrum
$h/\sqrt{Hz}$
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10
10^2
10^3
10^4
Frequency (Hz)

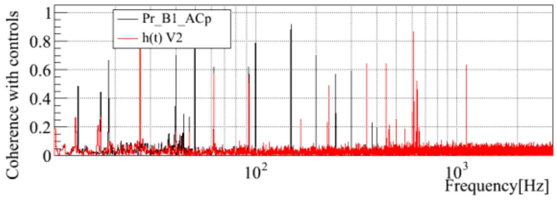

CheckHrec_V2_WE_967264109_modulus
Modulus
10^2
10^3
Frequency (Hz)

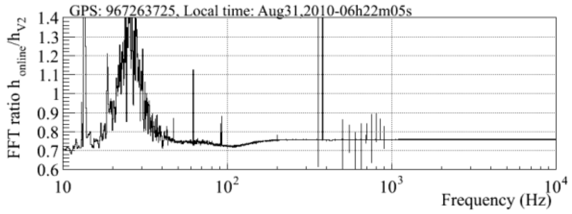

CheckHrec_V2_WE_967264109_phase
Phase (rad)
10^2
10^3
Frequency (Hz)

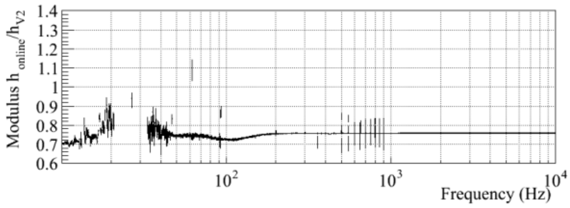

CheckHrec_V2_WE_967264109_coherence
10
10^2
10^3

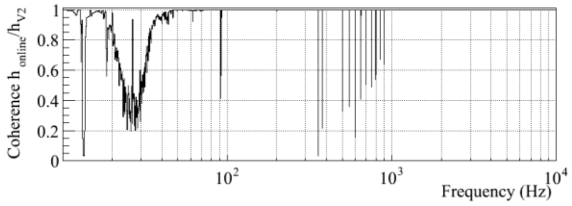

GPS: 967263750, Local time: Aug31,2010-06h22m30s
FFT[h(t)] / h(f)
10
10^2
10^3
10^4
Frequency (Hz)

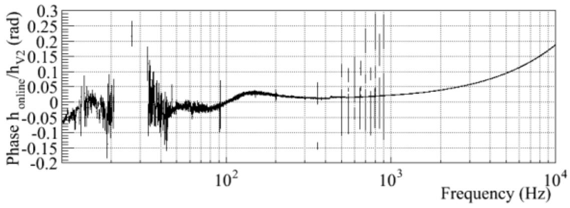

GPS: 967263725, Local time: Aug31,2010-06h22m05s
Coherence: h(t) and DF
10^2
10^3
Frequency[Hz]


Coherence with controls
Pr_B1_ACp
h(t) V2
10^2
10^3
Frequency[Hz]

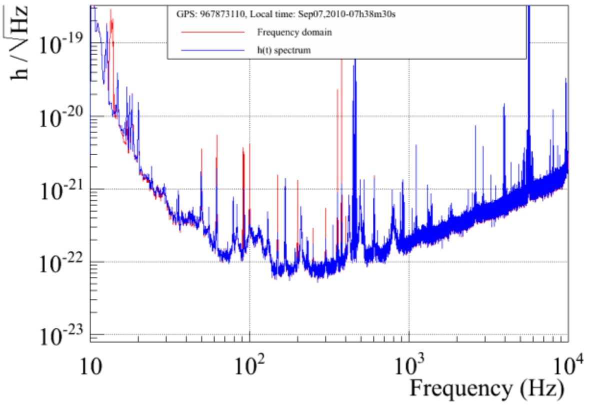

GPS: 967263725, Local time: Aug31,2010-06h22m05s
FFT ratio h_{online}/h_{V2}
10
10^2
10^3
10^4
Frequency (Hz)

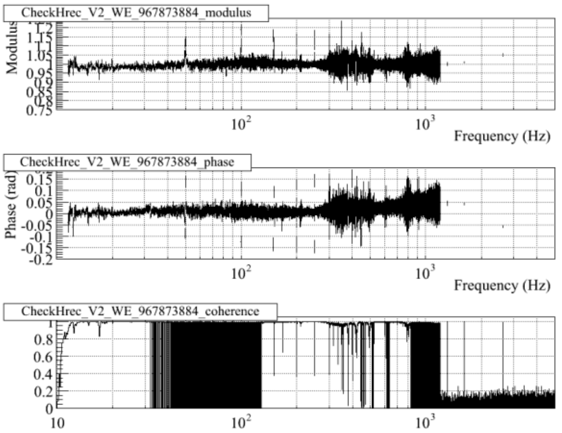

Modulus h_{online}/h_{V2}
10^2
10^3
10^4
Frequency (Hz)

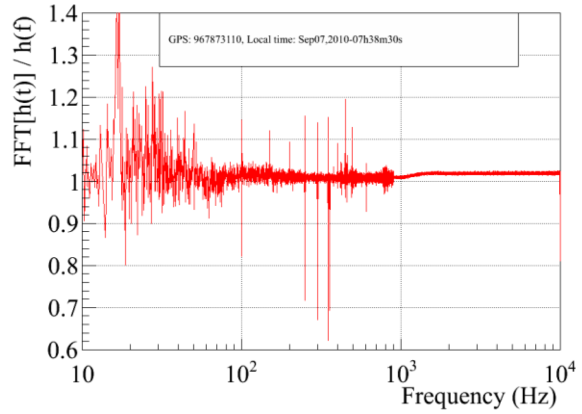

Coherence h_{online}/h_{V2}
10^2
10^3
10^4
Frequency (Hz)

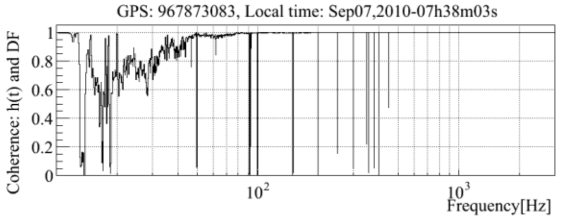

Phase h_{online}/h_{V2} (rad)
10^2
10^3
10^4
Frequency (Hz)

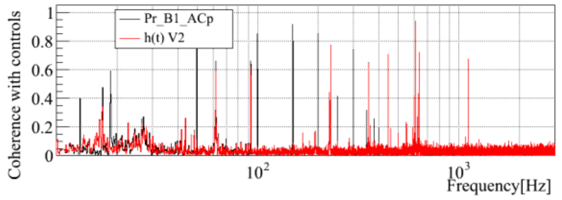
3

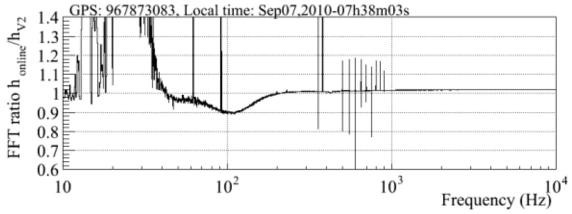

GPS: 967873110, Local time: Sep07,2010-07h38m30s
Frequency domain
h(t) spectrum
h / √Hz
10^-19
10^-20
10^-21
10^-22
10^-23
10
10^2
10^3
10^4
Frequency (Hz)

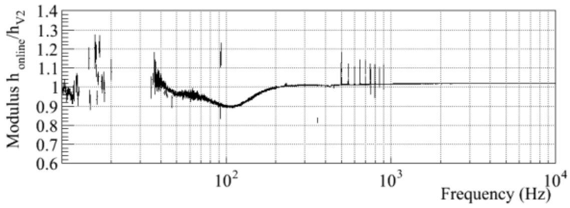

CheckHrec_V2_WE_967873884_modulus
Modulus
Frequency (Hz)
CheckHrec_V2_WE_967873884_phase
Phase (rad)
Frequency (Hz)
CheckHrec_V2_WE_967873884_coherence
10
10^2
10^3

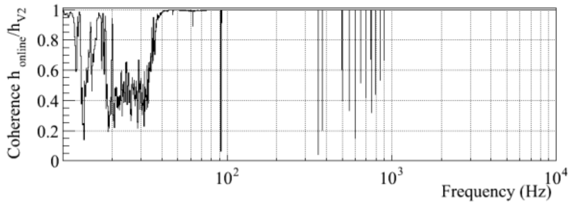

GPS: 967873110, Local time: Sep07,2010-07h38m30s
FFT[h(t)] / h(f)
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
10
10^2
10^3
10^4
Frequency (Hz)

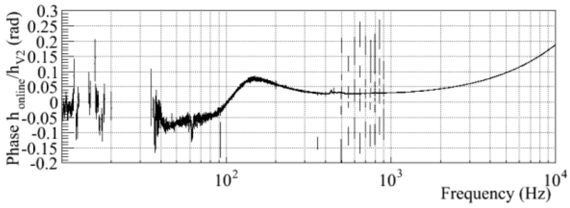

GPS: 967873083, Local time: Sep07,2010-07h38m03s
Coherence: h(t) and DF
10^2
10^3
Frequency[Hz]


Pr_B1_ACp
h(t) V2
Coherence with controls
10^2
10^3
Frequency[Hz]

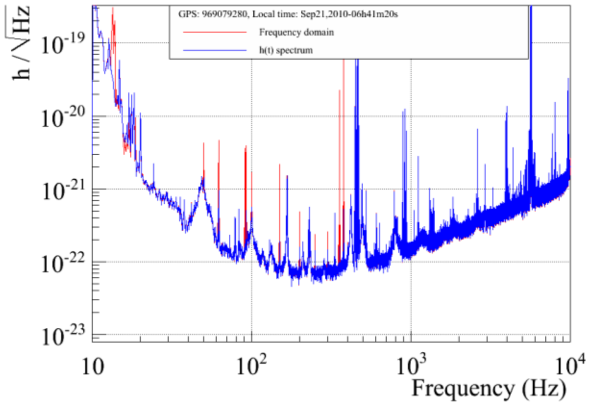

GPS: 967873083, Local time: Sep07,2010-07h38m03s
FFT ratio h_online/h_V2
10
10^2
10^3
10^4
Frequency (Hz)

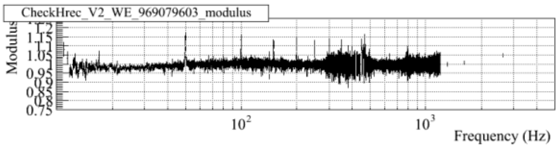

Modulus h_online/h_V2
10^2
10^3
10^4
Frequency (Hz)

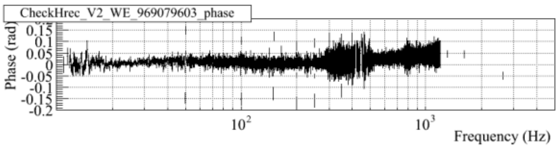

Coherence h_online/h_V2
10^2
10^3
10^4
Frequency (Hz)

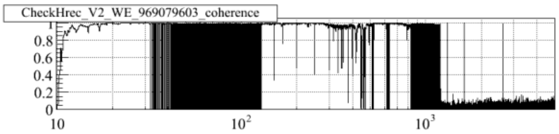

Phase h_online/h_V2 (rad)
10^2
10^3
10^4
Frequency (Hz)

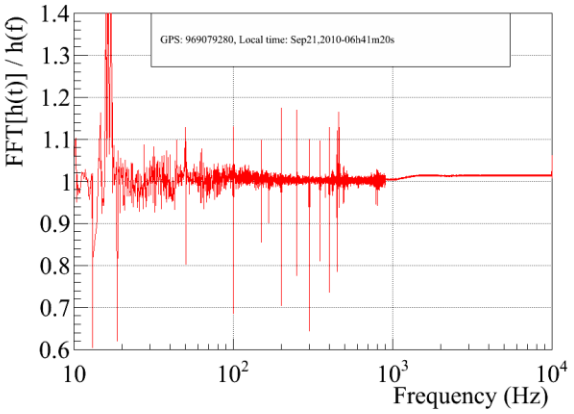
3

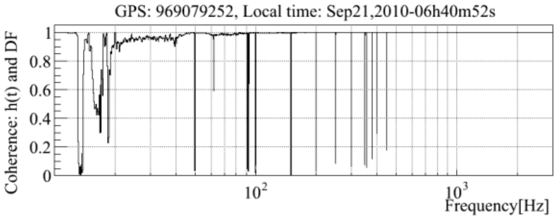

GPS: 969079280, Local time: Sep21,2010-06h41m20s
Frequency domain
h(t) spectrum
h / √Hz
10^-19
10^-20
10^-21
10^-22
10^-23
10
10^2
10^3
10^4
Frequency (Hz)

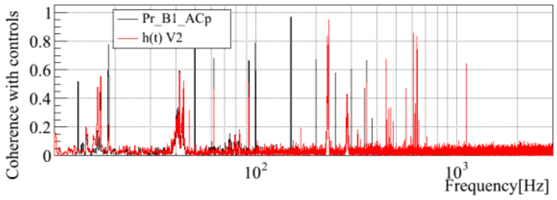

CheckHrec_V2_WE_969079603_modulus
Modulus
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
10^2
10^3
Frequency (Hz)

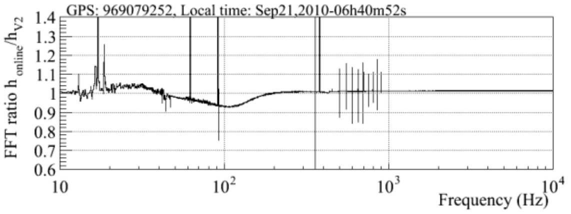

CheckHrec_V2_WE_969079603_phase
Phase (rad)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
10^2
10^3
Frequency (Hz)

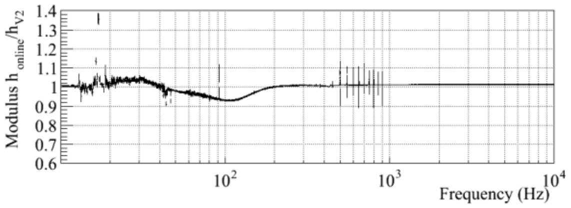

CheckHrec_V2_WE_969079603_coherence
1
0.8
0.6
0.4
0.2
0
10
10^2
10^3

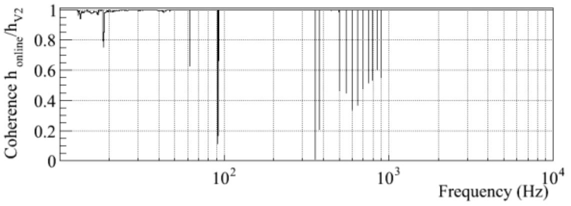

GPS: 969079280, Local time: Sep21,2010-06h41m20s
FFT[h(t)] / h(f)
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
10
10^2
10^3
10^4
Frequency (Hz)

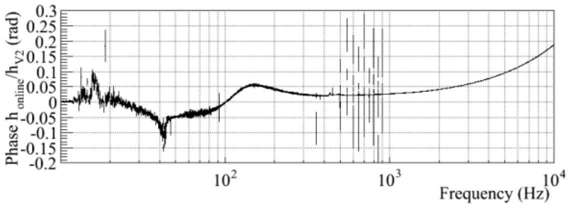

GPS: 969079252, Local time: Sep21,2010-06h40m52s
Coherence: h(t) and DF
1
0.8
0.6
0.4
0.2
0
10^2
10^3
Frequency[Hz]


Pr_B1_ACp
h(t) V2
Coherence with controls
1
0.8
0.6
0.4
0.2
0
10^2
10^3
Frequency[Hz]

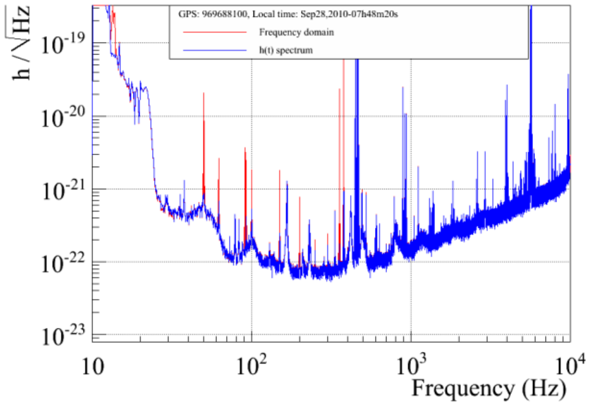

GPS: 969079252, Local time: Sep21,2010-06h40m52s
FFT ratio h_online/h_V2
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
10
10^2
10^3
10^4
Frequency (Hz)

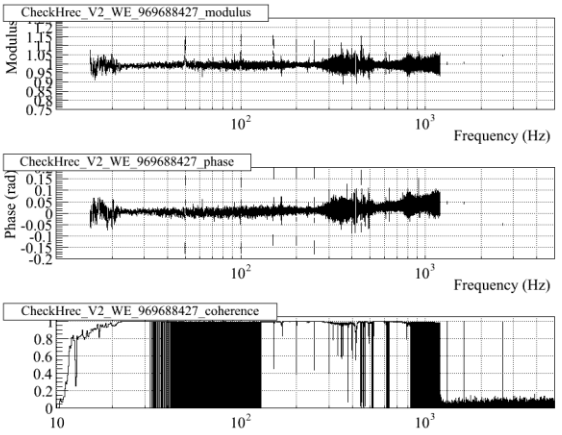

Modulus h_online/h_V2
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
10^2
10^3
10^4
Frequency (Hz)

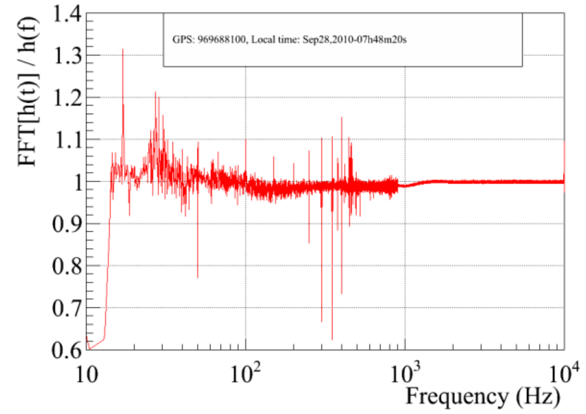

Coherence h_online/h_V2
1
0.8
0.6
0.4
0.2
0
10^2
10^3
10^4
Frequency (Hz)

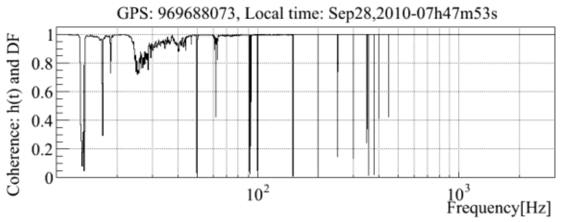

Phase h_online/h_V2 (rad)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
10^2
10^3
10^4
Frequency (Hz)

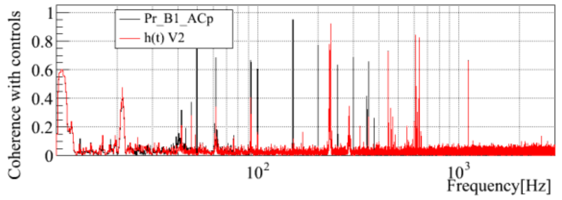
3

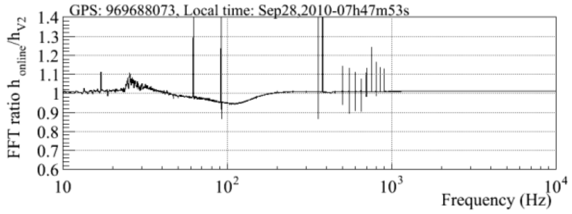

GPS: 969688100, Local time: Sep28,2010-07h48m20s
Frequency domain
h(t) spectrum
$h / \sqrt{Hz}$
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10
10^2
10^3
10^4
Frequency (Hz)

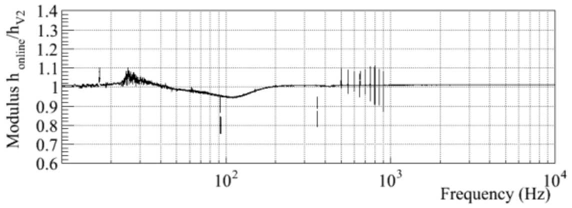

CheckHrec_V2_WE_969688427_modulus
Modulus
Frequency (Hz)
CheckHrec_V2_WE_969688427_phase
Phase (rad)
Frequency (Hz)
CheckHrec_V2_WE_969688427_coherence
10
10^2
10^3

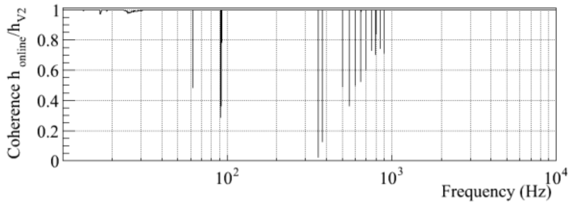

GPS: 969688100, Local time: Sep28,2010-07h48m20s
FFT[h(t)] / h(f)
10
10^2
10^3
10^4
Frequency (Hz)

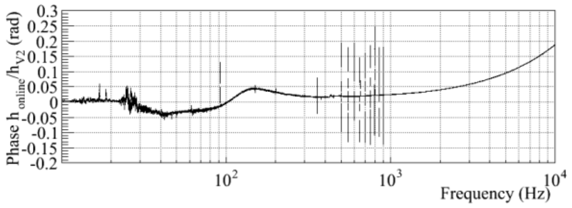

GPS: 969688073, Local time: Sep28,2010-07h47m53s
Coherence: h(t) and DF
10^2
10^3
Frequency[Hz]


Pr_B1_ACp
h(t) V2
Coherence with controls
10^2
10^3
Frequency[Hz]

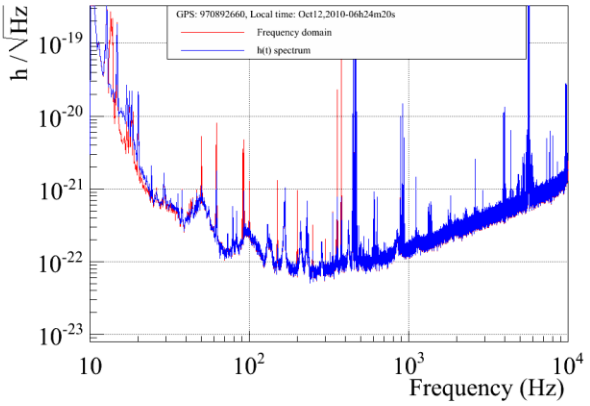

GPS: 969688073, Local time: Sep28,2010-07h47m53s
FFT ratio h_{online}/h_{V2}
10
10^2
10^3
10^4
Frequency (Hz)

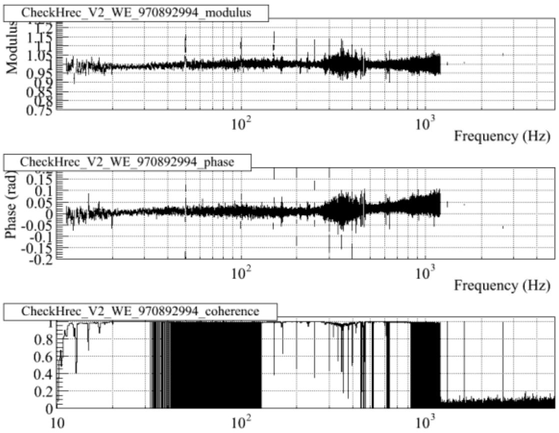

Modulus h_{online}/h_{V2}
10^2
10^3
10^4
Frequency (Hz)

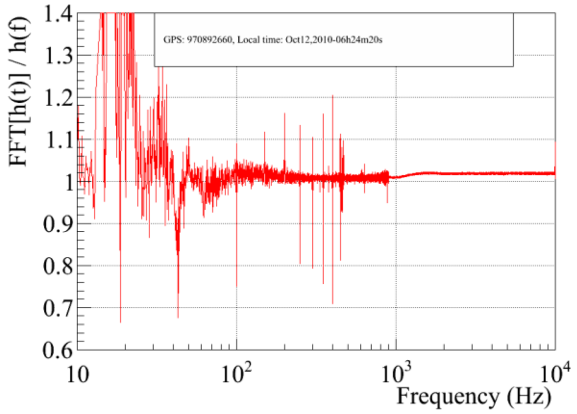

Coherence h_{online}/h_{V2}
10^2
10^3
10^4
Frequency (Hz)

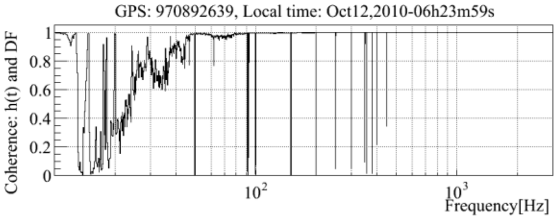

Phase h_{online}/h_{V2} (rad)
10^2
10^3
10^4
Frequency (Hz)

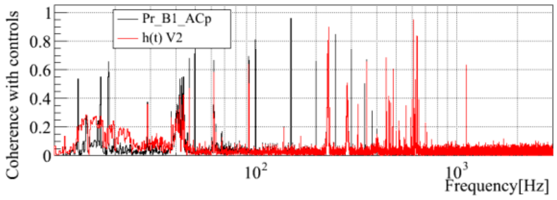
3

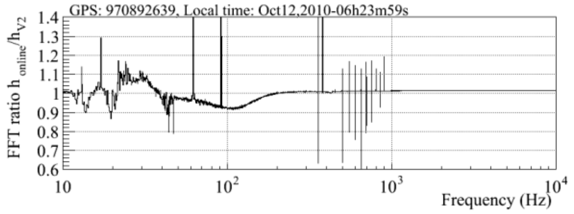

GPS: 970892660, Local time: Oct12,2010-06h24m20s
Frequency domain
h(t) spectrum
h / √Hz
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10
10^2
10^3
10^4
Frequency (Hz)

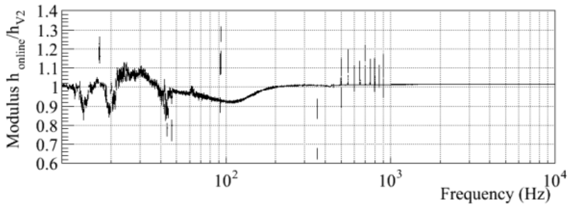

CheckHrec_V2_WE_970892994_modulus
Modulus
1.2
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
10^2
10^3
Frequency (Hz)
CheckHrec_V2_WE_970892994_phase
Phase (rad)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
10^2
10^3
Frequency (Hz)
CheckHrec_V2_WE_970892994_coherence
1
0.8
0.6
0.4
0.2
0
10
10^2
10^3

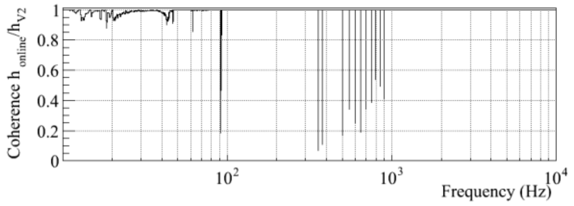

GPS: 970892660, Local time: Oct12,2010-06h24m20s
FFT[h(t)] / h(f)
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
10
10^2
10^3
10^4
Frequency (Hz)

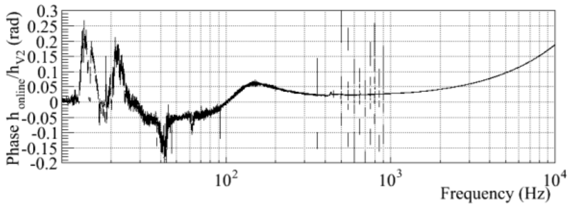

GPS: 970892639, Local time: Oct12,2010-06h23m59s
Coherence: h(t) and DF
1
0.8
0.6
0.4
0.2
0
10^2
10^3
Frequency[Hz]


Coherence with controls
Pr_B1_ACp
h(t) V2
1
0.8
0.6
0.4
0.2
0
10^2
10^3
Frequency[Hz]


GPS: 970892639, Local time: Oct12,2010-06h23m59s
FFT ratio h_{online}/h_{V2}
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
10
10^2
10^3
10^4
Frequency (Hz)


Modulus h_{online}/h_{V2}
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
10^2
10^3
10^4
Frequency (Hz)


Coherence h_{online}/h_{V2}
1
0.8
0.6
0.4
0.2
0
10^2
10^3
10^4
Frequency (Hz)


Phase h_{online}/h_{V2} (rad)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
10^2
10^3
10^4
Frequency (Hz)

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