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LIGO/Virgo comparison of issues related to reconstructed h(t) channels

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Virgo * A joint CNRS-INFN Project
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1) What is the accuracy to which we know the simultaneity of the timestamps generated by the two experiments?

Both experiments timestamps are based on the GPS timing system.
Possible sources of errors are:
- *the timing precision of the GPS system itself*. The GPS gives ~10 m precision on a map, it should thus gives ~30 ns precision on the timing received in different sites.
- *the use of different GPS receivers between the experiments.* It has been checked in 2002, by comparing the 1 PPS clock generated by a Virgo GPS antenna and receiver brought to a LIGO site to the 1 PPS clock generated by a LIGO GPS receiver. See talk from Sz. Marka: http://www.ligo.caltech.edu/docs/G/G020143-00/G020143-00.pdf. The relative accuracy was found to be better than 1 µs.
- *the presence of offsets between different sites* (correct synchronisation of the 1 PPS clocks, but an offset in the associated timestamps by an integer number of seconds). In 2002, the timestamps from the different sites have been compared to the time received from a NTP (Network Time Protocole) server, with a precision of ~100 ms. No offset was found.
Also see http://www.ligo.caltech.edu/docs/G/G020143-00/G020143-00.pdf

Then the precision of the timing distribution and timestamps with respect to the received GPS time received has to be checked and monitored by each site independently.

For what concern the region around 900 Hz, h(t) comes mainly from the dark fringe signal (with well known models for the power sensing and ITF optical response). The ITF controls are negligible. So calibration timing errors does not depend on actuation timing errors for example.

2) Do both experiments use the same convention for where the gravitational wave that create h is with respect to the interferometer at time t when generating h(t)? This might be a bit ambiguous in the long wavelength approximation where the instrument is treated essentially as a point detector, but it would be good to know that the definitions are compatible at least to within the constraints of the long wavelength approximation.

The same approximations are used in both experiments:
a - the response of the ITF to differential length is modeled by a simple pole,
b - the ITF is assumed to be point-like (long-wavelength approximation).
Only assumption *a* is used in the calibration process while the assumption *b* is used in the analysis process to estimate h(t) at the detector location and orientation.

In the long-wavelength approximation, the location of the GW that creates *h(t)* at time *t* is not really important since «it is everywhere». Depending on the source direction, the maximum error of this approximation is the propagation time along an arm, ~10 µs.
From a talk from R. Savage about the two approximations in the LIGO case (http://www.ligo.caltech.edu/docs/G/G060667-00/G060667-00.pdf), both models are false by ~10%/50 degrees (i.e. 10 µs) in amplitude and phase at 10 kHz, but the combination of them nicely cancels the errors down to better than 1%/10 degrees, which are below calibration uncertainties. Around 1 kHz, the errors are ~0.2%/1 degree.
Note that both hypothesis are even more close to the exact model in the Virgo case since the arm finesse is lower and the arms are shorter.

See also papers about these approximations:
- Rakhmanov M et al., Phys. Letter A (2002), 305, p239 (arXiv physics/0110061v1)
- Rakhmanov M et al., CQG 25 (2008) 184017.

3) Do both experiments agree on how time is recorded in frame files ? In particular, is the timeOffset variable from the frame specification used in a consistent way between the two experiments ?

We have checked that the timeOffset variable is 0 in all the FrAdcData used for the h(t) reconstruction, both in LIGO and Virgo. It is also 0 is the FrProcData containing the h(t) channels. The DAQ people confirmed that it is not filled.
The start time *t0* of a frame is given by the variables *GTimeS* and *GTimeN*. For a given time serie stored in the frame, with sampling period *dt*, the time of sample *i* is given by ($t0 + i \times dt$).

In Virgo, the timestamps of the raw data are offset from GPS time (~21 µs during VSR1). This delay is due to the propagation time of the 1PPS clock from the GPS receiver to the ADC, computers, … located in the different buildings (clock generation time and propagation optical fibers of ~3300 m).
This offset is accounted for in the h(t) reconstruction process such that the the time of the h(t)channel stored in the frames is GPS time (within calibration errors, of 6.5 µs during VSR1).

In LIGO, there are different GPS receivers at the corner and end-stations. The typical offset between them is on the order of 1 µs. As their clocks are used locally, delays due to the propagation of their clocks are negligible.
All known timing delays are part of the frequency domain models. The h(t) production process does not include any additional systematic corrections to the phase, timing, or amplitude. All this information is contained in the frequency domain models, from which the digital filters are constructed. The digital filters are designed to mimic as closely as possible the amplitude and phase response of their frequency domain counterparts.

In both cases, the time of the h(t) channel is the GPS time within calibration uncertainties.

4) Any other reasons why h(t) might not be in phase between the two experiments ?

The definition of h(t) is common to both experiments: the sign of h(t) is thus the same between the experiments. The sign is checked with photon calibrators in all sites.
No other reasons of mismatch are expected. The methods used in both experiments to check h(t), with different excitations of the mirrors through electromagnetic actuators or photon calibrators, are very similar.

5) We have amplitude uncertainties from the calibration teams of both experiments. Is the total calibration uncertainty just the quadrature sum of these, or is there some other relative uncertainty in h(t)amplitude we need to worry about?

For combining the errors, the sanest thing must be to combine the errors in quadrature.

As a conclusion, the differences in h(t) between instruments are much smaller than the uncertainties coming from calibration errors.