Contribution aux exercices de prospective nationale 2020-2030

Détecteurs et instrumentation associée

VERS DES DÉTECTIONS D'ONDES GRAVITATIONNELLES DE PRÉCISION

Auteur principal

Nom : Loïc Rolland

Affiliation : Laboratoire d'Annecy de Physique des Particules

Email et coordonnées : 0450095518 – loic.rolland@lapp.in2p3.fr

Co-auteurs (inclure aussi les collaborateurs internationaux si existants)

Groupes Virgo France : APC, ARTEMIS, ILM, IPHC, LMA/IP2I, LAL, LAPP, LKB

Informations générales

Titre : Vers des détections d'ondes gravitationnelles de précision

Résumé

In order to get sub-percent level calibration uncertainties of the advanced and third generation gravitational wave detectors, two calibration techniques must be upgraded in different steps following the detector sensitivity improvements. The photon calibrator is based on an auxiliary laser to move a mirror of the interferometer ; the Newtonian calibrator is a rotor that modifies the local gravity field to move the mirror. Both techniques are

independent and have completely different sources of systematic uncertainties that need to be reduced in the next decade.

Préciser le domaine technologique

- Optique
- Mécanique, integration
- Acquisition de données, Temps réel

Préciser la motivation principale de recherche visée par la contribution :

- R&D Détection d'ondes gravitationnelles

1. Description des objectifs scientifiques et techniques

Compact binary coalescences are detected every week during the on-going third Observing Run (O3) of the current LIGO-Virgo network of gravitational wave detectors. With the improved sensitivity of the detectors and more detectors coming into the network in the coming decade, more sources and with higher and higher signal-to-noise ratio will be detected. In order not to limit the estimation of the source parameters and the induced physics described within the GT04 working group, the precision of the detector calibration and of the reconstructed gravitational wave strain must be improved down to sub percent level in view of the third generation gravitational wave detectors as Einstein Telescope. For example, the first multi-messenger observation of a neutron star merger in August 2017 already lead to an independent measurement of the Hubble constant, within 11% [4,5]. In order to be competitive with other measurements, percent precision on the Hubble constant is needed, which requires precise calibration of the detectors, as well as well understood inter-calibration of the network detectors.

The O3 uncertainties on the gravitational wave strain reconstructed with the Virgo data are estimated to 5% in amplitude. Reducing this uncertainty down to sub-percent level is a challenge for the next decade, following the Advanced Virgo and LIGO upgrades and in view of Einstein Telescope. Different calibration methods are being used. They are based on different actuators used to move the interferometer mirrors. Knowing the induced motion on the end mirrors allows to calibrate the interferometer as a whole. The challenge is therefore to precisely calibrate the different and independent actuators. Among them, two are expected to be of main importance in the coming years:

- the "photon calibrator"(PCal) [1,2] uses the radiation pressure of an auxiliary laser to move one mirror of the Virgo interferometer by a known quantity. Such a system is used as reference for O3 calibration, but has margin for upgrades towards sub-percent calibration.

- The “Newtonian calibrator” (Ncal) [3] uses a rotating mass that modifies the local gravity field close to the mirror to move it by a know quantity. Such a system has been used for the first time in Virgo in 2017 and is being used more regularly during O3.

The photon calibration technique is also being used as reference for the LIGO detector calibration. The Newtonian calibration technique is being developed by LIGO collaboration with the plan to test it by the end of O3.

The Ncal method is expected to suffer from less systematic uncertainties than the Pcal one, but is limited to frequencies between few hertz and few hundreds of hertz. The Pcal technique has the advantage of actuating the mirror over the whole detection band, few hertz to few kilohertz. In this context, the Ncal would be used as calibration reference, and the Pcal could be cross-calibrated with respect to the Ncal and then used to extend the calibration to high frequency.

About cross-calibration of the detectors in the network (LIGO, Virgo, Kagra, LIGO-India and 3G detectors), cross calibration of the absolute power calibration is being started for the Pcal, but suffers for the difficulty to have absolute power reference for the difficulty to have stable optical system on the long term. Absolute calibration of the Ncal calibrators is expected to be more robust.

2. Livrables associés, calendrier et budget indicatifs

Both the Pcal and the Ncal hardware will be used and characterized on the Virgo detector and upgraded accordingly, following the Virgo sensitivity improvements. Collaboration with the LIGO and Kagra colleagues will be useful to understand and fix setup issues, and to define methods to cross-calibrate all the detectors.

Among the Pcal improvements, one can cite : reduction of the laser power noise (currently 3 W fibre laser at 1047 nm), better control of the beam polarisation, use optical elements whose reflection and transmission are better controlled and stable both in s- and p-polarisations (small variations with temperature and humidity are currently seen), improve photodiode sensing for lower noise and better stability in time and with environmental parameters. Variations at the 1% level were seen during O3a and found to be correlated with humidity. Installing the Pcal benches under light vacuum is another possible evolution towards being more independent from environment and a better cleanliness.

Another topic concerns the availability of powermeters with absolute power calibration, then used to calibrate the Pcal actuators : currently, there is few percent's differences between the power calibration measured in different national institutes. Sub-percent calibration of gravitational wave detectors with the Pcal require to improve it down to an even smaller level. A workshop with national institutes were organized in 2018. NIST is willing to improve their power calibration precision, but a possible collaboration with French or European institutes (BIPM) could be useful to push forwards in this direction.

With the current electro-magnetic (in Virgo) or electro-static (in LIGO) actuators, some material is added at the back of the mirrors, which must induce thermal noise. It is not limiting the current interferometer sensitivities, but may start contributing with 3G sensitivities and reduced coating thermal noise. In this case, the Pcal technique can be used as a mirror actuator. It will be needed to study the needed power of the Pcal laser, which will be probably higher than for calibration purpose only.

About the Ncal, a first prototype has confirmed its principle in 2018 around the run O2. A second prototype is being tested during O3 but further developments are planned to be pursued in the coming years. Part of the upgrade concerns the rotor itself : better balancing to reduce seismic and acoustic noise, better ball bearing to run the rotor in different orientations and at faster speed (currently around 70 Hz), low magnetic noise motorized system, precise machining of the rotating part, control of the rotation speed, ... The current prototype can only generate a single sinusoidal motion onto the interferometer mirror. Different designs of the rotor in order to generate more complicated mirror motion will be studied. Different material, with better compactness and less deformability under such rotation speed, will also be studied. In order to further reduce acoustic and seismic noise, a design with the rotor installed inside a vacuum tank should be studied.

Another part of the upgrades concerns the Ncal supports. In order for the Ncal to induce a strong enough mirror motion, the rotor must be located close to the interferometer mirrors (of the order of a meter), but seismic noise induced by the rotor residual unbalanced must be mitigated. Dedicated supports with resonant frequencies higher than the maximum Ncal speed (up to few hundreds of hertz for future versions) must be designed. The supports must also provide a precise positioning of the Ncal rotor since the induced mirror motion strongly depends on the relative position of the mirror and the Ncal. As the sensitivity of Virgo will improve, any residual noise will need to be better and better mitigated by both reducing the noise generated by the rotor and improving its attenuation by the supports.

3. Références

[1] T. Accadia et al. Reconstruction of the gravitational wave signal h(t) during the Virgo science runs and independent validation with a photon calibrator. Class.Quant.Grav., 31 :165013, 2014.

[2] B. P. Abbott et al. Calibration of advanced Virgo and reconstruction of the gravitational wave signal h(t) during the observing run O2. Classical and Quantum Gravity, 35 :205004, October 2018.

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[4] B.P. Abbott et al. A gravitational-wave standard siren measurement of the Hubble constant. Nature, 551(7678) :85–88, 2017.