Non-linear and geometrical models for bivariate signal. Application to polarized gravitational wave analysis.

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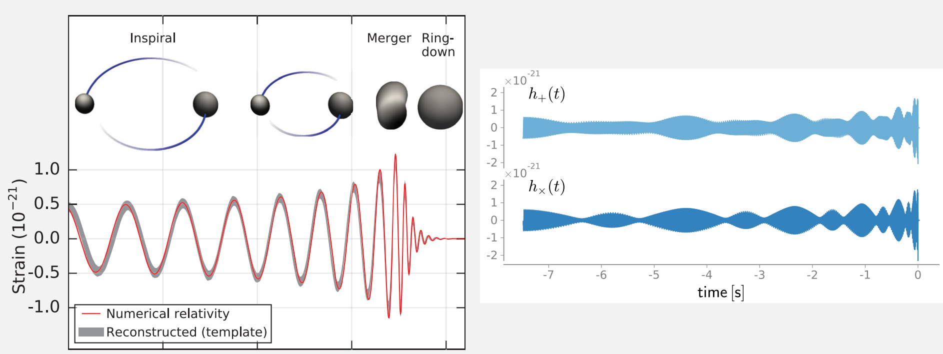
The direct observation of gravitational waves (GW) by the LIGO and Virgo detectors [1] is one of the breakthrough discoveries of the beginning of the 21st century. This new astronomy opens opportunities, specifically for the study of compact objects [2, 3] such as neutron stars and black holes. Similarly to electromagnetic waves, GW are polarized and their polarization provides important insights about the dynamics of the astrophysical source. **The subject of this PhD project falls into the modelisation, analysis and understanding of polarized signals emitted by sources of GW**. It aims at proposing new inference algorithms to decipher and exploit the polarization information. Providing efficient algorithms capable of efficiently taking into account the polarization of gravitational signals is of great interest for astronomers to better understand the dynamics of GW sources.

Gravitational waves being polarized, gravitational signals that may be recorded by ground-based detectors (LIGO/Virgo interferometers) can be modeled and analysed as *bivariate signals*. As an example, the polarization of GWs received from the merger of two compact stars is related to the dynamics of this binary system. Changes in the polarization over time indicate the presence of precession of the binary orbital plane during the merger, a phenomenon that provides decisive clues about the astrophysical processes that gave birth to the observed binary system. An example of the two polarization modes emitted by a precessing Binary Black Hole (BBH) are depicted in Figure 1. Accurate analysis of polarized signals can thus help in revealing valuable informations about the GW source.



Example of a bivariate gravitational signal
`Left`: $h_+(t)$ and $h_\times(t)$ waveform templates from a binary black hole (BBH) coalescence.
`Right`: Polarization fluctutations carry the signature of the BBH physical parameters.

This PhD project will be dedicated to develop new models and analysis tools to capture the polarization information of bivariate signals, together with new analysis techniques capable of extracting the polarization contents and reveal the physical information it carries about the source of GW. From the bivariate signal processing point of view, physics-inspired models for signal simulation/generation will be investigated as well as analysis methods. The recently introduced *geometrical theory* for bivariate signal processing in [4, 5, 6] will be used as a framework for the research conducted in this project. In particular, non-linear (Volterra [7]) filters design will be studied in the bivariate case, with a peculiar attention on the polarization effect they allow to model. Similarity measures between bivariate signal will also be investigated, including metrics on various manifolds, in order to take into account the geometric nature of polarization information. The developped algorithms will be evaluated and tested on simulated GW signals and potentially applied to real datasets when applicable.

The research work carried out during this PhD thesis project will take place within the framework of the ANR RICOCHET project, in collaboration with several research teams in signal processing (CRAN in Nancy and CRIStAL in Lille) and in gravitational astronomy (APC in Paris). Short visits to the above mentioned laboratories will be planned during the PhD to ensure active collaboration with other members of the project. The algorithms developed within the project will have to be integrable in the libraries of the LIGO/Virgo consortium. Regular reports on the progress of the work will be made within the RICOCHET project. The results obtained will be published in signal processing and astrophysics journals, as well as in international conferences in both fields.

- **Localization:** GIPSA-Lab, Grenoble, France.
- **Framework:** RICOCHET ANR Project.
- **RICOCHET collaboration network:** Gipsa-Lab (Grenoble), APC (Paris), CRIStAL (Lille) and CRAN (Nancy).
- **Prerequisites:** Candidats should have strong background in applied mathematics, statistical signal processing and computer programming; some solid knowledge in physics would be appreciated.

References

[1] B. P. Abbott et al. *Observation of gravitational waves from a binary black hole merger*. Phys. Rev. Lett., vol. 116, pp. 061102, 2016.

[2] B. P. Abbott et al. *GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs*. Phys. Rev. X, vol. 9, issue 3, pp. 031040, 2019

[3] R. Abbott et al. *GWTC-2: Compact binary coalescences observed by LIGO and Virgo during the first half of the 3rd observing run*. arXiv:2010.14527, 2020.

[4] J. Flamant, ”A general approach for the analysis and filtering of bivariate signals ”, PhD thesis, Ecole Centrale Lille, 2018.

[5] J. Flamant, N. Le Bihan and P. Chainais, ”Spectral analysis of stationary random bivariate signals”, IEEE Transactions on Signal Processing, Vol. 65, no. 23, pp. 6135-6145, 2017.

[6] J. Flamant, P. Chainais and N. Le Bihan, ”A complete framework for linear filtering of bivariate signals”, IEEE Transactions on Signal Processing, Vol. 66, no. 17, pp. 4541-4552, 2018.

[7] J.L. Lacoume, P.O. Amblard et P. Comon, ”Statistiques d’ordre supérieur pour le traitement du signal”, Masson, 1997.