The application of interferometric gravitational-wave detectors in astrophysics and gravity research

(Summary of the Ph.D. work and doctoral theses)

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Modern ground-based interferometric gravitational-wave (GW) detectors are capable of measuring induced displacements of their test masses below the $10^{-20} - 10^{-19}$ m/$\sqrt{\text{Hz}}$ scale (Hughes et al., 2001). This, theoretically, makes them capable of achieving direct detections of GWs from various astrophysical sources, including highly energetic events, such as the core-collapse of massive stars, or coalescing binaries of neutron stars and/or black holes (Hughes et al., 2001). Note, that both physical processes are associated with the astrophysical sources of gamma-ray burst (GRBs) (e.g. MacFadyen & Woosley 1999; Kochanek & Piran 1993; Abbott et al. 2008b). Beyond the goal of detecting GWs, modern interferometric sensors can be viewed as state-of-the-art experimental devices, that open up myriads of new possibilities for fundamental science. Such sensors include LIGO (Abbott et al., 2009b) and VIRGO (Acernese et al., 2006); as well as future second generation detectors like AdvLIGO (AdvLIGO web, 2011), AdvVIRGO (AdvVIRGO web, 2011), LIGO-India (LIGO-India web, 2011); and proposed third-generation detectors like the LCGT (Kuroda & LCGT, 2010), and the Einstein Telescope (ET web, 2011).

In my thesis, I explore and demonstrate the potential in these interferometric instruments from the perspective of astrophysics and experimental research on gravity. The thesis is based on the following refereed scientific papers: Thrane et al. 2011; Raffai et al. 2007; Baret et al. 2011; Matone et al. 2007; and Raffai et al. 2011.

In the first part of my thesis, I distinguish the long ($\mathcal{O}(1 - 10^5\text{sec})$) GW transients from short ($\mathcal{O}(\lesssim 1\text{sec})$) GW transients and persistent (($\mathcal{O}(> 10^5\text{sec})$) GW-signals, based on the fundamental differences of the search techniques that are dedicated to look for such signals. I give an overview on the astrophysical sources of long GW transients, and make estimations on the signals' detectability. Together with a dedicated LIGO working group, I have developed a novel analysis technique to bridge the gap between the analyses of short transients and persistent signals. Our technique utilizes time-frequency maps of GW strain cross-power between two spatially separated terrestrial GW detectors. The application of our cross-power statistic to searches for GW transients is framed as a pattern recognition problem. I propose to use two independent pattern-recognition techniques to look for narrow-band GW signals in coincidence with GRBs detected during the sixth LIGO science run. I demonstrate the applicability of the pattern-recognition algorithms by recovering simulated GW signals and environmental noise artifacts embedded in LIGO noise. As part of the project, we derive a conservative coincidence time window for joint searches of long GW-transients and GRB signals. By taking into account a broad range of emission mechanisms, we conclude with a time window of $t_{GW} - t_{GRB} \in [-350s; +150s]$.

In the second part of my thesis I present an approach to experimentally evaluate gravity gradient noise, a potentially limiting noise source in advanced interferometric GW detectors. In addition, I demonstrate that the method can be used to provide sub-percent calibration in phase and amplitude of modern interferometric GW detectors. Information on the calibration to such certainties shall enhance the scientific output of the instruments in case of an eventual detection of GWs. The method relies on a rotating symmetrical two-body mass, a *Dynamic gravity Field Generator* (*DFG*). The placement of the DFG in the proximity of one of the interferometer's suspended test masses generates a change in the local gravitational field detectable even with first-generation interferometric GW detectors.

Applying a *pair* of DFGs in a null-experiment, and taking advantage of the exceptional sensitivity of modern interferometric techniques, provides an experimental opportunity for the future to measure possible violations to Newton's $1/r^2$ law in the $0.1 - 10$ m range. The use of our proposed configuration allows us to test composition-independent non-Newtonian gravity significantly beyond the present limits. Advanced and third-generation GW detectors are representing the state-of-the-art in interferometric distance measurement today, therefore, we illustrate the method through their sensitivity to emphasize the possible scientific reach. Nevertheless, it is expected that due to the technical details of GW detectors, DFGs shall likely require dedicated custom-configured interferometry. However, the sensitivity measure we derive is a solid baseline indicating that it is feasible to consider probing orders of magnitude into the pristine parameter well beyond the present experimental limits significantly cutting into the theoretical parameter space.

The theses of my PhD work that are presented in the first part of my thesis document, are the following:

- We have defined the GW signals having a duration of $\mathcal{O}(1 - 10^5\text{sec})$ as *long GW transients*, and we have distinguished them from short ($\mathcal{O}(\lesssim 1\text{sec})$) GW transients and persistent ($\mathcal{O}(> 10^5\text{sec})$) GW signals. I point out that the distinction is strongly motivated by the differences between the physical mechanisms that lead to the GW emission, and by the differences between the technical approaches that need to be applied when searching for GW signals in the three different timescales.

- We have systematically overviewed the known models of astrophysical sources that are expected to emit long GW transients. Based on the source models, we have given numerical estimations on the detectability of the predicted signals with future second generation GW detectors.

- We have developed the *Stochastic Transient Analysis Multi-detector Pipeline* (*STAMP*), a computer code package that is specialized to search for long GW transients. The pipeline bridges the gap between techniques applied in searches for short GW transients and those applied to search for persistent GW signals. Our search pipeline produces time-frequency maps of GW strain cross-power by cross-correlating data from chosen pairs of GW detectors. The search for GW signals in the two-dimensional maps can then be framed as an image-processing problem. Along with introducing the test statistics of our search algorithm, we have pointed out the relation between our multi-pixel statistic and the isotropic-equivalent energy emitted by the potential GW source.

- We have investigated the empirical distribution of one of our test statistics for noise samples from LIGO H1 and L1 detectors, and concluded that the distribution can be reproduced by Monte Carlo simulations that assume a Gaussian distribution for the noise background. We have proved that with the simulations we obtained a practical tool that can be used to adjust our detection threshold for the search process with the different test statistics.

- We have developed the *Locust* and *Hough* algorithms, i.e. two image processing methods that are specialized to identify quasi-monochromatic long GW transients. We have demonstrated the applicability of these two methods in searches for long GW transients by reconstructing artificially simulated signals based on the *van Putten* GW emission model for GRBs, and noise glitches caused by certain types of environmental noise effects.

- We propose to apply the STAMP code package in a targeted search for long GW transients in coincidence with gamma-ray bursts (GRBs) that were observed during the LIGO S6 science run. As part of the search parameter optimization, we have derived a conservative time window for coincident gamma-ray and GW detection from the same GRB source. The time window of possible GW detection is expected to have a total length of 500 seconds, and it distributes as [-350s,+150s] around the time of the onset of the GRB prompt phase. The derivation of the time window mainly relied on model-motivated comparisons with GRB observations and simulations.

The theses of my PhD work that are presented in the second part of my thesis document, are the following:

- By recognizing that the sensitivity of future second and third generation GW detectors at low (< 10 Hz) frequencies is constrained by gravitational gradient noise (GGN) of the local environment, and knowing the limitations of the related theoretical models of the noise background and the coupling mechanisms, we have developed an experimental method that can be used for mapping the transfer function between the GGN and the output noise of a GW detector. The method suggests to use a periodically varying mass distribution (what we called a *DFG*) where the quadrupole term dominates the local gravitational field.

- We have proven with analytical calculations that a DFG with an $\mathcal{O}(0,1\mathrm{kg}\cdot\mathrm{m}^2)$ quadrupole moment, placed to a few meters from the test mass of a GW detector can identify the gravity gradient signal of the DFG within an integration time of

$\mathcal{O}(1-1000\,\text{sec})$. We have also shown that such a DFG device can allow an amplitude and phase calibration of GW detector below 1% precision.

- Using numerical simulations, we have determined the distance $(0,1-10\text{m})$ and strength $(> 10^{-5}-10^{-7})$ scale, where non-Newtonian gravitational potentials of Yukawa-type could be identified with currently feasible interferometric sensor techniques, below the current upper limits $(10^{-3}-10^{-4})$ on the Yukawa strength parameter. We propose to use a pair of DFGs in a null experiment for this purpose.

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