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SKY LOCALIZATION OF MASSIVE BLACK HOLE BINARIES WITH LISA: APPLYING CORONAGRAPHIC TIME-DELAY INTERFEROMETRY TO LOW-LATENCY SEARCHES

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Abstract. The Laser Interferometer Space Antenna (LISA) will be a space-borne gravitational wave (GW) detector to be launched in the next decade. Central to LISA data analysis is time-delay interferometry (TDI), a numerical procedure which drastically reduces otherwise overwhelming laser frequency noise. LISA data analysis is usually performed on subsets of TDI variables which form a basis e.g., Michelson variables (X, Y, Z) or quasiorthogonal variables (A, E, T). We investigate a less standard TDI variable, denoted κ, which depends on time and two parameters (β, λ). For any GW source located at sky position $(\beta_\star, \lambda_\star)$, κ has the singular property of canceling GW signal when (β, λ) tend to $(\beta_\star, \lambda_\star)$, very much like a coronagraph. Thanks to this property, coronagraphic TDI has the potential to be an efficient model-agnostic method for sky localization of GW sources with LISA. These characteristics make it relevant for low-latency searches of sources with a high multi-messenger potential, such as Massive Black Hole Binaries (MBHBs). Building upon previous theoretical work, and a first assessment of the sky localization capabilities of κ in the current LISA configuration, we investigate a sky localization algorithm based on coronagraphic TDI. We discuss the results in the context of the accuracy required by facilities susceptible of detecting electromagnetic counterparts emitted by such sources.

Keywords: gravitational waves, LISA, multi-messenger astronomy

1 Introduction

Our best description of gravity, general relativity, predicts the existence of gravitational waves, which can be thought of as ripples in the fabric of spacetime. A century after the formulation of this theory, gravitational waves were directly detected in 2016 by ground-based detectors. This major event marked the beginning of gravitational wave astronomy, giving us access to a new messenger. Indeed, gravitational waves are produced by objects which do not necessarily emit light, and were thus inaccessible otherwise. Now that the observation of gravitational waves is a reality, the next challenge in the field is to extend the observed spectrum. In fact, ground-based detectors are limited to the 10 Hz-10 kHz frequency range, while the Laser Interferometer Space Antenna (LISA)–a future space-based gravitational wave detector with launched planned for 2035–is designed to observe in the mHz band. Among the many exciting scientific prospects of LISA, is the possibility of multi-messenger detection, that is to detect the same source both with gravitational and electromagnetic waves. This presents a significant observational challenge, requiring the coordination of different instruments and communities.

From the perspective of LISA data analysis, this challenge implies the development of a dedicated low-latency alert pipeline (LLAP), designed to issue alerts to the broader multi-messenger community. At the core of this pipeline, lie algorithms which aim at rapidly identifying the sky location and time of coalescence of gravitational wave sources. Different algorithms are expected to be developed to fulfill the requirements of the LLAP, in particular model agnostic algorithms to ensure, for instance, that unmodeled sources are not missed. Importantly, these algorithms have to meet the requirements imposed by future electromagnetic instruments observing potential multi-messenger sources, such as the New Advanced Telescope for High ENergy Astrophysics (NewAthena) which sets the precision level to be achieved by LISA to less than $10\,\mathrm{deg}^2$ Colpi et al. (2024).

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In this study, we investigate a model agnostic sky-localization method for gravitational wave sources. We begin by outlining the basic principles of the proposed data analysis technique. We then consider its application to simulated LISA data. Finally, we discuss its limitations and future research directions.

2 Method

The method we propose is based on time-delay interferometry (TDI), a technique used in LISA processing to reduce otherwise overwhelming laser frequency noise. This technique gives rise to TDI combinations, or variables, which are the relevant quantities for data analysis. The combination we consider, coronagraphic TDI, was first developed in Tinto & Larson (2004); Nayak et al. (2003); Vinet (2007) and was recently further investigated in Costa Barroso et al. (2025). Below we give a brief overview of coronagraphic TDI and present a new Bayesian approach which builds on it. Note that derivations are omitted for conciseness. The interested reader is referred to Costa Barroso et al. (2025) for more details.

2.1 Coronagraphic TDI

Coronagraphic TDI, noted κ, is a linear combination of standard Sagnac TDI variables (α, β, γ). In frequency domain, it can be formally expressed as

$$\tilde{\kappa}(f, \beta, \lambda) = \vec{A}(f, \beta, \lambda) \cdot (\tilde{\alpha}(f)\ \tilde{\beta}(f)\ \tilde{\gamma}(f))^T, \tag{2.1}$$

where the tilde notation denotes the Fourier transform. It is important to note that, different from other TDI variables, coronagraphic TDI depends on two additional parameters: β, the latitude, and λ, the longitude. In fact, the coefficients $\vec{A}$ are constructed from the *geometric* response of LISA to gravitational waves and thus depend on the position of the source of the incoming signal with respect to the LISA constellation. In that sense, we can say that coronagraphic TDI is able to point at a certain direction, even though this is done purely algebraically.

In particular, when a gravitational wave signal, coming from a point-like source at position $(\beta_\star, \lambda_\star)$, is present in the data, the coronagraphic property of $\tilde{\kappa}$ consists in tending to zero as $(\beta, \lambda) \to (\pm\beta_\star, \lambda_\star)$, acting like a coronagraph. This property holds for *any* point-like source. Therefore, by scanning the sky with $\tilde{\kappa}$ and searching for a minimum, one can determine the position of a gravitational wave source in a model agnostic manner.

Additionally, as for any TDI variable, one can define an instrumental noise model for κ. Unlike other channels, the Power Spectral Density (PSD) of the noise in the coronagraphic channel, noted $S_{\kappa\kappa}$, depends on the position (β, λ). This is because it is constructed with the same coefficients $\vec{A}$, which carry the dependence on (β, λ).

2.2 Likelihood

To go further, we develop a complete Bayesian analysis based on coronagraphic TDI, similar to what is done with standard TDI channels in LISA data analysis. To do so, one needs to define a likelihood. For standard TDI combinations, the usual choice is the Whittle likelihood which assumes Gaussian stationary noise. Under the same assumptions, one can derive the following likelihood function

$$\mathcal{L}(\tilde{\kappa}|\beta, \lambda) = -\frac{1}{2} \prod_{f_{min}}^{f_{max}} \frac{|\tilde{\kappa}(f, \beta, \lambda)|^2}{\mathcal{S}_{\kappa\kappa}(f, \beta, \lambda)} + \log \mathcal{S}_{\kappa\kappa}(f, \beta, \lambda), \tag{2.2}$$

where $\mathcal{S}_{\kappa\kappa} = S_{\kappa\kappa}/4\Delta f$, that is the PSD of noise up to some factors. These factors come from the discrete implementation of the Fourier transform with $\Delta f = 1/N\Delta t$, where N is the number of points in the original time series and Δt the time between two samples. From this likelihood function, we then use a sampler and the standard Bayesian machinery to construct the posterior for parameters (β, λ).

To gain some intuition about Eq. 2.2, let us assume that data d comprises some gravitational wave signal s and some noise n, such that $d = s + n$. In this case, in the coronagraphic channel, as $(\beta, \lambda) \to (\pm\beta_\star, \lambda_\star)$ only noise remains in the data as the signal is suppressed. Then the first term in Eq. 2.2 tends to one and, as a consequence, the likelihood $\mathcal{L}$ reaches a maximum. The second term sets for the overall noise level. Importantly, it accounts for the loss of efficiency of $\tilde{\kappa}$ close to the plane of the constellation, which is a known limitation of coronagraphic TDI.

3 Application to Sky Localization of Gravitational Wave Sources

To test this method, we consider a relatively short simulation of LISA data of 5.8 days. During this period, we assume that the spacecraft which form the LISA constellation are static. We include a quasi-monochromatic gravitational wave signal. More specifically, we simulate the verification Galactic binary (VGB) ZTFJ2243. This is a known LISA source already detected in the electromagnetic domain Kupfer et al. (2024). We also include instrumental noise, at a level 10 000 times below the reference value given in Colpi et al. (2024). Dividing the reference noise level allows us to artificially increase the signal-to-noise ratio of the source. This allows us to test the method in a simplified and controlled scenario. Note that the simulation was generated with the LISA suite Bayle et al. (2022b,a, 2023). As a sampler, we use Eryn Katz et al. (2023); Karnesis et al. (2023), which has been developed within the LISA data analysis community.

The obtained posterior is showed in Fig. 1, where the {39%, 68%, 86%}–or 1σ, 1.5σ, 2σ–credible intervals are plotted. Given that the injected position was $(\beta_\star = 0.94, \lambda_\star = 0.23)$ rad, we notice that the method correctly recovers the injected position of the source within the 86% credible region. This result validates the method. However, in the context of the LLAP, one has to ensure not only that the injected position is retrieved, but that this is done with a precision of $10\,\mathrm{deg}^2$. From Fig. 1, we can deduce a rough estimate for the area of the 68% credible region. In fact, by taking $\Delta\lambda = 0.09$ and $\Delta\beta = 0.06$ rad, we get an error box of $\Delta\Omega \approx 18\,\mathrm{deg}^2$, which is above the required precision of $10\,\mathrm{deg}^2$.

Overall, this proof-of-concept study validates the principle of coronagraphic TDI for model-agnostic sky localization, while also highlighting the need for further development. Future work will extend this analysis to more realistic LISA data and target massive black hole binaries (MBHBs), which represent the primary low-latency sources of interest.

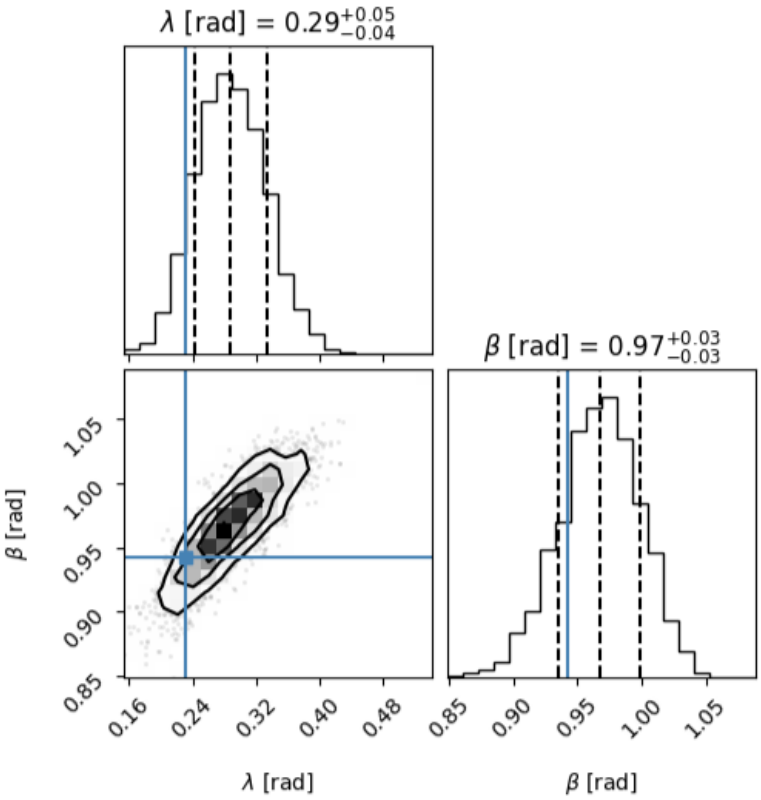

Fig. 1. Posterior distribution for parameters (β, λ) obtained for a simulation of VGB ZTFJ2243 including instrumental noise divided by a factor 10 000 with respect to the reference value. The blue lines indicate the injected position $(\beta_\star = 0.94, \lambda_\star = 0.23)$ rad, while the dashed lines represent the 68% credible region.

4 Conclusion

We have investigated the application of coronagraphic TDI to the model-agnostic sky localization of gravitational-wave sources with LISA, in the context of low-latency alerts. By defining a likelihood function for the $\tilde{\kappa}$ variable and applying a Bayesian analysis, we tested the method on a simplified simulation of the VGB ZTFJ2243. The source position was successfully recovered, validating the principle of the approach.

However, the localization precision obtained in this study ($\Delta\Omega \approx 18\,\mathrm{deg}^2$) remains above the $10\,\mathrm{deg}^2$ requirement set by future multi-messenger facilities. This indicates that further developments are needed. In particular, the extension to more realistic data and to massive black hole binaries (MBHBs), which are the typical targets of the LLAP.

Despite these limitations, coronagraphic TDI stands out as the only model-agnostic method currently proposed for this problem. Its potential for rapid and robust localization makes it a promising technique for the development of the LLAP.

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