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THE PREPARATION OF LISA DATA ANALYSIS WITH IMPERFECT MEASUREMENTS: DEALING WITH INSTRUMENTAL TRANSIENTS

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Abstract. The measurement of low-frequency gravitational waves with LISA presents many challenges for the data analysis. The satellite constellation will form a detector with a time-evolving response including 12 interferometric signals, that are likely to be affected by many artifacts related to the complexity of the experiment. Among other instrumental effects, the measurement is likely to be perturbed by transient glitches possibly due to short disturbances on the reference test-masses. Such transients were observed by LISA Pathfinder mission, the technological demonstrator for LISA which successfully flew from December 2015 to June 2017. We present preliminary simulations of instrumental glitches in LISA measurements based on LISA Pathfinder feedback. We show that these phenomena can degrade the scientific performance of the mission if not properly taken into account. This study sets the basis of further works to assess and mitigate the impact of glitches on the recovery of gravitational source parameters.

Keywords: LISA, gravitational waves, data analysis, instrument glitches

1 Introduction

The Laser Interferometer Space Antenna (LISA) (Danzmann et al. 2017) is a future space-based gravitational-wave observatory which will open up a new window on the Universe, by probing gravity in the low frequency band, between 0.1 mHz to 0.1 Hz. This instrument of a new kind will be able to detect tens of thousands of astrophysical sources from cosmic dawn to the present. These sources will be of various natures (e.g. stars, white dwarfs or black hole binaries) and will emit signals with different features, which can be classified in three categories (Petiteau 2008): periodic signals (e.g. binaries in their inspiral phase), burst signals (e.g. binaries entering coalescence) and backgrounds (e.g. broad-band and non-localized emissions). In addition, we may observe unmodeled and hypothetical sources such as cosmological phase transitions (Amaro-Seoane et al. 2012).

The global fit of the LISA data, i.e. the full detection and characterization of all resolvable sources present in the data, is a real challenge. This will be further complicated by the presence of spurious signals in the data stream, produced by instrumental effects. These phenomena have been observed by the technological demonstrator LISA Pathfinder (LPF) during in-flight acceleration measurements (Armano et al. 2018), but also during the observation of the binary neutron star merger with LIGO and Virgo (Abbott et al. 2017).

These perturbations, that we refer to as "glitches", can affect the accuracy of the gravitational-wave parameter estimation, or even be confused with astrophysical sources. Therefore, the characterization of glitches and the mitigation of their impact on the science performance is crucial to achieve the best scientific return of the mission.

After a brief description of the LISA measurement in Sec. 2, we present the glitch model that was adopted for LPF in Sec. 3 to fit for perturbations in the acceleration data. Then in Sec. 4 we describe our approach to translate this model into LISA data and assess the impact of the glitches with respect to the stochastic instrumental noise. Finally in Sec. 5 we present a preliminary estimation approach to fit and remove them.

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2 Description of the LISA measurement

LISA is a space-based interferometer, made of three satellites forming a near-equilateral triangular constellation which will fly on a heliocentric orbit, trailing Earth with a 20-degree delay. The spacecraft will be separated by a distance of 2.5×10^6 km, in order to ensure a strain sensitivity up to 10^{-21} for gravitational waves with frequencies in the band of interest.

The principle of the measurement is to probe the slight changes in space-time due to incoming gravitational waves propagating across the constellation. To this aim, free falling test-masses, which are the reference points, are housed in each satellite. The separations between test-masses and their variations across time are monitored by interferometric laser measurements where each spacecraft acts both as an emitter and as a receiver. An incoming gravitational wave will affect the round-trip path of the laser light between test-masses, inducing a detectable oscillating phase shift.

This phase shift, or equivalently the relative frequency shift, is actually read out by a combination of three interferometric measurements: (1) the science interferometer measurement, performed between the test-mass and the optical bench of the distant spacecraft; (2) the test-mass interferometer measurement, performed between the optical benches of the emitting spacecraft and the receiving spacecraft; (3) the reference interferometer measurement, between the optical bench and the test-mass of the receiving spacecraft.

The wavelength of the on-board lasers is 1064 nm, corresponding to a frequency of $\nu_0 \approx 282$ THz which fluctuates by several MHz. Contrary to the classical Michelson interferometers of ground-based observatories, one-way phase measurements are performed, over very long arms. Hence the frequency noise does not cancel naturally when interfering signals, and overwhelms the gravitational signal by 8 to 9 orders of magnitude. To circumvent this problem, a technique called time delay interferometry (TDI) (Tinto & Dhurandhar 2014) has been developed. Its principle is to perform linear combinations of delayed interferometric measurements, where the delays correspond to the light travel time over integer multiples of the interspacecraft distances, allowing to cancel the frequency noise contribution. In addition, other noises, such as optical bench displacement noise and clock noise, necessitate further combination to be canceled (Otto 2015).

Assuming that instrumental glitches comes from short kicks on the test-masses, they will mainly be measured by the test-mass interferometer measurement (2). In the following we assess how they translate into the interferometric data streams and how they propagate in the TDI combinations.

3 Glitch modeling in the acceleration data stream

Quasi-impulse force events were observed in the differential acceleration measurement performed by LPF (Armano et al. 2018), occurring at a rate of about 1.5 event per day, with amplitudes as large as $10^{-12}\,\mathrm{ms}^{-2}$ and duration ranging from one second to hours. While their exact origin remains to be investigated, glitches may be triggered by kicks on the test masses or electronic defects.

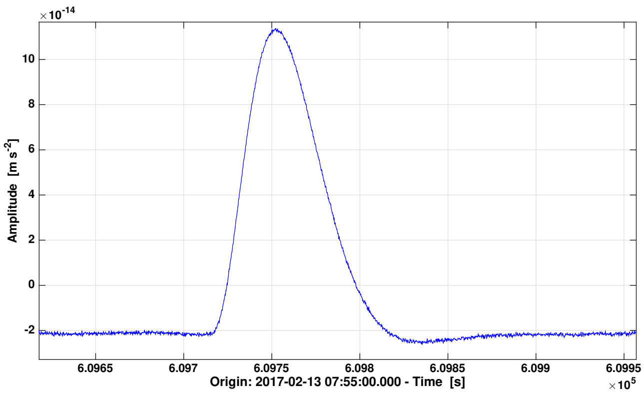

Fig. 1. Example of the glitches observed in LPF data during the noise run from the 13th of February 2017 to the 4th of March 2017. All such events must be collected and characterized for subsequent introduction in LISA data simulations.

A comprehensive catalogue of all observed events in LPF is currently under construction, that will provide a strong basis for realistic simulations for LISA (LISA Pathfinder Collaboration 2019). An example of transient event is reported in Fig. 1, showing a finite impulse response lasting about 3 minutes and slowly returning to zero. This waveform can be modeled by a sum of exponentially-damped functions of time as done by Armano et al. (2018), who use the following mode:

$$a_g(t) = A_0 \left[g_{\tau_1}(t - t_0) - g_{\tau_2}(t - t_0) \right] \quad \text{with} \quad g_\tau(t) = e^{-\frac{t}{\tau}} H(t - t_0), \tag{3.1}$$

where A_0, τ_1, τ_2, t_0 are respectively the amplitude, damping times, and arrival time of the transient, and H is the Heaviside step function, such that $H(t) = 1$ for $t \geq 0$, and $H(t) = 0$ otherwise.

4 Propagation of glitches in the TDI measurement

The model in Eq. (3.1) corresponds to a perturbation in the test-mass relative acceleration. However, as mentioned in Sec. 2, in LISA the observable which is sensitive to gravitational waves is a combination of delayed laser frequency shift measurements. Hence the model must be converted into a relative frequency shift, according to the relation (Petiteau 2008):

$$s_g(t) = \frac{\delta\nu}{\nu_0}(t) \quad = \quad \frac{1}{c}\int_0^t a_g(t')dt', \tag{4.1}$$

where c is the speed of light. Then the TDI responses are obtained by performing an operation of the form:

$$s_{g,\mathrm{TDI}}(t) = \sum_{k=0}^{K} \epsilon_k s_g\left(t - \tau_k\right), \tag{4.2}$$

where $\epsilon_k = \pm 1$ and τ_k are light travel times between two spacecrafts (in one direction or another, depending on the exact TDI combination).

We simulate a glitch using Eq. (3.1) with parameters values $\tau_1 = 2.47$ hours, $\tau_2 = 2.29$ hours, and $A_0 = 7.1 \times 10^{-13}\,\mathrm{ms}^{-2}$. These parameters are chosen to match one of the longest glitches observed in LPF measurements, since this kind of perturbation is likely to have the greater impact on low-frequency gravitational-wave observation. After concerting the signal into fractional frequency using Eq. (4.1) and downsampling from 10 Hz to 1 Hz (which is the expected LISA sampling rate), we simulate the propagation of the glitch in the TDI channels with the LISACode simulator (Petiteau et al. 2008), assuming that the excitation affects a single test-mass. Here we do not simulate other instrumental noises, in order to focus on the glitch perturbation signal. The results are presented in Fig. 2.

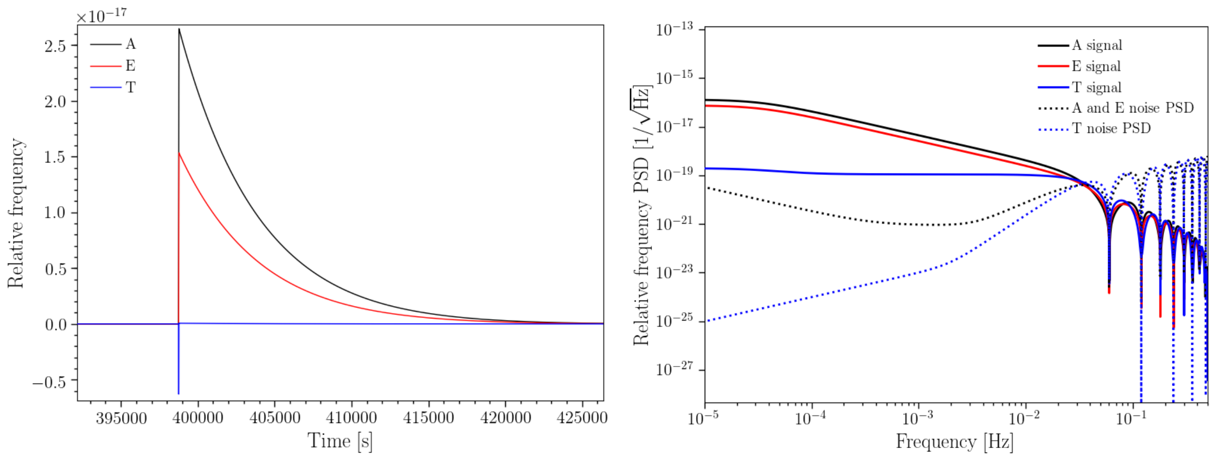

Fig. 2. Left: Time-domain simulation of a LPF-like glitch TDI signal for channels A, E and T. **Right:** Periodogram of the TDI simulation in the frequency domain. The glitch spectra are represented by the solid lines, while the LISA noise sensitivity is represented by the black dotted line for channels A and E, and by the blue dotted line for channel T.

The left-hand side panel represents the TDI signal induced by the glitch in the time domain on three different TDI channels labeled A, E, T which are approximately noise-orthogonal. The rather abrupt outbreak of the signal is due to the downsampling from LPF to LISA rate. The right-hand side panel shows the periodogram of the glitch TDI signals (solid curves) along with the power spectral densities (PSD) of the noise (dotted curves). We note that the glitch signal is significantly larger than the noise level by more than one order of magnitude in all the channels.

This simulation illustrates the impact of glitches on LISA's science measurement, and supports the need to tackle this problem as part of the data analysis.

5 Glitch impact mitigation

The mitigation of the impact of instrumental glitches on gravitational-wave parameter recovery can be done in two ways: i) discarding the data span during which the glitch occurs by an appropriate masking; ii) incorporating a parametric glitch model into the estimation process, and estimate the glitch parameters as part of the global fit. These approaches have been adopted in the analysis of ground-based observatory data (Pankow et al. 2018).

While the safest option is the masking of the corrupted data (combined with an appropriate estimation method to deal with the related gaps, see e.g. Baghi et al. (2016)) the option that is optimal with respect to the signal-to-noise ratio is the second one. For LIGO-Virgo data this is performed by fitting continuous Morlet-Gabor wavelets (Cornish & Littenberg 2015) taking advantage of coherence between different detectors (instrumental transients are expected to occur on a single detector, whereas gravitational transients should be observed on all detectors in a delayed way). This method is not directly applicable to LISA data analysis as it stands, since glitches have an exponential damping (Morlet-Gabor is not appropriate) and there is one single detector, preventing any coherence analysis.

As a preliminary study, we tested an estimation method based on discrete wavelets. It relies on a sparse representation on a the wavelet basis $\boldsymbol{\Psi}$ such that $s_{g,\mathrm{TDI}}(t) = \boldsymbol{\Psi}\boldsymbol{\alpha}$, where $\boldsymbol{\alpha}$ is the vector of wavelet coefficients. The log-likelihood ll used in the estimation can be written as:

$$ll\left(\boldsymbol{\alpha}\right) = \log p\left(\boldsymbol{y}|\boldsymbol{\alpha}\right) - \lambda \cdot \mathrm{pen}\left(\boldsymbol{\alpha}\right), \tag{5.1}$$

where $p\left(\boldsymbol{y}|\boldsymbol{\alpha}\right)$ is the model likelihood, and $\mathrm{pen}\left(\boldsymbol{\alpha}\right)$ is a penalizing term introducing a sparsity constraint on the solution, and λ is a parameter driving the detection threshold (She 2009).

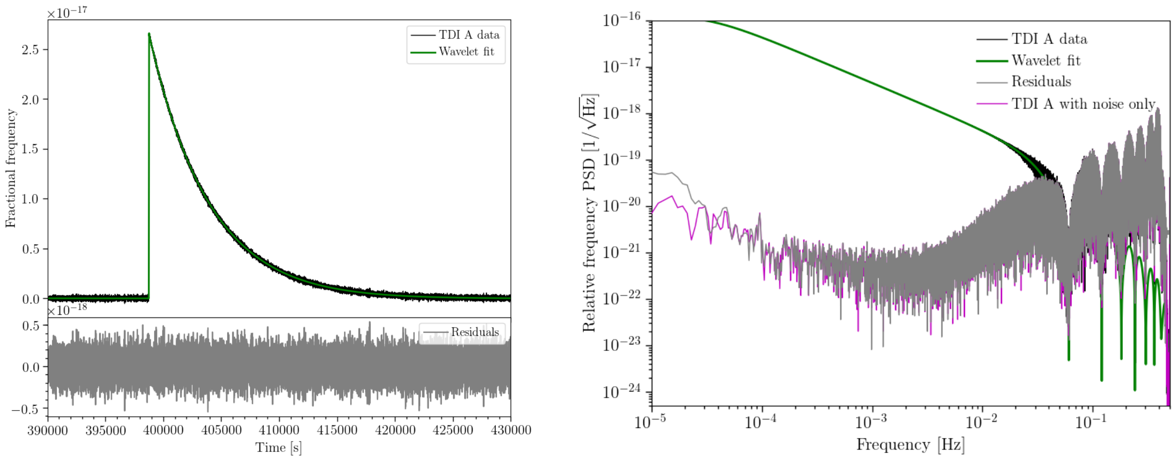

Fig. 3. Left: Result of the time-domain estimation using a sparse wavelet model. The top panel represents the observed data (black) and result of the fit (green) and the bottom panel represents the fit residuals. **Right:** The same data is plotted in the frequency domain, along with the same data with the stochastic noise only (magenta) for comparison.

We generate the same data as in Fig. 2 with LISACode, this time adding a stochastic noise whose PSD corresponds to the expected LISA sensitivity. We then perform a fit with Daubechies 4 wavelets (Daubechies 1988) using the sparse estimation method. The result is shown in Fig. 3. In most of the frequency band, the fit residuals (gray curve) are close to the case with stochastic noise only, i.e. without any glitch (magenta curve, right panel).

However, as it is, this estimation approach presents two main drawbacks. First, wavelets are symmetric functions and hence not well adapted to the abrupt signals that we expect. Second, it does not allow us to distinguish instrumental and astrophysical transients. In the future, we plan to adapt the method by using basis functions inspired by model (3.1) and by taking advantage of an explicit derivation of Eq. (4.2), thereby introducing more information about the glitches and providing a way to disentangle them from gravitational-wave signals.

6 Conclusions

We showed that the instrumental perturbations observed in LISA Pathfinder can be used to characterize the glitches that we expect to arise in LISA. We simulated the TDI response to a LPF glitch-like perturbation on a single test-mass, and showed that the perturbative signal stands above the stochastic instrumental noise, jeopardizing the accuracy of the gravitational-wave observations. This preliminary study suggests that a more careful assessment of the impact of glitches in the extraction of gravitational sources must be performed. In particular, dynamical simulations including the behavior of the drag free system should be done to take into account the possible propagation of glitches on the whole constellation.

In addition, this study advocates the need for adapted mitigation methods. As a basis for such development, we tested a wavelet estimation method allowing to fit for the glitches in the TDI channels. This method must be improved by incorporating *a priori* information on the way glitches propagate through TDI. Finally, we plan to incorporate this estimation into the Bayesian schemes usually used to recover astrophysical source parameters.

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