Effects of Injected LPF Type Glitches on LISA TTL Subtraction and Coefficient Estimation

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***Abstract* – The LISA Pathfinder (LPF) mission was very successful in demonstrating how a gravitational wave detector in space is expected to operate and react to its environment giving plenty of insight as to what should be expected of the Laser Interferometer Space Antenna (LISA). Considering the unprecedented sensitivity of the measurements taken by LPF, the data showed many unexplained noise sources in the form of faint transient signals lasting as long as about 150 seconds. These signals, called glitches, have been the focus of a previous study with the intention to catalog these glitches and summarize their common physical features including amplitude and duration [2]. This research studies the effects injected glitches on LISA tilt-to-length subtraction using simulated data. The analysis done in this paper is based on the results of many different configurations for artificial glitch injections. Tests vary in glitch type, injection site, amplitude, and injection time in order to cover as many potential glitch scenarios as possible. This research will allow for a more clear understanding of how effective the current method for TTL subtraction and coefficient estimation are in the presence of unexpected glitches found in LISA data.**

I. INTRODUCTION

The Laser Interferometer Space Antenna (LISA) is a gravitational wave detector comprised of three individual spacecraft that act as a large Michelson interferometer. Within each spacecraft there are two Moving Optical Sub-Assemblies (MOSAs) that hold a telescope, free-falling test mass, and optical bench. The components of the MOSA allow for Tilt-To-Length (TTL) coupling, defined as the angular jitter of the components caused by a misalignment within the physical setup. TTL noise leads to a decrease in the quality of measurements that LISA can obtain in the primary frequency range of 10^{-3} – 10^{-1} Hz.

Efforts have been made to minimize TTL noise as much as physically possible, but there is still an excess that must be subtracted post-processing to meet the requirement for LISA science operation. A method has been used to reduce this noise below the requirement of LISA's noise budget which follows a similar approach as for LISA Pathfinder (LPF) using simulated data [1]. This research studies the impact of transient glitch events originating in the combined misalignment of the spacecraft and MOSAs and their effect on this method of subtraction. LPF encountered two categories of glitches throughout its mission so this research injects similar glitches into the simulated LISA data [2]. In the data processing pipeline where TTL is subtracted, it cannot be assumed that glitches have been removed yet. Thus, it is crucial that there is an understanding of how glitches injected with different configurations affect the TTL subtraction and coefficient estimation.

II. Theory and Background

A. Data Processing Pipeline

LISA noise subtraction is a significant part of successful science operation, and TTL noise subtraction is one step in the initial noise reduction pipeline. After raw data is collected from LISA interferometers, it will be subject to pre-processing and filtering when it reaches Time Delay Interferometry (TDI) processing. Within this step, TTL noise is subtracted in addition to laser noise, optical bench noise, and clock noise. Once these sources have been reduced or subtracted, the data moves onto TDI data streaming [3]. The proper subtraction of TTL noise is critical to providing cleaner LISA data to be analyzed further down the data processing pipeline.

B. Interferometers in LISA

LISA is comprised of multiple types of interferometers that allow for its scientific operations. Two of these are taken into careful consideration when working with TTL noise. The inter-satellite interferometers, referred to as Long Arm Interferometers (LA IFOs) throughout the rest of this paper, maintain the connection and measurements between the three spacecraft. The Test Mass Interferometers (TM IFOs) maintain the connection and measurements within the Moving Optical Sub-Assembly (MOSA) of which each spacecraft has two. TTL noise stems from laser misalignment within one or more spacecraft and their MOSAs which is expected to be seen in the readout of these two types of interferometers.

C. TTL Noise and Subtraction

Considering that TTL noise is the result of optical set-up misalignment, it causes a change in the optical pathlength (δp) between spacecraft when the laser is transmitted or received. This is considered geometric TTL. Figure 1 gives a simple illustration of the change in pathlength as the laser beam reaches the test mass (a) and the MOSA (b). The incoming beam can reach the MOSA at an angle with components (η,φ) where ηcorresponds to pitch, and φcorresponds to yaw. These angular components are used to calculate the change in phase of the beam as equation 1 states.

$$\delta p = C_\eta \cdot \eta + C_\varphi \cdot \varphi \text{ (Eq. 1)}$$

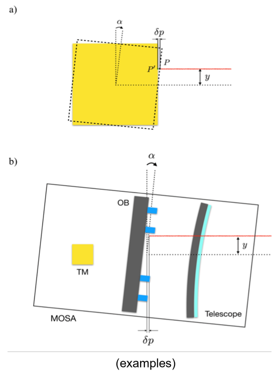


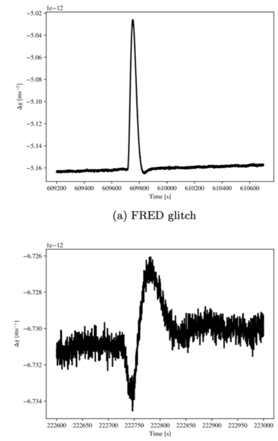
Fig. 1. simplified illustration of geometric TTL

C is a TTL coupling coefficient multiplied by the indicated degree of freedom. The LISA constellation requires 24 coupling coefficients which includes both geometric and non-geometric TTL contributions. There are 24 coefficients to account for six MOSAs each with two degrees of freedom and taking into account the transmitted and received laser beam. These coefficients would ideally be zero if there were no TTL noise present in the interferometer readout, but these values are expected to be at or near 2.3mm/rad [1].

The method for TTL subtraction is done post-processing, so the coupling coefficients cannot be estimated until after TDI is applied to the data. Since the mathematical relationship between the coefficients is simulated to be linear, TTL noise can be modeled into the the TDI as the direct sum of all 24 values [1]. Next, the jitters are measured with the Differential Wavefront Sensing (DWS) technique to produce the true jitter plus sensing noise. These terms are combined with the coupling coefficients. Using LISASim, a MATLAB based simulator for artificial LISA data, TTL coefficients are estimated for a 24 hour period of data via noise minimization which subtracts other noise sources already accounted for within the LISA noise budget. Lastly, the 24 hour time series of the estimated TTL noise is subtracted from the simulated noise sources so all that is left is the TTL contribution to the overall interferometer readout.

D. Glitches

LISA Pathfinder demonstrated the importance of glitches within space-bound gravitational wave detectors because of their high sensitivity. Glitches are isolated, transient events of different shapes and sizes that corrupt parts of the readout. LPF experienced a glitch population that has since been categorized into two groups: Fast Rise Exponential Decay (FRED) glitches and Sine-Gaussian glitches. FRED glitches are impulse carrying glitches and occur more commonly in the LPF population while Sine-Gaussian glitches are high frequency, low-impulse carrying glitches [4]. These are shown in Fig. 2. These glitches were dealt with by modeling them with shapelets to create a systematic glitch detector that can fit each identified glitch in LPF data to a template. This template was used to put each glitch into one of the two glitch types [2]. This model has successfully been able to subtract the effect of glitches from the Power Spectral Density (PSD) in LPF data. When translating this method to LISA, the two glitch types seen in LPF can be injected into artificial LISA data to study their impact on TTL coefficient estimation and subtraction.



(a) FRED glitch

(b) Sine-Gaussian glitch

Fig. 2. Two LPF glitch types in the form of shapelets

III. Methods

The glitches being used for this research are the result of testing different amplitudes, decay times, injections points, and injection times of glitch examples into artificial LISA data using the MATLAB based tool, LISASim. It is crucial to the analysis of simulated glitches that they have a sufficiently large amplitude and duration to be seen with respect to other noise sources. This is not including laser noise since TTL coefficient estimation and subtraction are done after TDI is applied. The amplitude of the original glitches from LPF are on the order of 10^{-14}m, so these glitches must be amplified for LISA in order to see their effect on the simulated PSD. The number of injected glitches must also be increased because LISA is comprised of three spacecraft rather than one. LPF's one spacecraft experienced roughly one glitch per 24 hour period, so this is scaled up to roughly three glitches per 24 hour period for LISA. Figure 3. shows examples of the two glitch types seen in LPF and the amplified glitches being used for this research. To see a worst case scenario for LISA, the FRED glitches are injected as sensing glitches rather than force noise glitches as seen in LPF. This allows for a bigger change in the PSD within the frequency window of interest 10^{-3} – 10^{-1} Hz.

The tests conducted in this research include many different configurations that LISA could possibly experience. Since we cannot assume glitches are present at this point in the data processing, the tests conducted must cover as many scenarios as possible. To start, two nominal data sets were produced that do not include any glitches, one with TTL noise and one without. These two data sets are used as references for where how much the injected glitches impact the subtraction of TTL. The following tests vary several key properties:

1. Glitch shape - FRED or Sine-Gaussian

2. Number of glitches - 1-3 glitches per test

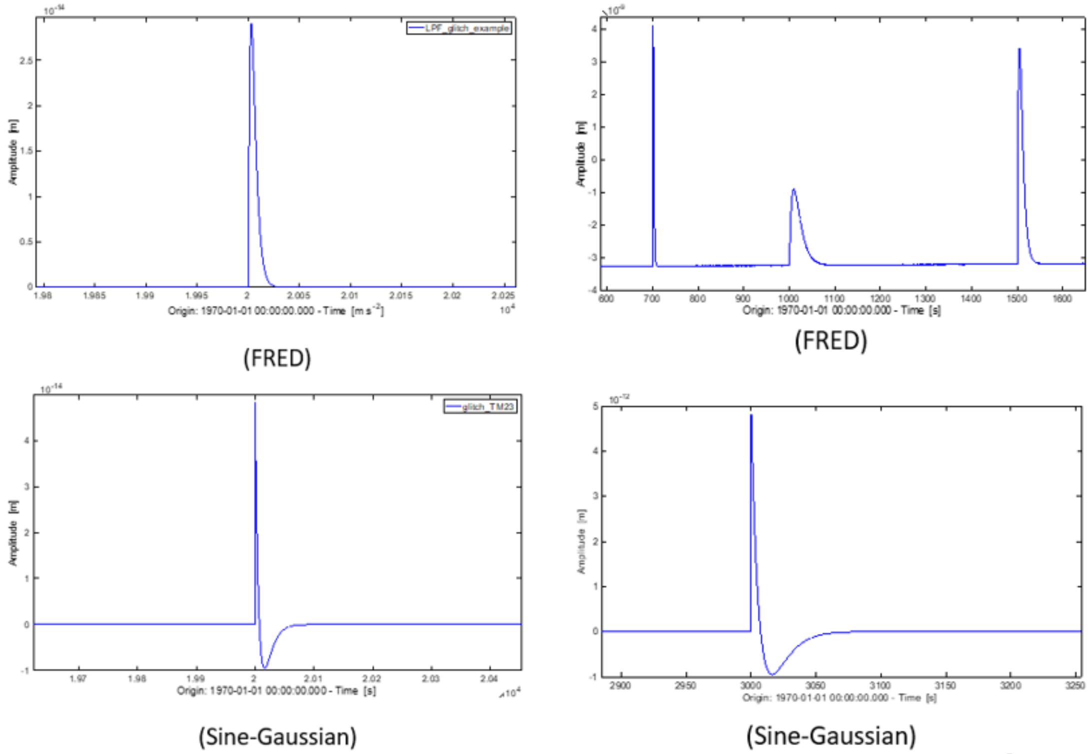


Fig. 3. The glitches for LISA Pathfinder (left) have very small amplitudes so they are increased for the simulated LISA glitch injections (right). The FRED glitches now have an amplitude on the order of 10^{-9}m and the Sine-Gaussian glitches have an amplitude on the order of 10^{-12}m

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3. Duration - spreading glitches over 1-24 hours of data
4. Injection point - spread over 1-3 TM IFOs or LA IFOs

IV. Results

After TTL subtraction from data sets including glitches, TTL noise was not always subtracted successfully across all frequencies within the window of interest. This is independent of whether or not the coupling coefficients were estimated properly. Fig.4 demonstrates an example of the TTL subtraction from one tested configuration. Both nominal cases (black and blue lines) on the plot act as references for where perfect subtraction should be and to how much the glitches affect the PSD respectively. The dashed green line is the corrected line for TTL once it is removed from the total noise signal (red line). If this had been a perfect subtraction, the dashed green line would match the black line since both do not contain TTL noise. However, at the second peak in the data, the TTL correction deviates from the nominal data. This is an indication that there are remnants of the injected glitch in the TTL subtraction that cannot be removed with this method which is a concern since glitches may not be distinguishable from the rest of the noise at this point in data processing.

Coefficient estimation was conducted one test at a time and then 24 values from each test were compiled into a single line shown on the root mean square plots below. The y-axis represents the deviation each set of 24 coefficients is from the initial coefficient estimation value of 2.3mm/rad. The dashed line at 0.1mm/rad is the required accuracy so it can easily be seen which tests fail the estimation.

Fig. 5 consists of all tests conducted for injecting FRED glitches into the TM IFOs. The two tests injecting three FRED glitches into three TM IFOs spread over 24 hours of the data period fail to accurately estimate the coefficients since they sit far above the dashed line.

Fig. 6 follows the same formatting as the first plot but these are for tests injecting Sine-Gaussian glitches. None of the tests fail the required accuracy and they all remain well below the dashed line. The tests injecting 3 Sine-Gaussian glitches over three TM IFOs spread over 24 hours of data did not affect the coefficient estimation at all like they had for the FRED glitches. So it is likely that the glitch amplitude used is too small and must be increased to see an effect.

Fig. 7 includes the tests where Sine-Gaussian glitches were injected into the long arm interferometers. Again, none of the tests fail the coefficient estimation. This is likely also a consequence of small glitch amplitude.

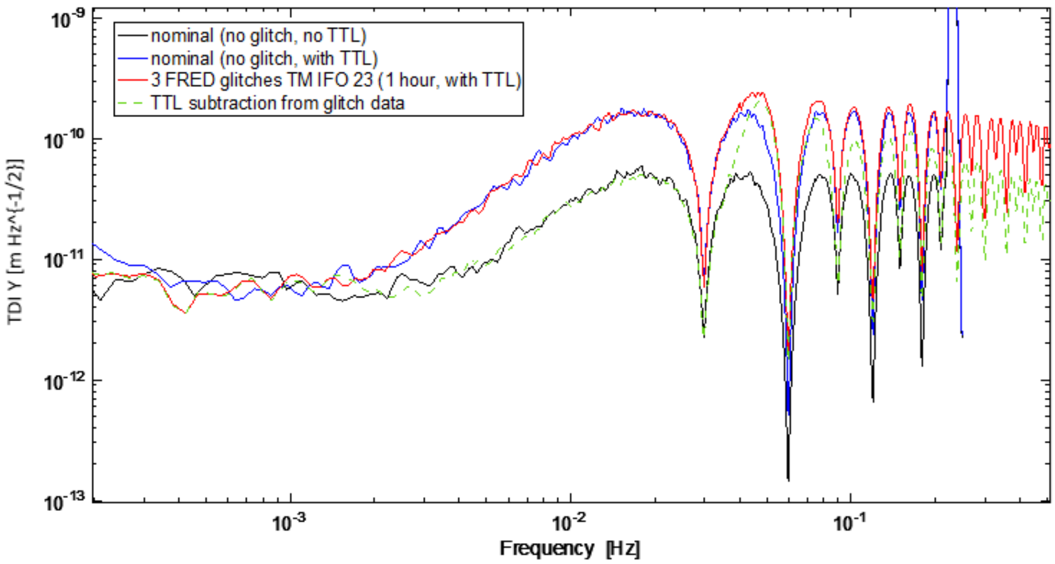

Fig. 4. Test conducted for three FRED glitches injected into TM IFO 23 spread over one hour of data.

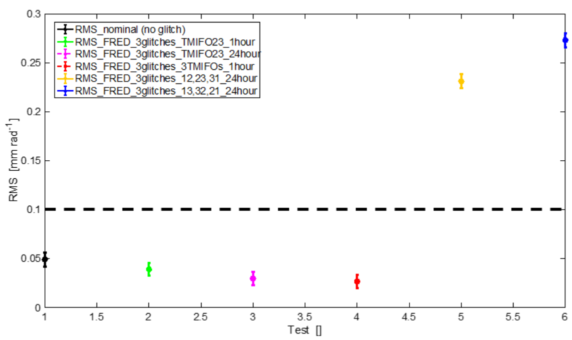

Fig. 5. Root mean square plot for FRED glitch test deviations

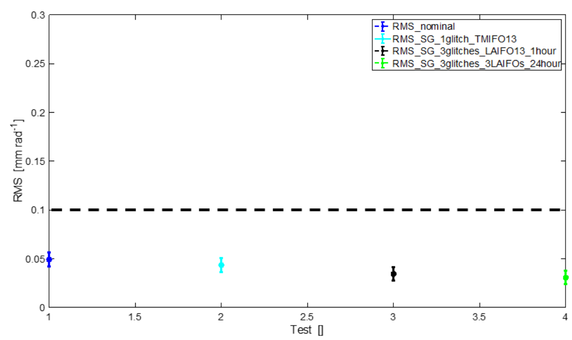

Fig. 7. Root mean square plot for LA IFO, Sine-Gaussian glitch test deviations

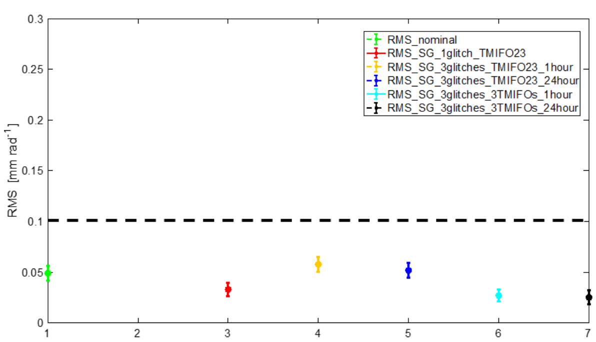

Fig. 6. Root mean square plot for Sine-Gaussian glitch test deviations

V. Conclusion

The original goal of this research was to study the impact of injected glitches on tilt-to-length subtraction and coefficient estimation using simulated LISA data. It was found that spreading three FRED glitches over time and test mass interferometers creates the biggest impact on the PSD to disturb the coefficient estimation. Further analysis of the two configurations that gave these results is required to better understand why this happens. Additionally, other combinations of three glitches injected into three test mass interferometers spread over 24 hours will be tested to see if the same results can be produced. To improve the small Sine-Gaussian glitch amplitudes, an amplitude of 10^{-9}m is required to see a comparable effect on the PSD as the FRED glitches. The same tests as described in this paper for the TM IFOs and LA IFOs can be conducted again with this new glitch amplitude. Having tested such a large array of configurations to see the effects of glitches on artificial LISA data, a more improved method for eliminating TTL noise can be developed.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

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